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Interpretation of Dye Tracing Data Collected November 13–December 2, 2017, at the Savoy Experimental Watershed as part of the Advanced Groundwater Field Techniques in Karst Terrains Course, Savoy, Arkansas

Scientific Investigations Report 2019–5016

U.S. Department of the Interior
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Top Left. Students observing dye emerging from Wow Spring near Savoy, Arkansas (photograph taken by Eve Kuniansky, U.S. Geological Survey).

Top Right. RhodamineWT dye emerging from Langle Spring and coloring the water behind the weir near Savoy, Arkansas (photograph taken by Cassi Crow, U.S. Geological Survey).

Bottom Right. RhodamineWT dye injection at sinking stream upgradient of Langle Spring, Savoy, Arkansas (photograph taken by Joshua Blackstock, University of Arkansas).

Cover. Fluoroscein dye entering the Illinois River downstream of Wow Spring near Savoy, Arkansas (photograph taken by Cassi Crow, U.S. Geological Survey).

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J. Van Brahana

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U.S. Department of the Interior
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Field method courses require intensive logistical effort in planning and arranging equipment and qualified equipment operators. This first U.S. Geological Survey (USGS) course GW2227 Advanced Groundwater Field Techniques in Karst Terrains was in planning stages with hydrologists from the USGS Water Mission Area offices in Little Rock and Fayetteville, Arkansas, and Austin, Texas; faculty at the University of Arkansas; and the USGS Water Mission Area Groundwater Specialists at Headquarters beginning in earnest in 2014. The course would not have happened if not for the assistance of faculty members from the Department of Geosciences, University of Arkansas (UA). Emeritus Professor J. Van Brahana, who set up the Savoy Experimental Watershed (SEW) in the pastures of the Department of Animal Science beef farm, has conducted numerous UA HydroDays workshops, conducted numerous student research projects at the site, and assisted with the dye tracer testing part of the course. Associate Professor Matt Covington provided the use of two submersible field fluorometer/data loggers and use of his laboratory and laboratory spectra-fluorometer for the quantitative dye tracing part of the course. Adjunct Professor Fred Paillet assisted in teaching the borehole dye dilution part of the course. Additionally, Matt Covington allowed Joshua Blackstock, a Ph.D. candidate at UA, to use his laboratory for developing standards and for conducting work related to the tracer tests; Joshua Blackstock also assisted in teaching and conducting the field exercises for both the point-to-point and quantitative dye tracing.

Finally, thanks go to the USGS Texas Water Science Center for sending geophysicists, equipment, and instructors to help with the surface and borehole geophysics and the USGS Branch of Geophysics for supporting the course by providing temperature equipment and an instructor for the course.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per minute (ft/min)	0.3048	meter per minute (m/min)
foot per hour (ft/h)	0.3048	meter per hour (m/h)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($[ft^3/s]/mi^2$)	0.01093	cubic meter per second per square kilometer ($[m^3/s]/km^2$)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) or World Geodetic System 1984 (WGS 84) as noted and in the conterminous United States, for all practical purposes the geographic coordinates for WGS84 are equivalent to NAD83 with handheld global positioning system units.

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Use of liter (L) as a special name for cubic decimeter (dm3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter.

Abbreviations

CST	Central Standard Time
nm	nanometer
NWIS	National Water Information System
PME	Precision Measurement Engineering, Inc., Vista, California
ppm	parts per million
ppb	parts per billion
r^2	coefficient of determination
RWT	RhodamineWT
SEW	Savoy Experimental Watershed, University of Arkansas, Savoy, Arkansas
UA	University of Arkansas
USGS	U.S. Geological Survey

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By Eve L. Kuniansky,[1] Joshua M. Blackstock,[2] Daniel M. Wagner,[1] and J. Van Brahana[2]

Abstract

The first course on the use of advanced groundwater field techniques for karst aquifers was conducted November 13–17, 2017, at the University of Arkansas Savoy Experimental Watershed (SEW), which is located on pastures for beef livestock research conducted by the Department of Animal Sciences at the University of Arkansas at Savoy, Arkansas. The SEW is an interdisciplinary, collaborative, long-term research site for the study of animal-waste management in a mantled karst setting. The course focused on advanced field activities appropriate for karst aquifer studies: dye tracing, groundwater/surface-water interactions, geophysical methods, and geochemistry. This report summarizes the data collected and interpreted from the dye tracing part of the November 2017 course, other USGS field courses, and past dye tracing investigations conducted by University of Arkansas students.

Introduction

The first U.S. Geological Survey (USGS) "Advanced Groundwater Field Techniques in Karst Terrains GW2227," course was held November 13–17, 2017, in Fayetteville, Arkansas, with field data collection at the University of Arkansas (UA) Savoy Experimental Watershed (SEW) at Savoy, Arkansas. The SEW is an interdisciplinary, collaborative, long-term research site for the study of animal-waste management in a mantled karst setting. Planning for this first course began in 2014 with meetings in Fayetteville, Ark. The final list of instructors, including biographical information, is provided in appendix 1. The USGS has used the SEW for the course "Introduction to Groundwater Field techniques GW1227" twice—April 13–17, 2015, and March 6–10, 2017—with a focus on well and spring inventory. These two introductory courses provided an opportunity for initial reconnaissance and development for the advanced course discussed in this report. Additional planning for the course leveraged site experience and knowledge gained while conducting research at the SEW by several of the USGS instructors who received degrees from UA.

The SEW was conceived and developed by UA Department of Geosciences Professor J. Van Brahana as a premier water-quality research collaborative beginning in the 1990s. In addition to the UA Department of Geosciences, original collaborators included the UA Department of Animal Science, the USGS office in Fayetteville, Ark., and other UA departments. The SEW is located about 10 miles west of the main UA campus in Fayetteville at Savoy, Arkansas. Numerous research studies have been conducted at the SEW. Appendix 2 lists known graduate student research theses, dissertations, and papers updated from the list in Brahana (2011), which summarizes some of the lessons learned from field research at the SEW. Brahana (2011) was published as part of the USGS Karst Interest Group Proceedings (Kuniansky, 2011), which includes other research from the SEW and the Ozarks Plateau aquifer system; the Karst Interest Group workshop was hosted by the University of Arkansas Department of Geosciences in April 2011.

The main objective of the advanced groundwater field techniques course (GW2227) was to introduce USGS hydrologists and hydrographers to field methods that can be used to understand groundwater flow in karst and fractured rock aquifer systems. The course focuses on advanced field activities appropriate for karst aquifer studies: dye tracing, groundwater/surface-water interactions, geophysical methods, and geochemistry. The planned agenda for the course is provided as appendix 3.

[1]U.S. Geological Survey.

[2]University of Arkansas.

Purpose and Scope

The purpose of this report is to document the interpretation of the dye tracing data collected during and after the "Advanced Groundwater Field Techniques in Karst Terrains GW2227" course and provide links to the companion USGS data release (Kuniansky, 2019), such that the data and interpretation of the data are preserved for planning future courses at the SEW. Additionally, guidance for future dye tracing investigations is provided. Most of the data were collected during the course; however, some dye trace and geophysical data collection both preceded the course and continued after the course ended. Personnel from the USGS Texas Water Science Center conducted reconnaissance for surface and borehole geophysical activities and began data collection prior to the course. The point-to-point and quantitative dye tracing activities began November 13–15, 2017, with preliminary results discussed on November 16 during the course; however, the field fluorometers for RhodamineWT (RWT) dye detection were placed at two springs to begin logging on November 13 and were left at the site until December 2, 2017. The investigation of groundwater/surface-water interactions included seepage run analysis, dye/salt dilution methods, temperature methods, one-dimensional heat flux methods with field activities conducted during the course; some preparation was conducted on Sunday, November 12, and Monday, November 13. All field data were collected at the SEW.

Description of the Savoy Experimental Watershed

The SEW is located at Savoy, Ark., approximately 10 miles west-northwest of the main UA campus in the city of Fayetteville in northwest Arkansas. The SEW is bounded on the north and west by the Ozark National Forest and on the south and east by small private farms involved in cattle and poultry operations. Six delineated watershed basins intersect the 4.82 square-mile (mi^2) property of the SEW (fig. 1). The basin numbering is from Brahana (2011). Only small parts of basins 4, 5, and 6 intersect SEW property and basin 3 touches a corner of the SEW. The data collection occurred within basin 1. The datasets for the quantitative dye trace are available as a USGS data release (Kuniansky, 2019).

The SEW is in the southern Ozarks on the Springfield Plateau and is underlain by several carbonate-rich strata—considered a mantled karst terrain. "The karst of the SEW is not immediately apparent to most people. The setting is a dissected plateau with steep, dry valleys and few sinkholes. In most of the area, regolith covers the bedrock, leaving a thin, rocky soil that masks the carbonate bedrock beneath. The SEW is typical of the Springfield Plateau province of the Ozark highlands. Most of the site (>70 %) is covered in second- and third-growth forests, and the remaining land is in pasture" (Brahana, 2011) as can be seen in the aerial image in figure 2.

The SEW has pastures for beef livestock of the UA Department of Animal Science (approximately 30 percent of the area, mostly in surface watershed basins 1 and 6, see figures 1 and 2). The terrain is somewhat hilly. The upland altitude is about 1,220 feet (ft) at ridges, and the Illinois River flood-plain altitude is about 1,020 ft (National Geodetic Vertical Datum of 1929 [NGVD 29]). Thus, there is an approximate 200-ft range in altitude from ridges to the Illinois River. Weathered-in-place regolith overlies the original carbonate rocks and the regolith varies in thickness from 0 to approximately 10 ft. Regolith is a region of loose unconsolidated rock and dust that sits atop a layer of bedrock. The soil and regolith layers at land surface help store infiltrated rainwater, which is slowly released to the epikarst and base-level springs.

The karst groundwater system at the SEW is composed of a chert-rich carbonate-rock sequence that has been selectively dissolved to form an open network of caves, enlarged fractures, bedding planes, conduits, sinking streams, and springs. Groundwater flow within wider aperture conduits typically is rapid with flow directions difficult to predict, interaction between surface and groundwater typically extensive, and contaminant attenuation processes inherent within porous media groundwater systems absent (White, 1988; Ford and Williams, 2007; Palmer, 2007; Brahana, 2011).

The relatively flat-lying formations of the Springfield Plateau have been affected by reactivated basement faulting associated with the Ouachita orogeny during early Mississippian time (Brahana, 2011). The stratigraphy at the SEW from top to bottom is as follows: soil and weathered carbonates that form a mantle of regolith or epikarst, Boone Limestone, St. Joe Limestone (the Boone Limestone and St. Joe Limestone are considered members of the Boone Formation by the Arkansas Geological Survey), and Chattanooga Shale, which is incised by quaternary alluvium along the Illinois River flood plain. The Boone Formation (Boone and St. Joe limestones) are Mississippian in age and the Chattanooga Shale is Devonian in age. A photograph taken from the flood plain 0.5 miles south of SEW facing east from the flood plain east of the Illinois River north of Highway 16 with farm road 845 (also called West University of Arkansas Beef Farm Road) at the base of the bluff shows formation or rock contacts delineated by J. Van Brahana (fig. 3, location of where photo taken shown on fig. 1). Over time, weathering has created fractures within these formations, creating the mantle-karst properties at the site. The St. Joe Limestone member of the Boone Formation is a fine-grained, crinoidal limestone that contains chert beds (Chandler, 2001). At the SEW, the upper Boone Limestone ranges in thickness from 0 (where eroded) to 30+ ft thick, and the St. Joe Limestone ranges from 0 where eroded and missing in the flood plain to 20± ft thick, with the Chattanooga Shale being more than 50 ft thick.

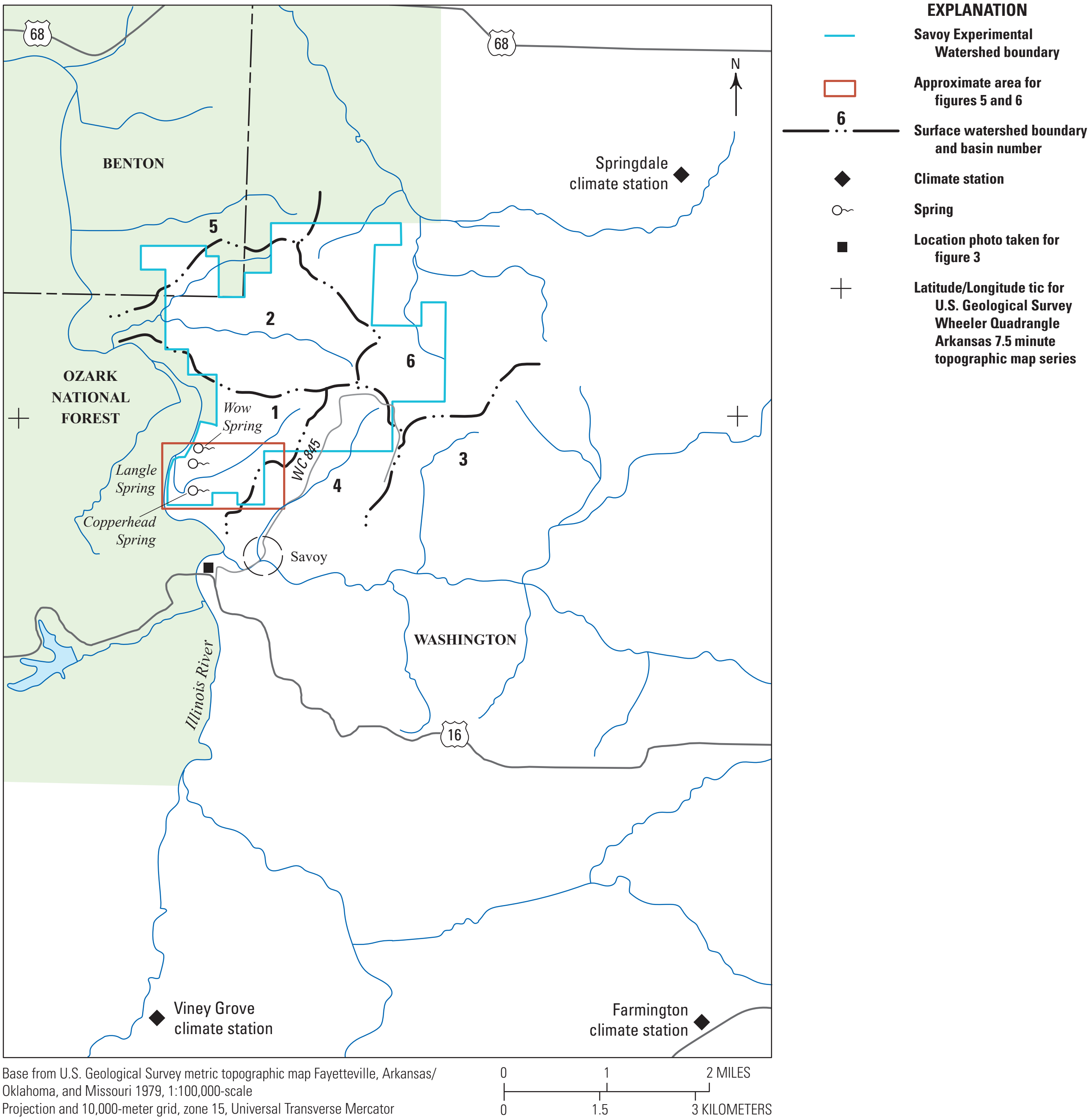

Figure 1. Location of Savoy Experimental Watershed and six surface watershed boundaries (modified from Brahana, 2011).

Chert within the Boone Formation is insoluble; however, limestone when exposed to rainwater over time dissolves, and miniature caves (that is, solution channels) form within the limestone. In turn, water flows laterally across chert until it moves downward through a vertical fracture or reaches an outlet at an exposure of the formation at land surface. There is some speculation that linear stream segments formed along joint or graben structures where rainwater more easily moved into the rocks and dissolved the limestone (Brahana, 2011). Mechanical and chemical dissolution processes facilitate chert gravel formation within the epikarst and within streams that incise the Boone and St. Joe Limestones with many of the epikarst springs issuing from the top of slightly dipping chert planes (fig. 4).

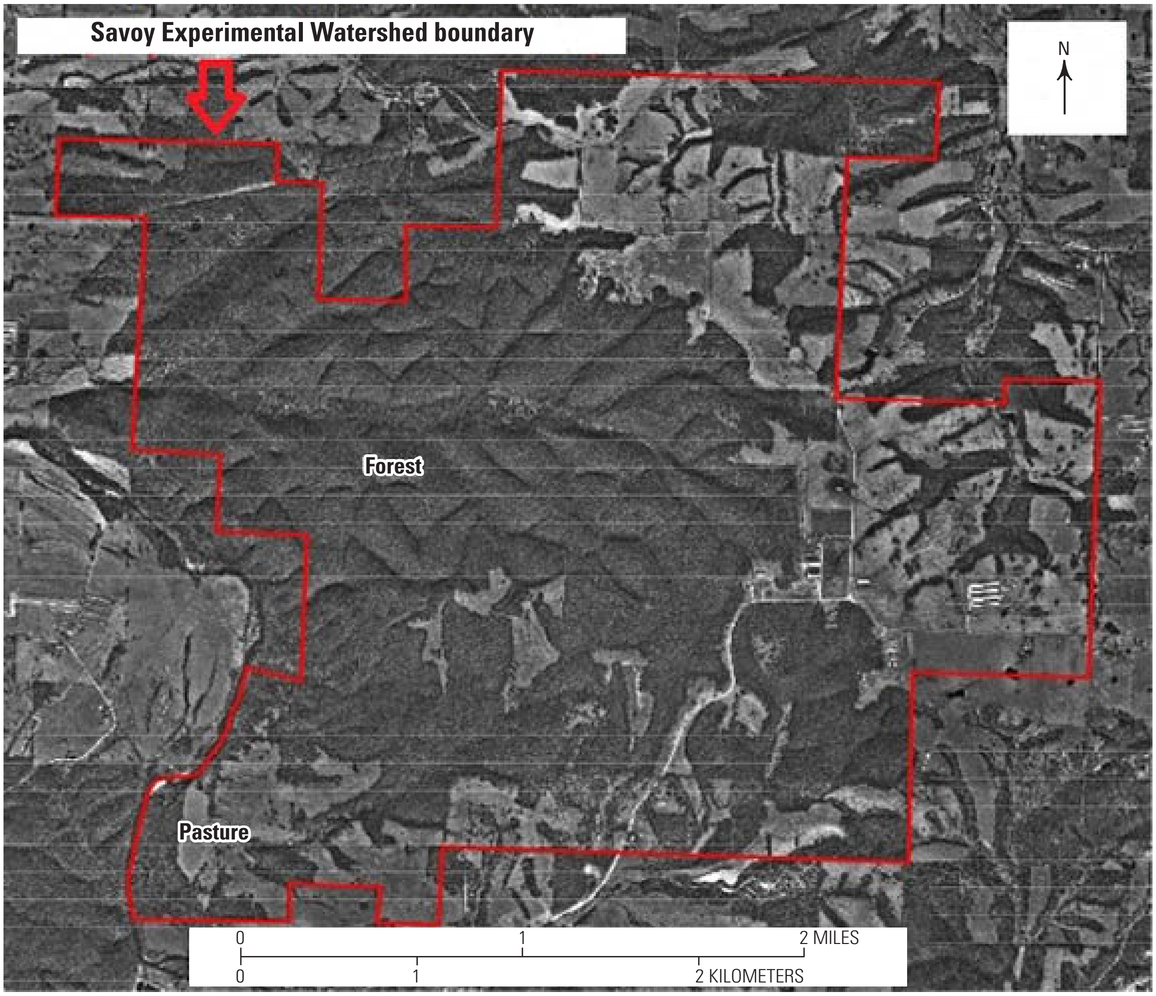

Figure 2. Aerial image of the Savoy Experimental Watershed (SEW) (modified from J. Van Brahana, November 2017 class presentation).

The Illinois River graben forms the western boundary of watershed basin 1 along the Illinois River at the SEW (fig. 1). A fault along the graben was identified by displacement of the St. Joe-Chattanooga contact, an escarpment, and the appearance of springs along the escarpment base during wetter than average rainfall, and a zone of low permeability. Geophysical studies, field reconnaissance, and surveying helped map the top of the Chattanooga Shale and other structures at the SEW (Stanton, 1993; Unger, 2004). Observations indicate that the fault along the Illinois River graben serves as a groundwater dam, which focuses groundwater discharging to Langle and Copperhead Springs (fig. 1).

Several springs at the SEW have permanent weirs in place that have been gaged at varying times in the past. Langle and Copperhead Springs formed at the contact between the Boone Limestone and the underlying St. Joe Limestone and are the base-level springs in the surface watershed basin 1 boundary (fig. 1). Discharge from Langle and Copperhead Springs flows to the Illinois River. The Illinois River flood plain overlies the Chattanooga Shale, which prevents immediate infiltration of surface water to the underlying aquifers (Hamilton, 2001).

Numerous small epikarst springs issue from the top of slightly dipping chert planes within the upland areas at the SEW (fig. 4). The topographic map of part of basin 1 at the SEW (fig. 5) reflects the inferred dip of chert beds. In addition to the almost north-south Illinois River graben, the incised stream valley approximately perpendicular to the Illinois River graben may have been formed along another graben because there is a slight difference in the dip direction of the chert beds north of this intermittent and sinking stream from beds to the south of the stream.

During the field methods course held at the SEW during March 2017, the incised stream valley (labeled “Graben along incised valley???” in figs. 5 and 6) was mostly dry and was completely dry at the dirt road just north of Tree Spring. In fact, any flow in the valley segment north of Tree Spring and the road had sunk underground. According to course

Figure 3. Annotated photograph of geologic contacts taken from the flood plain looking east near the Illinois River at Arkansas Highway 16 at the outcrop along the West University of Arkansas Beef Farm Road (labeled WC Rd 845, fig. 1), Savoy, Arkansas (photograph by J. Van Brahana, February 25, 2012).

instructors that have done research at the site over many years, the intermittent stream shown on the topographic map flows as one stream only during flood events. Tree Spring, as well as the other epikarst springs upslope from the incised valley, generates a small stream that flows to the west, downslope in watershed basin 1. (See the aerial image in fig. 6 from early 2018 of approximately the same area as the topographic map in fig. 5.) This small stream from the epikarst springs near Tree Spring completely sank into the ground at the location where the RWT dye was injected for the quantitative dye tracing part of the course (figs. 5 and 6).

Perched groundwater that moves laterally and discharges to small springs and then sinks underground is typical of epikarst springs in northwest Arkansas. Several course activities took place near these epikarst springs: discharge measurements using salt dilution were made, temperature methods for calculating discharge were demonstrated, and volumetric discharge measurements were made (Kurylyk and others, 2017; Rantz, S.E., 1982). Table 1 provides information about these named springs from signs posted at the SEW; latitude and longitude data, in North American Datum of 1983, and altitude data, in feet NGVD 29, were retrieved from the USGS National Water Information System (NWIS; https:waterdata.usgs.gov/nwis, accessed, October 29, 2014, to retrieve site information for wells and springs within SEW for earlier training classes) or were gathered by handheld Global Positioning System and are included if available. The altitudes of the springs, in meters above mean sea level, as posted on signs at the site were assumed to be accurate but were not an exact match when converted to feet and compared to the altitudes in NWIS; it is not known which altitude is more accurate.

The climate in the area is considered humid continental. Average annual precipitation in Fayetteville, Arkansas, is 45 inches. Winters are short and mild with brief periods of snow cover and frost with a mean January low of 26 degrees Fahrenheit (°F) and average snowfall of 2 inches. Summers are long, warm, and humid with a mean July and August high temperature of 89 °F. Rainfall occurs throughout the year with monthly average rainfall ranging from 2 to 5 inches and monthly rainfall greater than or equal to 4.5 inches in May and June and less than 3 inches in January and February (U.S. climate data, 2018a).

Daily precipitation at SEW from November 1 through December 2, 2017, was estimated by averaging daily rainfall data, when available, from one to three nearby weather stations (table 2, locations shown on fig. 1). As shown in table 2, it was dry during the 12 days preceding, during, and immediately after the field methods course. Total precipitation was estimated to be 1.42 inches for the month of November with the majority falling during the last 2 days of November and no precipitation the first 2 days of December (fig. 7). Daily temperatures in Fayetteville were mild with lows ranging from 34 to 51 °F and highs from 54 to 70 °F during the course (U.S. climate data, 2018b). Daylight hours were short; thus, evapotranspiration was assumed to be zero during the course.

Figure 4. Photograph of Tree Spring (see figs. 5 and 6 for location), an epikarst spring flowing on top of a chert layer forming the headwater of a small stream that picks up flow from a few other springs before sinking underground at the Savoy Experimental Watershed, Arkansas (photograph provided by Cassi Crow, November 2017, taken looking to the southeast).

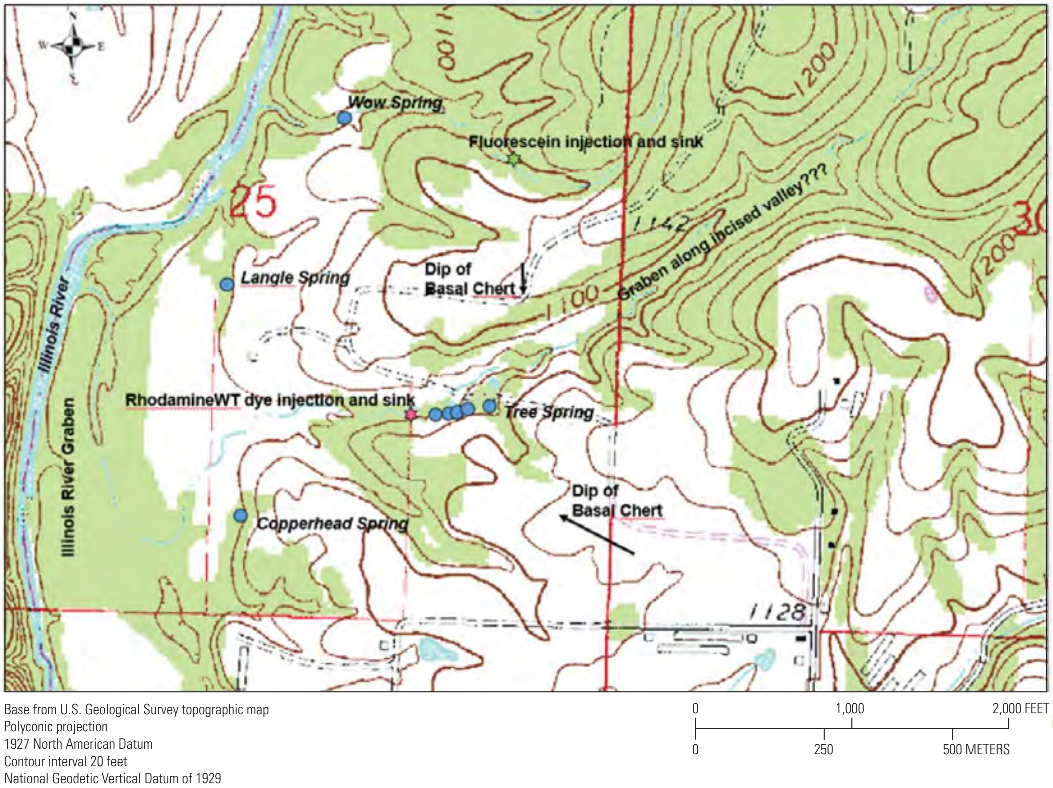

Figure 5. Topographic map of basin 1 at Savoy Experimental Watershed, Arkansas (modified from J. Van Brahana training materials, November 13, 2017).

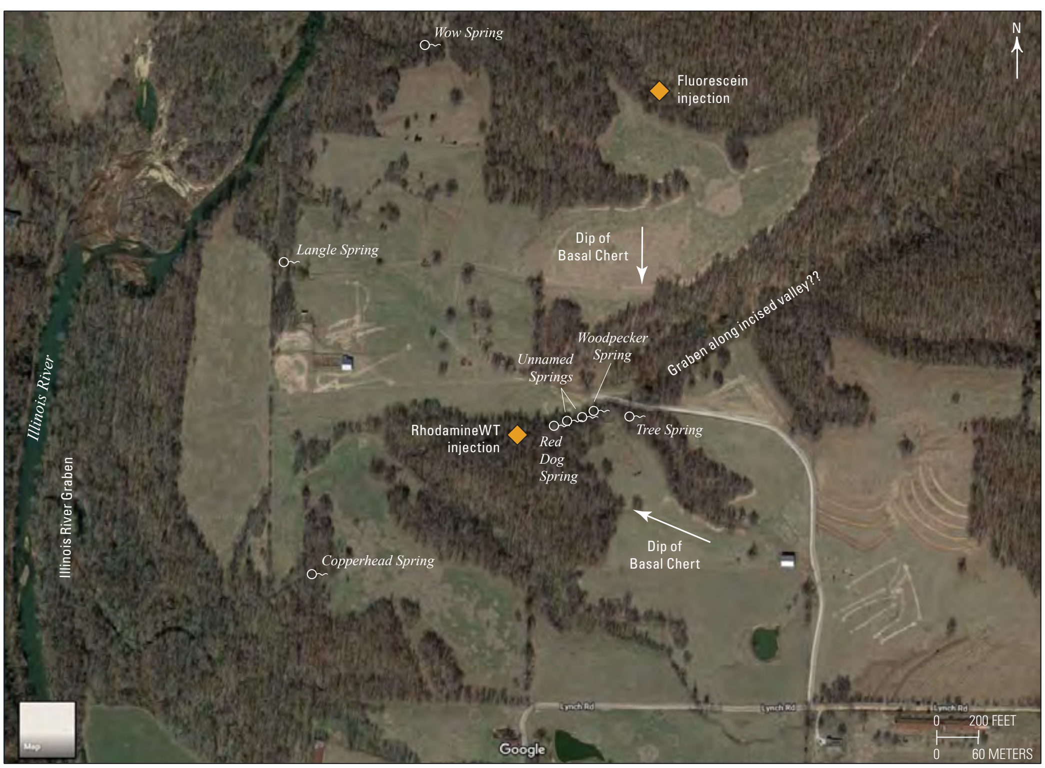

Figure 6. Aerial image of basin 1 at Savoy Experimental Watershed, Arkansas (modified from Google maps, April 21, 2018).

Table 1. Information on some of the springs, miscellaneous discharge measured, and rhodamineWT dye injection location collected during the class at the Savoy Experimental Watershed, Basin 1, Savoy, Arkansas.

[GPS, Global Positioning System; latitude in decimal degrees; n.d. (no data), indicates that a data observation was not reported; NAD83; longitude in decimal degrees NAD83; L/s, liters per second; NGVD29, National Geodetic Vertical Datum of 1929; NWIS, National Water Information System; USGS, U.S. Geological Survey]

Name	USGS Site ID	[1]latitude	[1]longitude	Description	Altitude (m) NGVD29	Typical discharge low (L/s)	Typical discharge high (L/s)	Discharge during class November 13–15, 2018 (L/s)	Comment
Base springs in Basin 1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Langle Spring	71948218	36.118969	−94.345489	Underflow spring, St. Joe Formation	314.32	0.85	89.5	2.9	From rating curve
Copperhead Spring	71948215	36.114802	−94.345211	Overflow spring, St.Joe Formation	314.39	0.293	379	0.4	Volumetric measurement
Epikarst Springs in Basin 1 and locations of discharge from salt dilution and temperature parts of class									
Tree Spring	n.d.	36.116915	−94.339859	Epikarst of the Lower Boone Formation	328.22	0.09	0.62	0.23	Volumetric measurement
Discharge measured in stream downstream of Tree, but upstream of Woodpecker	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.32	From salt dilution
Woodpecker Spring	n.d.	36.116983	−94.340355	Epikarst of the Lower Boone Formation	325.63	0.05	0.38	0.062	From salt dilution
No sign on fence spring more to the east between Woodpecker and Red Dog	n.d.	36.116836	−94.340628	Epikarst of the Lower Boone Formation	n.d.	n.d.	n.d.	Very small trickle	Visual observation
No sign on fence spring more to the west between Woodpecker and Red Dog	n.d.	36.116822	−94.340762	Epikarst of the Lower Boone Formation	n.d.	n.d.	n.d.	Very small trickle	Visual observation
Red Dog Spring	n.d.	36.116784	−94.340854	Epikarst of the Lower Boone Formation	324.29	0.06	0.48	0.096	From salt dilution
Discharge measured in stream downstream of Red Dog but before stream begins to lose flow to karst	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.64	From salt dilution
Discharge measured in stream right before all goes into sink where dye was injected	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.35	From salt dilution
Location of RhodamineWT dye injection	n.d.	36.116813	−94.341281	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Point to Point Tracer Test Spring	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Wow Spring	n.d.	36.121810	−94.343023	n.d.	n.d.	n.d.	n.d.	Very small trickle	Visual observation

[1]Latitude and longitude data for Langle and Coppperhead Springs from NWIS (North American Datum 1983 [NAD83]) all the other spring locations from Joshua Blackstock GPS unit reporting maximum location error 16 feet (World Geodetic System 1984, which for practical purposes is the same as NAD83 in the conterminous United States).

Table 2. Daily precipitation from nearby climate observation stations near the Savoy Experimental Watershed, Arkansas, November–December 2, 2017.[1]

[in., inches; T, values in the precipitation or snow category indicate a "trace" value was recorded; n.d. (no data), indicates that a data observation was not reported; pink shade is quantitative tracer test period of data collection]

DATE	Station: Farmington 0.6 WSW, AR US US1ARWS0025 current location: elev: 1205 ft. lat: 36.0378° N long: –94.2507° W (in.)	Station: Springdale 6.4 WSW, AR US US1ARWS0032 current location: elev: 1270 ft. lat: 36.1584° N long: –94.2571° W (in.)	Station: Viney Grove 2.4 NW, AR US US1ARWS0022 current location: elev: 1193 ft. lat: 36.0449° N long: –94.3576° W (in.)	Average precipitation (in.)
11/1/2017	0.05	T	0.02	0.04
11/2/2017	0.01	0	0	0.01
11/3/2017	n.d.	0	0	0.00
11/4/2017	n.d.	0	0	0.00
11/5/2017	n.d.	0	0	0.00
11/6/2017	n.d.	0	0	0.00
11/7/2017	0.1	0.17	0.11	0.13
11/8/2017	0.06	0.02	0.02	0.03
11/9/2017	n.d.	0	0	0.00
11/10/2017	n.d.	0	0	0.00
11/11/2017	n.d.	0	0	0.00
11/12/2017	n.d.	0	0	0.00
11/13/2017	n.d.	0	0	0.00
11/14/2017	0.04	T	0.02	0.03
11/15/2017	0.25	0.3	0.12	0.22
11/16/2017	0.03	n.d.	0	0.02
11/17/2017	n.d.	n.d.	0	0.00
11/18/2017	n.d.	n.d.	0	0.00
11/19/2017	n.d.	n.d.	0	0.00
11/20/2017	n.d.	n.d.	0	0.00
11/21/2017	n.d.	n.d.	0	0.00
11/22/2017	n.d.	n.d.	0	0.00
11/23/2017	n.d.	n.d.	0	0.00
11/24/2017	n.d.	n.d.	0	0.00
11/25/2017	n.d.	n.d.	0	0.00
11/26/2017	n.d.	n.d.	0	0.00
11/27/2017	n.d.	n.d.	0	0.00
11/28/2017	n.d.	n.d.	0	0.00
11/29/2017	0.25	0.59	0.98	0.61
11/30/2017	0.22	1.3	0.1	0.54
12/1/2017	n.d.	0	0	0.00
12/2/2017	n.d.	0	0	0.00
Total during period				**1.42**

[1]Data are from the U.S. Department of Commerce, National Centers for Environmental Information, obtained April 11, 2018.

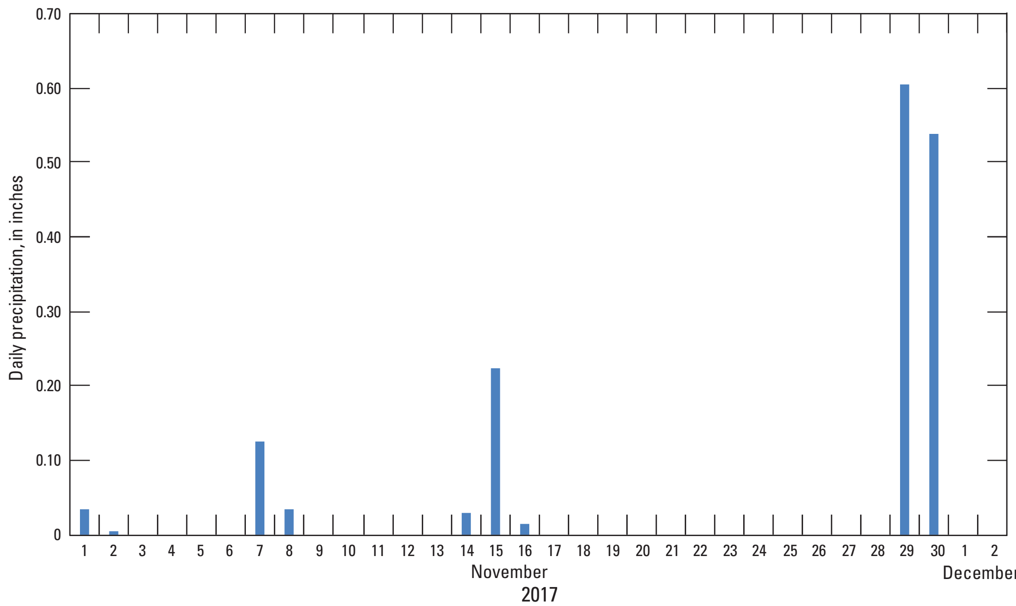

Figure 7. Estimated daily precipitation at Savoy, Arkansas, November 1–December 2, 2017.

Fluorescent Dye Tracing

Two types of dye trace field experiments were conducted as part of the groundwater field methods course: point-to-point and quantitative dye traces. Numerous dye traces have been conducted at the SEW (Brahana, 2011); however, previous dye traces were not conducted under the dry conditions and low flows observed at both Langle and Copperhead Springs during this course. To prevent dye interference between the point-to-point and quantitative dye, the quantitative test was conducted using RWT (red dye fluorescence peak around 575 nanometers) in basin 1 that was known to flow toward Langle and Copperhead Springs, and the point-to-point test was conducted using fluorescein (green dye fluorescence peak around 510 nanometers) in a different spring subbasin of basin 1 that flows toward Wow Spring (altitude is slightly higher than Copperhead Spring and Langle Spring based on estimation from the topographic map; fig 5). In this way, if both dyes show up at any of the springs, the injection location will be confirmed. If only one dye is used or two dyes with a similar fluorescence peaks at two injection locations, it would be uncertain of the source of the dye emerging from any spring.

For many epikarst dye traces, it is necessary to use a tanker of water to flush the dye into the unsaturated zone, particularly if rainfall during the study period is minimal. If a sinking stream is present, however, there may be no need to supply additional flushing water. Moreover, the introduction of large flushing volumes of water may induce groundwater flow paths that are uncharacteristic of the groundwater system even during high-flow events. Although the SEW is in an epikarst area, there were sinking streams upgradient from known discharge springs and thus no tanker or flushing water was required. In general, if flushing water is required, deionized water should be used.

Point-to-point tracer tests at the SEW were generally conducted to determine if a sink was connected to a specific outlet location (such as a well, spring, or cave). Hydraulic connections can be verified with visual confirmation or through the deployment of "bugs," which are dye-absorbent material, typically activated carbon, in a flow-through mesh bag that is anchored in the well, stream, or spring (fig. 8). If used, the bugs absorb the dye and can be deployed for days or months before retrieval and analysis. These qualitative tests are commonly used and are almost always performed before a quantitative tracer test is conducted. In practice, point-to-point tests determine which sinks are connected to which outlets but are often conducted over long periods whereby the exact time it takes for the dye to move through a system cannot be the primary objective. If bugs are retrieved and replaced with new bugs sub-daily, daily, or at weekly intervals, the approximate number of days or weeks for the dye to reach the outlet can be estimated. If activated carbon bugs are used in a qualitative point-to-point test, a laboratory spectra-fluorometer can be used with the elutant from the bugs (an elutant liquid is used to remove dye from the activated carbon bugs). Although the instructors brought bugs for the dye trace and had these anchored at several springs, the bugs were for demonstration purposes and were not analyzed.

Quantitative tests can provide detailed information regarding hydraulic properties (hydraulic conductivity, contaminant travel time) for a karst aquifer, but are far less commonly conducted than point-to-point tracer tests. Quantitative tests require information on the amount of dye injected and the time series of concentration and groundwater discharge (spring flow or well discharge rates and concentration). With fluorescent dye tracers, a field fluorometer and data logger typically are calibrated with standards in the field according to the manufacturer's instructions, and the equipment is installed at the discharge location. Grab samples, however, are collected frequently, and a laboratory spectrafluorometer is calibrated with standards and the grab samples are analyzed in the laboratory. It is always advisable to collect and analyze grab samples even when a field fluorometer/data logger is deployed.

References for conducting dye tracing in karst include Mull and others (1988a), Aley (2002), Field (2002, 2003), Worthington and Smart (2003), and Goldscheider and others (2008). Some USGS reports that include tracer testing are Mull and others (1988b), Mull (1993a, 1993b), Robinson (1995), Bayless and others (1994), Taylor (1997), Kidd and others (2001), Spangler and Susong (2006), Kozar and others (2007), Long and others (2012), and Spangler (2012).

Past Dye Tracing at Langle and Copperhead Springs

Past dye tracing and flow monitoring at Langle and Copperhead Springs under various hydrologic conditions have shown that the spring-basin size is related to groundwater levels in basin 1 (Brahana, 2011). Both Langle and Copperhead Springs are base-level underflow springs in basin 1; however, Langle is the lowermost underflow spring with the spring outlet being approximately an inch lower than Copperhead. During storm events, Copperhead Spring typically flows at a greater discharge rate than Langle Spring, indicating that the dissolution openings feeding Copperhead are larger than those feeding Langle. In addition, more water can be transmitted to Copperhead Spring at higher groundwater-level conditions; however, Langle Spring maintains greater flow during dry conditions (fig. 9). During the course, both springs flowed at almost a constant rate. Volumetric measurements were made at both springs, using a stopwatch and a 2-liter (L) graduated cylinder. Flow at Copperhead Spring remained constant at 0.4 liter per second (L/s; 0.01 cubic foot per second [ft^3/s]). The standard deviation from multiple teams conducting volumetric measurements during the course was 0.01 L/s (0.0004 ft^3/s). During the course, the instructor demonstrated how to use the acoustic flow instrumentation and monitored the stage behind the weir at Langle Spring. This monitoring indicated a constant flow of 2.9 L/s (0.1 ft^3/s) or 10 times the low flow of Copperhead Spring. Langle Spring has not been observed to go dry historically, but Copperhead Spring was observed to be dry for a few days in the late summer of 1998 (fig. 9). Although there are only 2 years of flow data available in NWIS for these two springs, the flow during the course was similar to the lowest observed flow for 1997–98 at both springs (NWIS; https://waterdata.usgs.gov/nwis accessed April 17, 2018, to retrieve this flow data).

A previous dye tracing study at the SEW in April of 2001 was conducted at high discharges and groundwater levels using RWT dye and salt (chloride measured). RWT was poured into the sinking stream at approximately the same injection site as used in the November 2017 course (fig. 5). In the 2001 study, the first appearance of dye after injection occurred in 16.5 hours for Langle Spring and 11.5 hours for Copperhead Spring; the peaks occurred at 24.5 hours for Langle Spring and 16.5 for Copperhead Spring (fig. 10). As shown in figure 10, the chloride peaks occurred sooner than the RWT peaks (3 hours sooner at Langle Spring and 1 hour sooner at Copperhead Spring). The much longer tail on the dye-normalized curve compared to the chloride-normalized curve indicates some adsorption and desorption of dye in the system. (Each curve is normalized by dividing the concentration for each curve by the peak concentration of that constituent, allowing all curves to plot on a zero to 1 y-axis.)

Figure 8. Photographs of a hydrologist setting a bug (dye-absorbent material in a flow-through mesh bag) at Tree Spring at the Savoy Experimental Watershed, Arkansas (photograph by Eve Kuniansky, November 12, 2018).

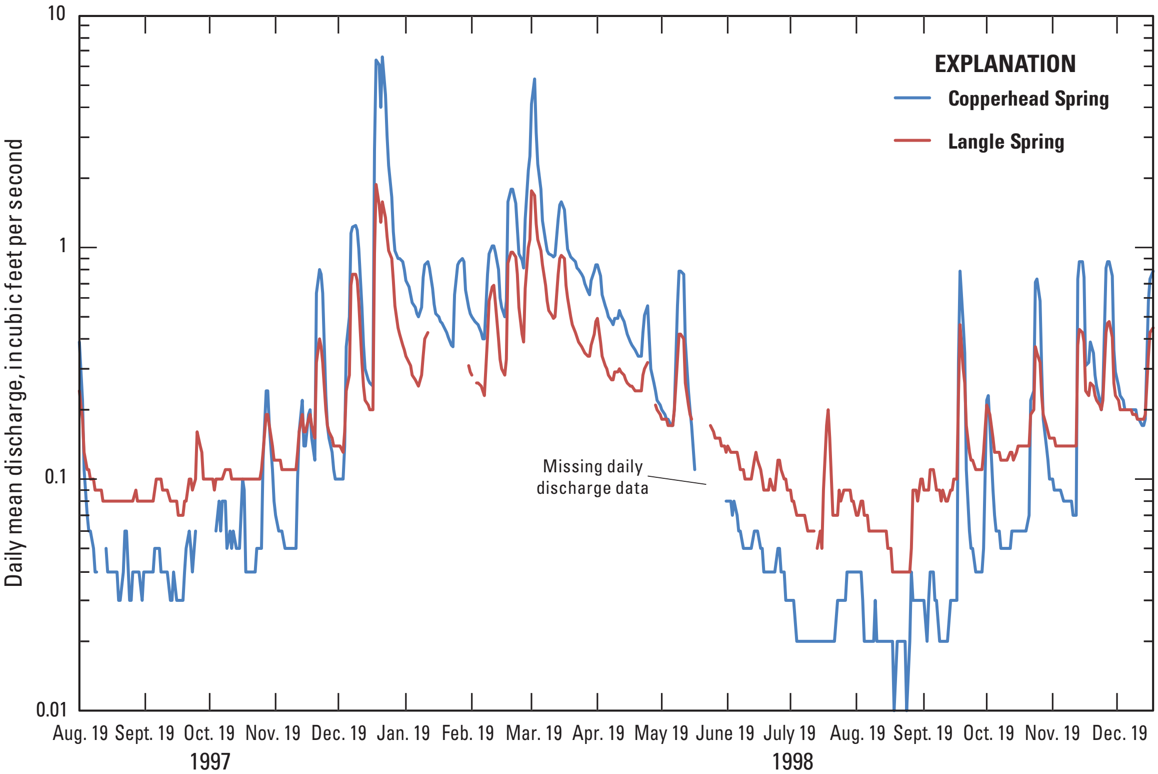

Figure 9. Daily mean discharge at Copperhead and Langle Springs, Savoy, Arkansas (data are from the U.S. Geological Survey National Water Information System).

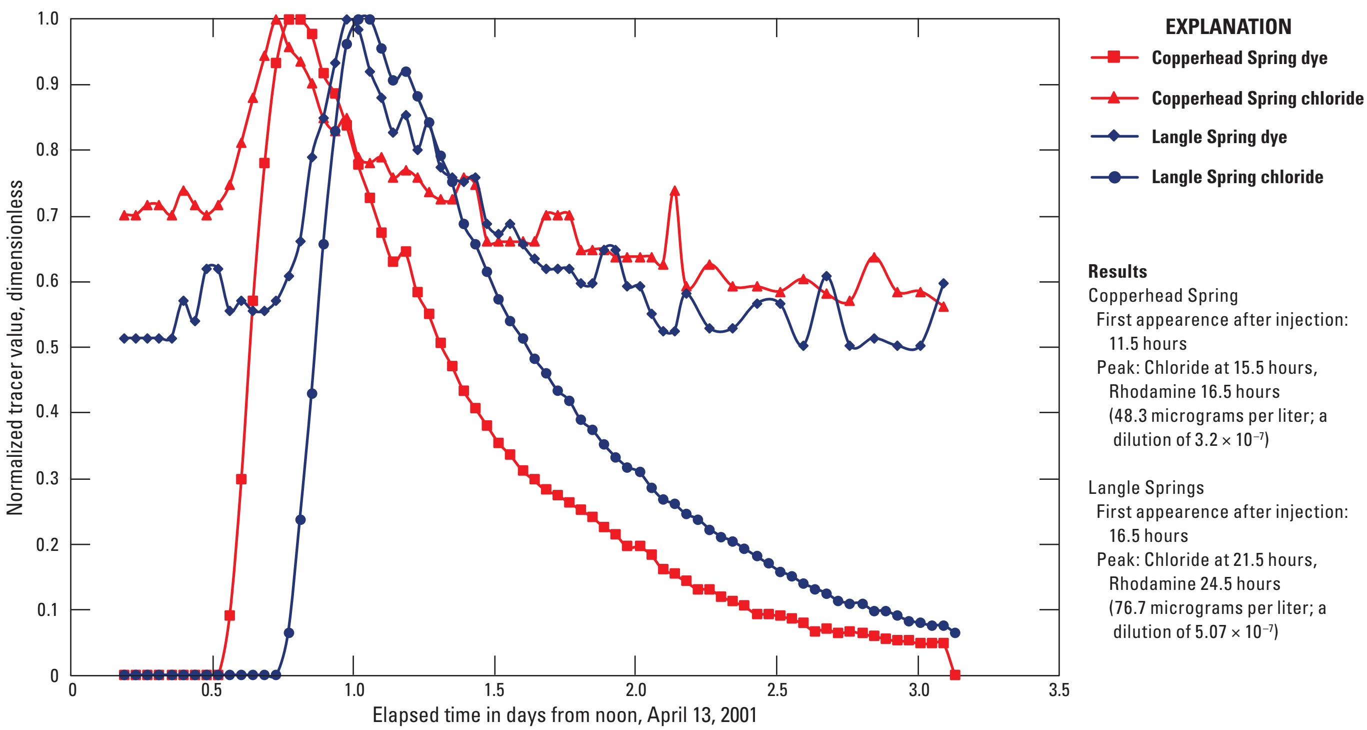

Figure 10. Normalized RhodamineWT dye and chloride tracer breakthrough curves for Copperhead and Langle Springs, Savoy, Arkansas, April 13–17, 2001 (modified from image provided by J.V. Brahana, November 13, 2017).

Dye Tracing Conditions During Course

Discharge from the small epikarst springs at the SEW that included Tree Spring and springs west of Tree Spring forms a small stream that sinks underground updip/upgradient from both the Copperhead and Langle Springs discharge points (fig. 6). For the class quantitative test, RWT dye tracer was poured at the sink point at the end of this small stream the night before grab samples were collected. Before and during the course,volumetric measurements were made at Tree Spring, and salt-dilution methods (Rantz and others, 1982) were used to measure discharge during the course at Woodpecker Spring, Red Dog Spring, and unnamed springs (table 1). The sum of the flows from these epikarst springs, as well as the estimated flow rate at the sink point, was about 0.4 L/s. The natural spring discharge stream that sinks upgradient from Langle and Copperhead Springs was deemed adequate to flush the dye into the system as opposed to using a tank of deionized water.

A similar sinking stream situation was needed for a successful point-to-point test with visual confirmation. Fortunately, the instructors knew of another spring (Wow Spring, fig. 6) with an upgradient sinking epikarst stream in the sub-watershed just north of Langle Spring. Fluorescein dye (green) was selected for the point to point test at Wow Spring, such that RWT dye (red) could be used for the quantitative test at a different injection location. From experience, Dr. Brahana suggested that we pour the dye for both dye tracing tests on Monday night, November 13, 2017, between 10 and 11:00 p.m., which was the night before the field day, hoping the dye would be visible some time the next day (Tuesday).

Because the dye trace experiment was part of a training course and the dye needed to be poured at night, we discouraged course attendees from being present to observe the dye injection. By limiting student exposure during the dye injection, contamination was essentially eliminated during subsequent grab sampling by student attendees. Only one course attendee accompanied four instructors to assist in the dye pouring and aided in locating the sinking stream section for Wow Spring.

Safety Notes for the Dye Tracing Tests and Future Courses

Locating the sinking stream that emerges at Wow Spring involved patience with the resident cows as well as walking through the woods in the dark along a steep hillside to find the stream section, all while hauling two large containers of mixed fluorescein dye. The assistance of Jason, Dan, and Joshua was greatly appreciated by the older members of the team (Van and Eve) who feared falling on the sharp chert nodules in the dark. We recommend keeping this safety issue in mind for future courses because the chert nodules are very sharp and can easily cut through clothing or cause injury if one falls on them. Additionally, if anyone stays to collect grab samples the following day and night, be aware that a camp fire on top of chert, or within a chert rock enclosure, could also be dangerous because entrapped air within the chert can cause these rocks to explode when heated. Another safety concern is poison ivy, which is abundant at the site. Individuals involved in walking through the woods to locate the sinking stream upgradient from Wow Spring should be careful not to grab vines if they are allergic to poison ivy. This course was conducted in relatively cold weather, so no snakes were observed; however, during the spring and summer, poisonous snakes may be on the property. If preclass time permits, the sinking epikarst stream upgradient from Wow Spring could be located during the day and a path cleared to the pasture area. Wow Spring itself is easily accessible for visual confirmation of dye. The sinking epikarst stream upgradient from Copperhead Spring and Langle Spring is easily accessible as are other springs described in table 1.

Additionally, arrangements were made preclass with the UA cattle breeding farm to remove the cattle from the area near Copperhead and Langle Springs as a safety precaution; however, cattle were in the fields at the entrance to the SEW and in the subbasin with Wow Springs. It is critical to remind students to close all fence gates during the class so that cattle do not move out of fenced areas because livestock breeding research is ongoing at the SEW.

Point-to-Point Tracer Test at Wow Spring, November 2017

Two large containers of mixed fluorescein dye (2 pounds [lbs] in each 2-gallon jug) were obtained by Dr. Brahana for use in previously planned tracer tests at the SEW, but the dye was not used and needed to be discarded. This large amount of dye was not necessary for the short point-to-point tracer distance between the sink and Wow Spring (approximately 1,100 ft or 0.2 mile). In retrospect, about a half pound of dye would have been enough; however, Dr. Brahana wanted to dispose of the dye that he had on hand and he was certain that no harm would be done in using that amount of dye because no drinking-water intakes are within miles downstream of the SEW on the Illinois River, which is where all the dye would eventually discharge. After finding the sinking stream, Joshua and Dan poured a total of 4 lbs of fluorescein dye into the sinking stream upgradient from Wow Spring at the injection location recorded in field notes (latitude 36.1211222, longitude −94.33930555, World Geodetic System 1984 datum with an accuracy of plus or minus 20 ft; the fluorescein injection and sink in figs. 5 and 6) on Monday, November 13, 2017, at 2211 CST (fig. 11).

Dye was observed coming out of Wow Spring some time prior to 1400 on Tuesday, November 14, 2017, less than 16 hours after injection of the dye, and had made it half way to the Illinois River by that time (fig. 12). Because more than enough dye was injected, the concentration was too high for a field fluorometer to detect; however, the high concentration was ideal for visual confirmation because there would be no doubt if dye was present (fig. 12). By November 15, fluorescein dye was in the Illinois River (fig. 13).

Figure 11. Photograph of fluorescein dye in sinking stream upstream of Wow Spring, Savoy Environmental Watershed, Arkansas (photograph by Eve Kuniansky, Monday, November 13, 2017, at 2215 Central Standard Time).

Figure 12. Photographs of visual confirmation of fluorescein dye at Wow Springs (photograph by Eve Kuniansky, Tuesday, November 14, 2017, at 1430 Central Standard Time).

Figure 13. Photograph of fluorescein dye in the Illinois River (photograph by Cassie Crow, Wednesday, November 15, 2017, at 1346 Central Standard Time).

Quantitative Test at Langle and Copperhead Springs, November–December 2017

For successful quantitative tests it is critical to (1) consult local geology experts in selecting injection and discharge location(s), (2) collect background samples of water to determine if there is any background fluorescence that may interfere with the test, (3) select the dye that is appropriate for the hydrogeologic setting, (4) use regression equations, once the appropriate dye is selected, to estimate the amount of dye required (Field, 2003; Worthington and Smart, 2003), (5) run point-to-point tests to confirm the link(s) from the sink(s) to the discharge location(s), (6) determine which method of collecting the time series of discharge and concentration (or fluorescence) data will be used, (7) determine the thickness of the unsaturated zone and whether or not a tanker of deionized water is required to flush dye into the karst system, (8) determine if a pulse of dye will be used or if a continuously injected concentration will be used, and (9) use dark sample bottles, or have a dark place to store the grab samples, because many organic dyes will lose fluorescence if exposed to sunlight.

As stated previously, numerous point-to-point and quantitative dye tracer studies have been conducted at higher groundwater levels and springflow discharge rates at the SEW site. The location of the quantitative test at Langle and Copperhead Springs was chosen based on these past tracer tests. RhodamineWT (RWT) was the organic dye used for the quantitative test. Two continuous RWT fluorometer/data loggers were borrowed from UA for this test. The two field fluorometers/loggers were Precision Measurement Engineering, Inc. (PME) data loggers, using a Turner Design Submersible Cyclops-7 RWT fluorometer (PME, Inc., Vista, California, and Turner Design, San Jose, California). RWT has a fluorescence wavelength peak at 575 nanometers (nm) and is one of the most common harmless organic dyes used for tracer tests. Because RWT is an organic chemical, however, it adsorbs to organic material and thus is not totally conservative in terms of its transport properties. Although the point-to-point test at Wow Spring was conducted in a different subbasin of basin 1, fluorescein was used for that test. Fluorescein is an organic dye that has a wavelength peak at 510 nm and therefore, even if this dye made it to Langle or Copperhead Springs, it should not interfere with the RWT peak.

Field fluorometers do not measure a spectrum of wavelength as does a laboratory spectra-fluorometer. Most field fluorometers are used to detect a range of voltage/concentration for a specified range of wavelength. Therefore, it is important to try to estimate the amount of dye to use, such that the range of detection of the field fluorometer is not exceeded. The Cyclops-7 fluorometer is designed to detect fluorescence from chlorophyll *a*, cyanobacteria, and RWT tracer dye. The device has two light-emitting diode (LED) sources that act as the excitation light source and can measure fluorescence of RWT from 0.01 to 1,000 parts per billion (ppb) (http://www.turnerdesigns.com/products/submersible-fluorometer/cyclops-7f-submersible-fluorescence-and-turbidity-sensors).

The laboratory spectra-fluorometer at UA was a Shimadzu RF-5301PC and was set up by Joshua Blackstock to record spectra from 540 to 680 nm (the full range for RWT). The Shimadzu fluorometer was used to analyze a small volume of liquid sample in a proprietary vial. The device allowed for two different sensitivity settings—high and low—for recording a full visible spectra intensity of fluorescence. These instruments were calibrated using a set of standards for the RWT dye created in the UA laboratory from the purchased RWT dye.

Background samples analyzed using the Shimadzu fluorometer indicated some interference with RWT in the range of 554 to 566 nm. The SEW is in an agricultural area and, according to Aley (2002), agricultural chemicals can interfere with RWT. Additionally, many dye traces have been conducted at this same location, thus degraded organic dye may be present. Most of the other common sources of interference mentioned by Aley (2002) are unlikely for the SEW because it is not in an urban or industrial area. Funding was not available for full water-quality analysis of the background spring discharge. Thus, the background interference source is unknown. The background low-sensitivity spectra at Langle Spring and Copperhead Spring is shown in figure 14. Note that these background grab samples were collected post-dye injection, but well before any dye was present because previous sample spectra were not kept. It should be noted that the recorded intensity is a relative reading. A slightly higher background interference intensity value was recorded at Langle Spring than at Copperhead Spring (fig. 14). The peak background intensity was 559 nm at Langle Spring and 560 nm at Copperhead Spring, below the 575 nm peak for RWT (fig. 14).

For the quantitative tracer test, we wanted visual confirmation without too much exceedance of the range of the field fluorometers. In general, visual confirmation of RWT is obvious at a concentration of 500 ppb and is possible at a concentration of 100 ppb. However, sample water in a clear vial would need to be viewed in front of a white background for concentrations less than 100 ppb because the solution would be tinted and not obvious otherwise. Certainly, at a concentration of 500 to 1,000 ppb, the dye in the discharge is visible to the human eye.

The Martel (1913) and Dole (1906) empirical regression equations are commonly used to estimate the appropriate mass of tracer to use in a quantitative tracer test. Although numerous empirical equations have been developed to estimate tracer mass, only four had coefficient of determination (R^2) values greater than 0.6 and only the two mentioned above had R^2 values greater than 0.9 (Worthington and Smart, 2003, table 1). Worthington and Smart (2003) compiled results from 185 tracer tests to obtain new regression coefficients for the Martel (1913) equation and the Dole (1906) equation ($r^2 > 0.9$):

Martel (1913): $\text{Mass (grams)} = 19*(LQC)^{0.95}$

Dole (1906): $\text{Mass (grams)} = 0.73(TQC)^{0.97}$

where

L is straight line length from sink to spring in meters,

Q is spring discharge in cubic meters per second,

C is concentration in parts per million, and
T is travel time (consistent unit in seconds).

The travel time typically is not known. Based on our targeted peak dye concentration of 1 part per million (1,000 ppb) at the springs, table 3 gives the amount of dye estimated for the planned injection. Spring discharges were small during the training course, however, and may have been below the range of data used to create the regression equations for estimation of the mass of dye required for injection (Field, 2003; Worthington and Smart, 2003).

In preparing for the course, J. Van Brahana suggested that 2 lbs of dye be ordered in case substantial rainfall preceded the experiment, which would cause flows at Langle Spring and Copperhead Spring to be closer to peak discharge and more dye would be necessary for visual confirmation. Two lbs of dye is more than the estimated amounts needed for visual confirmation at the small springflow rates during the class. RWT comes in liquid form, whereas fluorescein comes in a powder form and must be mixed. A rule of thumb in the oral tradition (no regression equation developed) for dye mass amounts is to use 1 lb per mile distance between sink and spring; for example, the approximately 400 meters between the sink and Langle Spring or Copperhead Spring is approximately 0.2 mile, thus 0.2 lbs would be required for the injection mass. Two lbs is 10 times more than the rule of thumb, 50 to 100 times greater than the estimates provided in table 3 using the Martel (1913) regression, and 3 to 10 times greater than the estimates using the Dole (1906) equation. We were assuming, however, that because the dye mass would go to both Langle Spring and Copperhead Spring, the peak concentration would be half the 1 ppm—or 500 ppb—at each spring.

Although the amount of dye injected at the sink on Monday November 13, 2017, at 2250 Central Standard Time (CST), should have been carefully measured, a graduated cylinder was not available, so we put half of the mixed volume of dye (approximately 1 lb) into the sinking stream to ensure a strong visual signal. Photographs of the sinking dye and field team are shown in figure 15. If there is concern about dye entering a downstream user intake, the lower estimate of dye should be used; however, there is no such issue at the SEW.

On Monday, November 13, 2017, Joshua Blackstock and Dan Wagner installed new batteries and powered on the PME Cyclops-7 field fluorometer and data logger (serial number 473746) at Langle Spring at 1632 CST. At 1743 CST, they powered on the PME Cyclops-7 field fluorometer and data logger (serial number 196807) at Copperhead Spring and submerged the equipment at 1758 CST). Note that the time and dates stored within the two data loggers were not reset to match exactly or match the watch time recorded in the instructor's field notes (image of field notes available in Kuniansky, 2019). Thus, the date and time should be adjusted according to the times from the field notes as to when the fluorometer and data logger were powered up, knowing that the measurements were recorded every 5 minutes starting 5 minutes after the unit was powered up. A good practice for all future projects and data collection would be to set the date and time within the data loggers with an atomic clock, using the same laptop computer, such that both data loggers have the same date and time setting. Additionally, all time keepers should synchronize their watches to the atomic clock time. (Note that class attendees were instructed to set their watches to the same time on Monday, but the instructors did not check all the students' watches.) The field fluorometers were calibrated to standards prepared in the laboratory by Joshua Blackstock prior to the course and set to read out in parts per billion. The field fluorometers could be set to raw uncalibrated voltage and grab samples could be used with the spectra-fluorometer to calibrate the raw uncalibrated field fluorometer voltage data based on standards and the field grab samples.

Owing to background interference from the native groundwater, native spring water was used for dilution to create standards in the laboratory (one at 1,000 ppb and the other at 500 ppb RWT). The spectra were measured with the low-sensitivity mode on the Shimadzu spectra-fluorometer because the high-sensitivity setting caused the spectra output to peak and plateau. This peaking is due to optical oversaturation of the light sensor used in the high-sensitivity mode. It would also have been good to have 100 and 10 ppb standards; however, by assuming that the 0,0 intercept represents no RWT, a calibration equation (Predicted RWT concentration in ppb = 16.644 × intensity at 575 nanometers − 2.1113) was developed for the RWT concentration at a wavelength peak of 575 nanometers (fig. 16).

We expected the RWT dye to appear at Copperhead Spring in about 11 to 12 hours (by 1000 to 1100 CST Tuesday, November 14) and at Langle Spring in about 16 to 17 hours (by 1600 CST Tuesday). However, dye never made it to Copperhead Spring throughout the week or through December 2, 2017, when the field fluorometers were removed. Dye was not visible before sunset at about 1700 CST on Tuesday, November 14, 2017, at Langle Spring. Grab samples were collected at approximately hourly intervals starting around noon on Tuesday, November 14 at both springs, and sample collection continued until just after midnight on Wednesday, November 15. Bottles were labeled by the student collecting the sample with spring name, date, and time; resulting concentrations from laboratory analyses conducted Wednesday, November 15, by Joshua Blackstock are provided in table 4.

On the basis of the grab samples, the leading edge of the dye appeared at Langle Spring between 2012 and 2238 CST almost 23 hours after the dye was placed into the sinking stream. There was no sign of dye visible at Langle Spring until late in the evening at about 2000 CST on November 14, 2017, when Eve Kuniansky thought there was a tinting of pink in the discharge at Langle Spring. By 2200 CST, more people agreed they saw the pink tint in the discharge at Langle Spring. By 0015 CST, on November 15, all those still in attendance concluded pink water was observed by the time the last grab sample was collected. The spectra for all the grab samples at Langle Spring reflected some background interference and only the last three samples had discernible RWT detection peaks at a wavelength of 575 nm above the background interference peak at 559 nm (fig. 17).

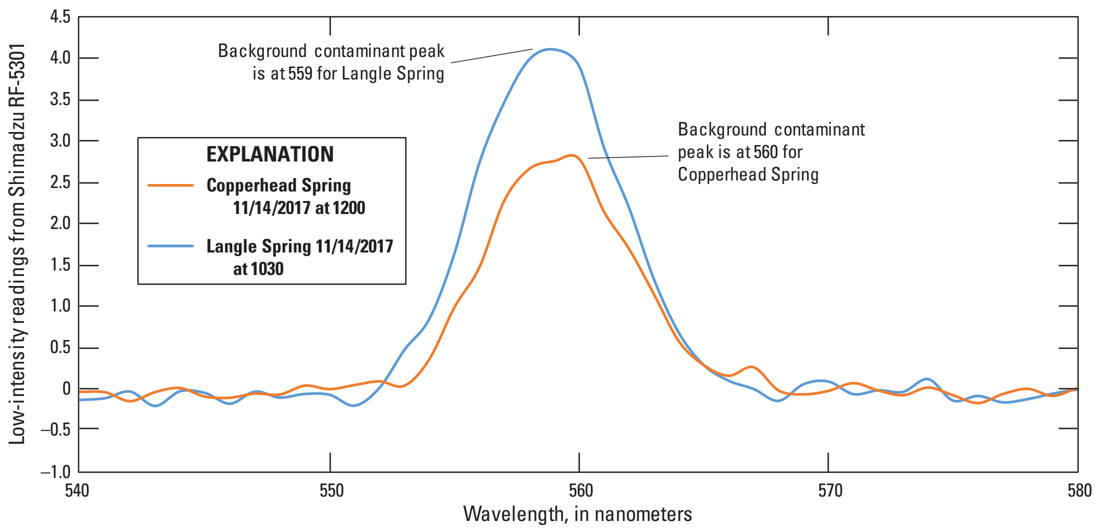

Figure 14. Low-sensitivity spectra interference from background samples at Langle Spring and Copperhead Spring, Savoy, Arkansas.

Table 3. Estimated mass of dye required for 1 part per million at Langle Spring and Copperhead Spring, Savoy Experimental Watershed, Arkansas.

[L, length; C, concentration; M, mass; m, meter; Q, discharge; T, time; m^3/s, cubic meter per second; g, gram; Kg, kilogram]

Spring	Length (m)	Q (m^3/s)	T (s)	Martel (1913) $M = 19*(LQC)^{0.95}$		Dole (1906) $M = 0.73*(TQC)^{0.97}$	
				Mass (g)	Mass (Kg)	Mass (g)	Mass (Kg)
Langle	433	0.002	59400	16.557	0.017	75.144	0.075
Copperhead	374	0.001	41400	7.456	0.007	27.028	0.027

Figure 15. Photographs of RhodamineWT sinking underground at end of the sinking stream location latitude 36.116772 longitude -94.341883 North American Datum 1983 (photograph by Eve Kuniansky, November 13, 2017 2250 Central Standard Time) and dye injection field crew (photograph by Joshua Blackstock, November 13, 2017, at 2305 Central Standard Time).

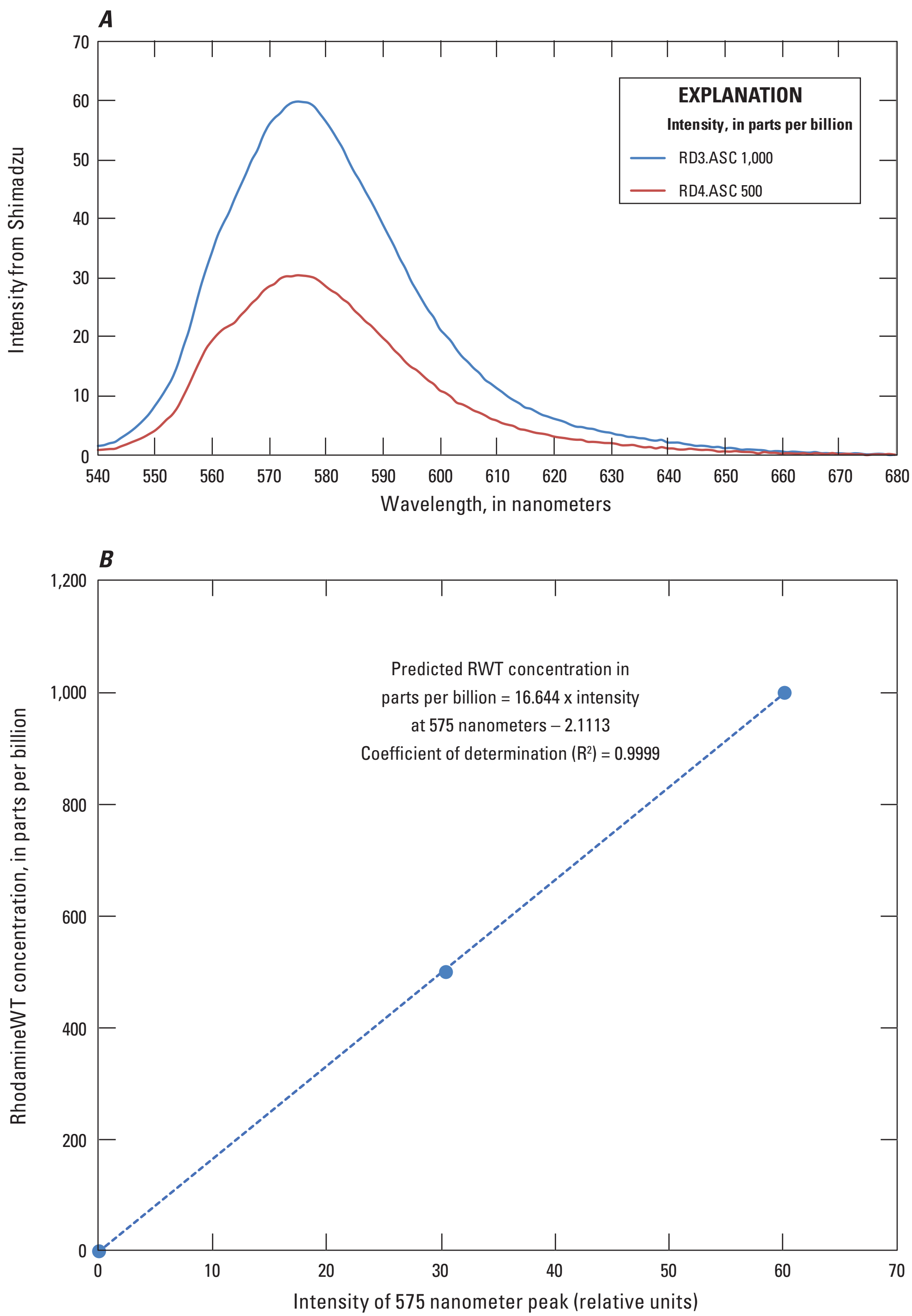

Figure 16. *A*, Low-sensitivity spectra from calibration standards. *B*, Linear calibration equation for converting intensity to concentration for RhodamineWT (RWT).

Table 4. Grab sample laboratory analysis at Copperhead and Langle Springs.

[intensity, dimensionless; ppb, parts per billion; PME, Precision Management Engineering, Inc.]

Date	Time	Sample name	Peak intensity at 575 nanometers	Laboratory concentration (ppb)	Field fluorometer (ppb)	Visible by eye
Copperhead Spring (using field fluorometer)						
11/14/2017	12:00	C1	none	nondetect	1.16	No
11/14/2017	13:00	C2	none	nondetect	0.64	No
11/14/2017	13:00	C3	none	nondetect	0.64	No
11/14/2017	14:00	C4	none	nondetect	0.70	No
11/14/2017	15:00	C5	none	nondetect	0.37	No
11/14/2017	16:00	C6	none	nondetect	0.45	No
11/14/2017	17:00	C7	none	nondetect	0.95	No
11/14/2017	18:00	C8	none	nondetect	0.67	No
11/14/2017	19:23	C9	none	nondetect	0.40	No
11/14/2017	20:27	C10	none	nondetect	0.30	No
11/14/2017	21:00	C11	none	nondetect	0.35	No
11/14/2017	22:49	C12	none	nondetect	0.30	No
Langle Spring (using PME field fluorometer)						
11/14/2017	10:30	L1	none	nondetect	0.44	No
11/14/2017	12:00	L2	none	nondetect	0.41	No
11/14/2017	13:00	L3	none	nondetect	0.54	No
11/14/2017	14:15	L4	none	nondetect	0.37	No
11/14/2017	15:00	L5	none	nondetect	0.45	No
11/14/2017	17:00	L6	none	nondetect	0.67	No
11/14/2017	18:04	L7	none	nondetect	1.22	No
11/14/2017	19:03	L8	none	nondetect	5.41	No
11/14/2017	20:12	L9	none	nondetect	29.42	Tinted??
11/14/2017	22:38	L10	8.84	145	216.35	Tinted yes
11/14/2017	23:00	L11	11.372	187	313.80	Yes?
11/15/2017	0:15	L12	23.1	382	572.79	Obvious

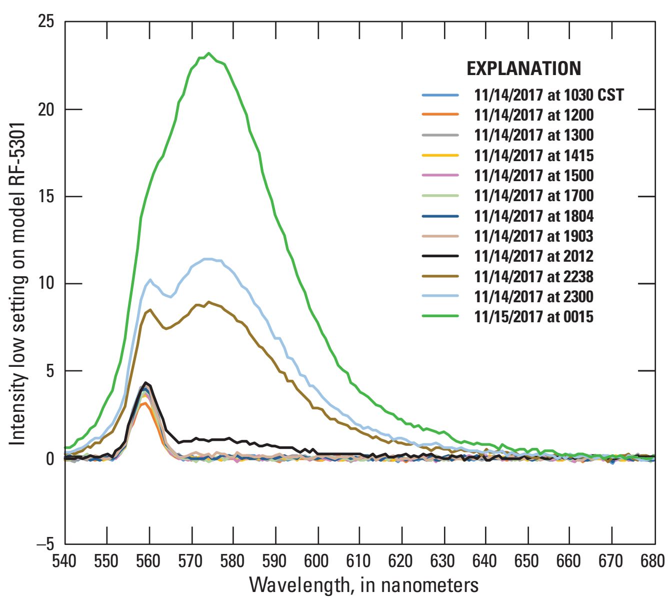

Figure 17. Graphs of spectra-fluorometer analyses for grab samples collected at Langle Spring (low-sensitivity setting), Savoy, Arkansas, November 14–15, 2017.

Unfortunately, the grab sample concentration from the spectra-fluorometer analyses did not match the readings on the PME field fluorometer from approximately the same time, and the background concentrations on the PME field fluorometers were non-zero. Additionally, the average background concentration for the two PME field fluorometers, calculated on the basis of readings made prior to dye injection, did not match exactly (table 5). However, from the laboratory spectra-fluorometer, the background fluorescence (29.42 ppb) is a large part of the signal for sample L9 collected at 2012 CST. Thus, the spectra-fluorometer is less sensitive than the PME field fluorometer for quantification of RWT at lower concentrations owing to this background interference peak. In reviewing the higher sensitivity sensor setting file for Langle Spring grab sample L9 (not shown), a second peak at 575 could not be identified. As shown in table 5, there is a higher background concentration at Copperhead Spring, as well as a greater range and standard deviation, than in the data from Langle Spring even though both devices were calibrated using the same standards. It is possible that this difference is due to background interference results from the different groundwater source areas. Pink RWT coloration was not observed at Copperhead Spring throughout the rest of the week, whereas Langle Spring remained pink for the duration of the course (fig. 18).

Using a background RWT concentration of 1 ppb at Langle Spring necessitated setting all values less than 1 ppb to zero and subtracting 1 ppb from the rest of the PME field-fluorometer values to set up the data for use with the QTRACER2 software (Field, 2002). The QTRACER software analyzes the input data for tracer-breakthrough analysis. The adjusted RWT concentration at the time of removal of the equipment was 5 ppb, indicating that the concentration had almost returned to background levels (fig. 19). By collecting data every 5 minutes, the graph of the data is smooth (fig. 19). The elapsed transport time for the RWT from the time of injection to when the leading edge reached Langle Spring at about 1900 CST was 1,135 minutes (18 hours and 55 minutes). The peak concentration was 1,313 ppb, which is slightly above the maximum concentration range of the field fluorometer of 1,000 ppb. The peak occurred after 1,860 minutes (31 hours). Using these background-adjusted data, RWT dye recovery was 96 percent for this experiment. This percentage of recovery is unusually good and indicates that the PME field fluorometer may be inaccurately calibrated because recovering almost 100 percent of dye is almost unheard of in the field, especially when the shape of the curve indicates some sorption of dye (note the long tail on the breakthrough concentration curve [fig. 19]). A conservative tracer such as chloride (fig. 10) would be expected to have a more symmetric shape with no long tail as it returns to its background value.

Table 5. Statistics on background rhodamineWT parts per billion readings from the field fluorometers installed at Langle and Copperhead Springs, Savoy, Arkansas.

[Units are parts per billion]

Statistic	Langle	Copperhead
Average	0.42	1.63
Maximum	0.80	4.25
Minimum	0.03	0.27
Median	0.43	1.39
Standard deviation	0.14	0.98

The grab sample results were used to calibrate the PME field-fluorometer data and set up a second QTRACER2 dataset. On the basis of a line fit through the three grab sample values (slope of 0.6821, intercept of −12.768, and a coefficient of determination (R^2) of 0.9896 (fig. 20*A*, equation A: Predicted laboratory RWT concentration = 0.6821 × field concentration − 12.768), concentrations less than 22 ppb for RWT cannot be determined. However, if the y-intercept is forced to be 0 ppb, we get a linear function that still fits the PME field-fluorometer data and still has a very good R^2 of 0.9874 with a slope of 0.6523 (fig. 20*B*, equation B: Predicted laboratory RWT concentration = 0.6523 × field concentration). Nevertheless, it would have been better to have had additional standards at the 100, 10, and 1 ppb for RWT and not have exceeded the range of detection for the PME field-fluorometer RWT concentration. For this test, however, if half of the RWT had gone to Copperhead Spring and half to Langle Spring as planned, then perhaps the peak concentrations would have been ideal at both springs. Additionally, it would have been better to exactly measure the mass of dye injected. Nevertheless, by using about half of the volume based on the height of the liquid in the bottle yielded a close approximation (probably within 10 percent as that would be plus or minus a half inch of the height of liquid in the cylindrical bottle). On the basis of the PME field-fluorometer data, equation B, and assuming a constant discharge 0.1 ft^3/s and 1 lb of dye injected as a slug, 63 percent of the mass was recovered. The leading edge and peak travel times are the same for the original PME data. (Note: We would have had to set all values below 22 ppb to a nondetect, which would have resulted in negative RWT values using equation A, which is why that equation was rejected.). Therefore, with equation B, the peak concentration based on laboratory adjustment of the field peak concentration of 1,313 ppb (fig. 19) is calculated as 856 ppb from the linear regression equation (see fig. 20*B*).

The QTRACER2 program provides other useful information that has been compiled into table 6. Most of the calculated values in table 6 are the same for the original PME field-fluorometer data and for the PME field-fluorometer data that is adjusted to the laboratory concentration; the adjustment only modifies the concentration and does not change the shape of the breakthrough curve. However, the big difference in mass recovered has a large effect on the accuracy index computed by QTRACER2. The Reynolds number is calculated assuming a pipe diameter of 1.4 meters (estimated subsurface conduit diameter to the spring). Reynolds numbers are dimensionless numbers used in fluid mechanics to indicate whether flow is laminar or turbulent. The Reynolds number represents the ratio of fluid inertial to viscous forces. The upper and lower critical Reynolds numbers are the values above which flow becomes turbulent and below which flow becomes laminar and is a function of flow velocity, fluid density, and viscosity. In pipe-flow experiments when flow goes from laminar to turbulent this occurs at the upper critical Reynolds number, and when flow goes from turbulent to laminar this occurs at the lower critical Reynolds number. Thus, flow would most likely be laminar if the Reynolds number is computed to be near the lower critical Reynolds number for pipe flow. The lower critical Reynolds number for pipes is 2,000, and the upper critical Reynolds number for pipes is 10,000. Therefore, it is unclear whether there was turbulent flow during this test. The Peclet number is the ratio of the rate of advection versus the rate of diffusion and indicates that advection was more dominant than diffusion for this tracer test. Diffusion is dominant for Peclet numbers below 0.4, and the transition between diffusion-dominated and advection-dominated transport occurs for Peclet numbers from 0.4 to 6 (Field, 2002).

This quantitative test was somewhat anomalous compared to previous tracer tests conducted at the site because discharge at Copperhead Spring and Langle Spring was very small. This test conclusively proved that Copperhead Spring is not the base spring in the flow system. The test proved that Copperhead Spring receives water from the sinking stream only after the spring basin water levels are higher than at the dry conditions that were present during this test when Copperhead Spring was at extremely low flow. Greg Stanton and J. Van Brahana stated that they have never conducted a tracer test at a low flow such as during this test and never one where dye injected into this sinking stream did not show up at Copperhead Spring first and then at Langle Spring.

Figure 18. Images of Langle Spring and Copperhead Spring, Savoy, Arkansas, on November 15, 2017. From left to right: Looking down into Langle Spring orifice at 0008 Central Standard Time (photograph by Eve Kuniansky); Langle Spring outflow behind the weir 1109 Central Standard Time (photograph by Cassie Crow); and Copperhead Spring at 1424 Central Standard Time (photograph by Eve Kuniansky).

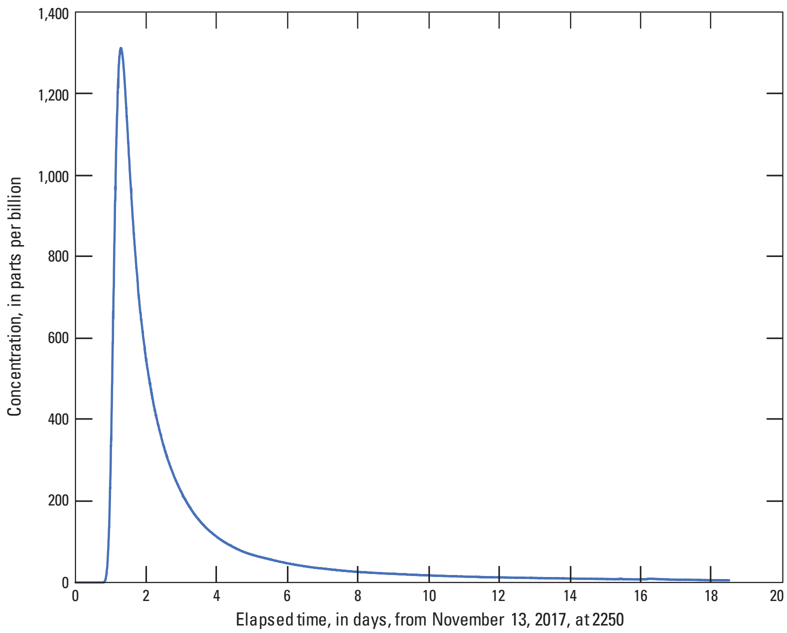

Figure 19. Breakthrough curve for RhodamineWT data at Langle Spring, Savoy, Arkansas.

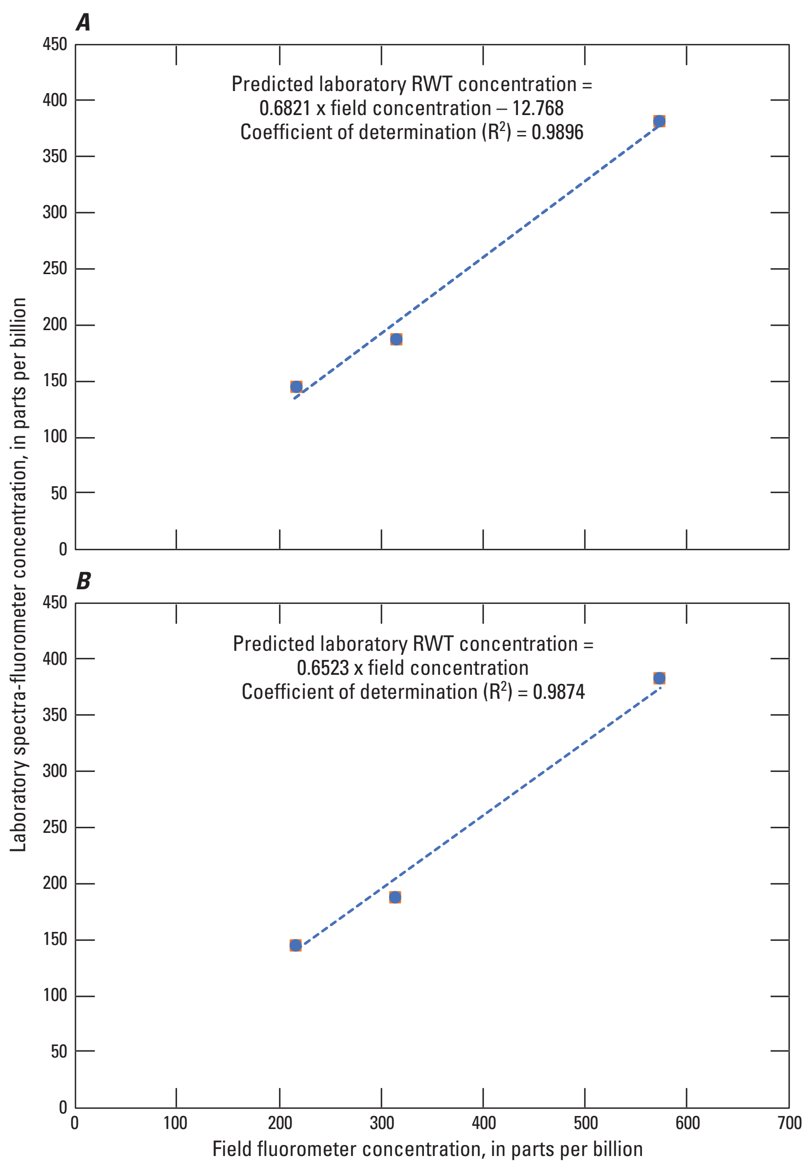

Figure 20. Linear regressions for calibration of field-fluorometer RhodamineWT (RWT) concentration to laboratory estimated grab sample values. *A*, No set intercept. *B*, Intercept set to zero.

Table 6. Summary of information from the QTRACER2 program.

[m^3, cubic meter; m^2, square meter; m, meter; mm, millimeter; m/d, meter per day; m/s, meter per second; m^2/s, square meter per second; ppb, parts per billion]

Description of QTRACER2 computed result	Field fluorometer data	Field fluorometer data adjusted to lab concentration
Quantity of tracer recovered	0.96111 pounds	0.62693 pounds
Percent recovery of tracer injected	96.112	62.693
Accuracy index (0.0 = Perfect Recov.)	0.0389	0.3731
Total aquifer volume estimate	751.37 m^3	same
Total aquifer surface area estimate	81,504 m^2	same
Final tracer sorption coefficient (coef.)	0.37296E-03 m	.54857E-02 m
Time to first arrival	1,135 minutes	same
Time to peak concentration	1,860 minutes	same
Concentration at peak	1,313.3 ppb	856.65 ppb
The mean tracer transit time	4,421.9 minutes	same
Standard deviation for tracer time	4,255.4 minutes	same
The mean tracer velocity	166.75 m/d	same
Standard deviation for tracer velocity	157.54 m/d	same
Dispersion coefficient	0.12497 m^2/s	0.12498 m^2/s
Longitudinal dispersivity	64.750 m	64.754 m
Peclet number	7.9083	7.9076
The maximum tracer velocity	649.67 m/d	same
Hydraulic head loss along channel	0.36693E-04 m	0.36694E-04 m
Estimated Reynolds number (based on estimated tube diameter of 1.3669 m)	2,314	same
Estimated Froude number (based on estimated hydraulic depth 1.0735 m)	5.95E-04	same
Molecular mass transport parameters		
Shear velocity	0.86857E-03 m/s	same
Estimated Schmidt number	1,140.00	same
Estimated Sherwood number	148.98	same
Mass transfer coef. from wall to flow	0.10899E-06 m/s	same
Molecular diffusion layer thickness	9.1748 mm	same

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Appendixes 1–3

Appendix 1. Instructor Profiles GW2227 Advanced Groundwater Field Techniques in Karst Terrains Fayetteville, Arkansas, November 13–17, 2017

Eve Kuniansky, Course Coordinator/Instructor
U.S. Geological Survey—Water Mission Area
Integrated Modeling and Prediction Division
Earth Systems Modeling Branch
1770 Corporate Drive, Suite 500,
Norcross, Georgia 30093
elkunian@usgs.gov
Office: 678–924–9211 Cell 404–548–9211
https://www.usgs.gov/staff-profiles/eve-l-kuniansky

Eve moved to the new Integrated Modeling and Prediction Division, Earth Systems Modeling Branch, October 1, 2017, and had been the Water Science Field Team Southeastern Region Groundwater Specialist, providing technical assistance for groundwater projects throughout the Southeastern U.S.A., Puerto Rico, and the Virgin Islands, since 1998. She has always liked science and nature and earned a degree in physics from Franklin and Marshall College in 1978 and Bachelor of Civil Engineering in 1981, with highest honor, and Master of Science in Civil Engineering (hydrology/hydraulics) in 1982 (both from Georgia Institute of Technology). In January 1983, she began a career with the U.S. Geological Survey (USGS) and gained experience in surface-water modeling, project management, borehole geophysics, geologic mapping, field data collection, groundwater flow and transport simulation, geographic information system (GIS), karst hydrology, and aquifer hydraulics. Because of her expertise, Eve is frequently asked to provide training within the USGS and has been selected for short-term international assignments by the USGS International Water Resources Branch (China, Israel, Cyprus, Ethiopia, Kenya, and South Africa) where she has either conducted groundwater training or worked on groundwater projects. Eve has been interested in karst aquifers since 1986 when she encountered the Edwards-Trinity aquifer and has coordinated the USGS Karst Interest Group since 2000.

Eve is coordinating this first course, but it is a team effort involving several of the former "Regional Groundwater Specialists" (Geoff Delin, Devin Galloway, Eve Kuniansky, and Rod Sheets), some noted USGS retirees that teach at the University of Arkansas (Van Brahana and Fred Paillet), the Fayetteville Office (Dan Wagner and Phil Hays, who also is on the faculty at the University of Arkansas), staff from the current Branch of Geophysics (Martin Briggs assisted by Marian Domanski from the Urbana, Illinois, office) and staff from the Texas Water Science Center that are involved in geophysical studies of the Edwards-Trinity aquifer (Greg Stanton, Jason Payne, Sam Wallace, and Jon Thomas). Additionally, Joshua Blackstock, a Ph.D. candidate at the University of Arkansas and a former USGS employee, is voluntarily assisting in the dye tracing part of this course.

The intent of the course is to introduce attendees to field techniques used in the study of groundwater flow in karst and fractured rock aquifer systems, but not provide details on any topic because a full week could be spent on any of the methods presented. Another byproduct of these courses is the networking with others in the USGS. So enjoy!

Joshua M. Blackstock, Instructor
Ph.D. Candidate
Department of Geosciences
University of Arkansas
216 Gearhart Hall,
Fayetteville, Arkansas 72701
jmblack@uark.edu

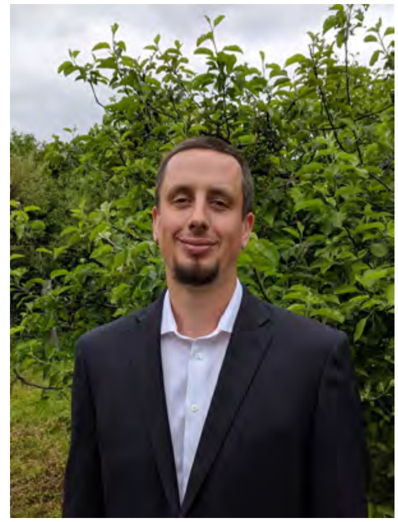
Joshua is a student at the University of Arkansas, working toward a Ph.D. in Geosciences. He received his B.S. in Geology from the University of Arkansas, Little Rock, in 2008 and his M.S. in Geology with First Class Honors from the University of Canterbury, New Zealand, in 2012. He was employed with the USGS at the Arkansas Water Science Center and Lower Mississippi Gulf Water Science Center as a Hydrologic Technician from 2006 to 2015 where he participated in data collection and analysis and coauthored publications for numerous groundwater and surface-water studies and monitoring programs. A portion of this work included tracing fluid flow in karst aquifer systems and implementation of geochemical tracing methods. His research is primarily focused on sources, movement, and geochemical evolution of crustal fluids encompassing deep- and shallow groundwater systems and, importantly, their interactions. Research methods include geochemical analysis, with emphasis on stable and radiogenic isotope geochemistry, numerical modeling, and the burgeoning field of low-cost environmental sensor platform fabrication and deployment. Experience and lessons learned from USGS experience in standardized protocols and “field checks” have been integral in development, management, and quality assurance and quality control for these platforms.

For this course, Joshua assisted in the field component and lecturing on the collection, analysis, and interpretation of dye trace samples.

Van Brahana, Instructor
Research Scientist Emeritus (1999)
U.S. Geological Survey, Water Resources Division
Professor Emeritus (2013)
University of Arkansas
Department of Geosciences
Fayetteville, Arkansas 72701
brahana@uark.edu

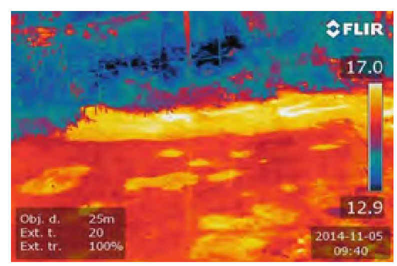
Van Brahana received his formal education from the University of Illinois (B.A.) and the University of Missouri (M.A., Ph.D.). He has more than 50 years of hydrogeologic and karst teaching and research experience with the Illinois Geological Survey, the USGS, Vanderbilt University, the University of Arkansas (UA), consulting and participating in local, regional, and national technical review boards and consortia. Van initiated his USGS career as a Hydrologist in 1971 as part of the intense, 6-month training program at the Denver Training Center. He served in Mississippi, Tennessee, and Arkansas, the last assignment as a split USGS/UA assignment. His research has focused on tectonic control of groundwater flow boundaries, karst hydrogeology, and interdisciplinary involvement to address challenging environmental problems. Tom Sauer (U.S. Department of Agriculture—Agricultural Research Service) and Van initiated and instrumented the Savoy Experimental Watershed, a site that allows study of the long-term effects of sustainable animal production on karst lands. At the UA, Van has mentored and supervised scores of students and received multiple teaching awards and the Geological Society of America Distinguished Service Award; he has published more than 75 peer-reviewed technical papers, reports, and book chapters. He currently conducts pro bono water-quality sampling and dye tracing on Big Creek, site of a 6,500-pig concentrated animal feeding operation on a major tributary to Buffalo National River.

Martin Briggs, Instructor
U.S. Geological Survey—Water Mission Area
Earth Systems Processes Division
Hydrogeophysics Branch
11 Sherman Place,
Storrs, Connecticut 06238
mbriggs@usgs.gov
Office: 860–487–7402 x19
https://www.usgs.gov/staff-profiles/martin-a-briggs



Martin earned a B.S. in Geology from the University of Massachusetts, Amherst, in 2002; his M.S. from the Hydrologic Sciences and Engineering Program at the Colorado School of Mines in 2009; and was awarded his Ph.D. in 2012 from Syracuse University. Although his specialty is in understanding and quantifying surface-water/groundwater exchange processes, Martin works on a wide range of hydrological issues in his position as research hydrologist with the Hydrogeophysics Branch at the USGS. The Branch supports State Water Science Centers when hydrogeophysical tools and training are required, and the staff collaborates with academic institutions on pioneering water research. One of the Branch's central missions is training and method development, so Martin travels around the country instructing at workshops and field testing new methodology. Martin has specifically contributed to advancements in the application of heat tracing methodology and integrating fine-scale electrical geophysics at the groundwater/surface-water interface. Much of his current research involves defining the physical hydrogeological template that controls niche aquatic habitat and beneficial biogeochemical processes in a time of baseline change.

For this course Martin led the demonstration of heat tracing methodology to locate and quantify exchanges of surface and groundwater in karst regions. For example, the infrared image below, taken at the Fayetteville, Ark., site, shows how relatively warm groundwater discharge from karst springs (hot colors) can be pinpointed for geochemical sampling and discharge measurements.



Geoff Delin, Instructor
Retired from the Water Science Field Team,
Groundwater Specialist, Central U.S.A.
U.S. Geological Survey
Denver Federal Center
Box 25046, Mail Stop 406
Denver, Colorado 80225
delin@usgs.gov
Office: 303–236–1471
https://www.usgs.gov/staff-profiles/geoffrey-delin

Geoff retired from the USGS (April 2017) as the Water Science Field Team Groundwater Specialist for the Central part of the United States, including the Southwest Region and the western half of the Midwest Region of the USGS. He currently has USGS emeritus status. Prior to Geoff's retirement, he provided technical assistance to groundwater projects in the Arizona, Colorado, Iowa, Kansas, Minnesota, Missouri, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, and Utah Water Science Centers. Geoff received his undergraduate and graduate education in Geology and Hydrogeology from the University of Minnesota. Prior to joining the USGS, Geoff worked for 2 years as a geologist at a consulting firm. He began his USGS career as a Hydrologic Technician in 1979 in the Minnesota District. As a Technician, his duties included running the District auger drilling rig. As a Hydrologist, Geoff conducted numerous investigations on groundwater quality and quantity, including simulation of groundwater flow and solute transport. Geoff was the site coordinator and Research Grade Evaluation researcher for the Management Systems Evaluation Area and Bemidji Crude-Oil Spill Toxics Substances Hydrology research studies from 1992 to 2008. His research activities involved evaluating the fate and transport of agricultural chemicals and petroleum hydrocarbons, as well as estimation of groundwater recharge using multiple methods, including conducting several tracer tests. Geoff served as the Minnesota Water Science Center Groundwater Specialist for about 12 years. Geoff is the author or coauthor of more than 65 hydrogeologic publications and has given more than 75 technical conference presentations. Geoff has been the instructor for the USGS Groundwater Field Methods course, the Groundwater/Surface-Water Interaction course, as well as for webinars relating to aquifer testing, well integrity testing, and model archiving.

Marian Domanski, Instructor
U.S. Geological Survey
Illinois-Iowa Water Science Center
405 N Goodwin Avenue,
Urbana, Illinois 61801
mdomanski@usgs.gov
Office: 217–328–9758

Marian Domanski has been with the USGS Illinois-Iowa Water Science Center in Urbana, Illinois, since 2011. Marian received his B.S. and M.S. in Civil Engineering from the University of Illinois at Urbana-Champaign. Since beginning with the USGS, Marian has worked with developing software tools for scientific applications, including emerging technologies for real-time estimates of suspended-sediment characteristics. He has also been involved with the development of USGS policy for real-time estimates of suspended-sediment concentration using acoustic backscatter. Marian has recently co-instructed the USGS Sediment Acoustic Index Methods course.

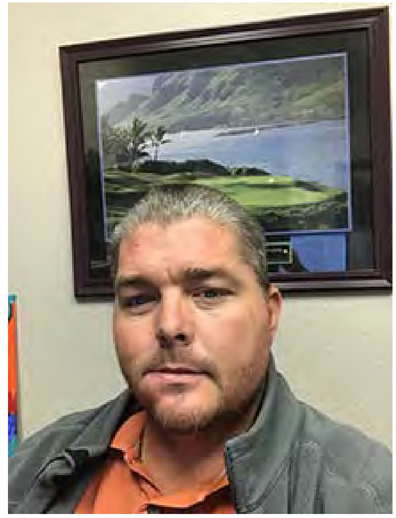
Phillip D. Hays, Instructor
U.S. Geological Survey-LMG, University of Arkansas
University of Arkansas
340 N Campus Drive
Geosciences Department, 216 Gearhart Hall
Fayetteville, Arkansas 72701
pdhays@usgs.gov
Office: 479–575–7343
https://www.usgs.gov/staff-profiles/phillip-d-hays

Phil Hays is a hydrogeologist with a background in stable isotope geochemistry and groundwater geochemistry. He completed an M.S. at Texas A&M University in 1986 and a Ph.D. at Texas A&M in 1992. He worked as an exploration geologist with Sun Oil Company from 1985 to 1988 before joining the USGS in 1992. During his USGS career he has worked in groundwater modeling, aquifer characterization, karst hydrology, and contaminant hydrology. Dr. Hays joined the Geoscience faculty with the University of Arkansas in 2000 in a USGS cooperative study and works half time as a research professor. Dr. Hays pursues research in application of stable isotopes and other geochemical indicators in delineating movement and behavior of contaminants in groundwater systems and in characterizing paleoclimate and paleoenvironment. He has worked across the United States and abroad with the goals of advancing science in management and sustainable use of natural resources and protection of the human environment; this work involves such diverse research areas as delineating the relation between karst development and water quality in the Ozark Mountains, mercury contamination in the Guianas Ecoregion, the thermal springs of Hot Springs National Park, sustainable resource use curricula development in central Africa, salt-marsh restoration in coastal New England, and characterization of groundwater impacts in shale-gas fracking production areas in central Arkansas..

Fred Paillet, Instructor
Retired U.S. Geological Survey Geophysicist
Adjunct Professor, University of Arkansas
340 N Campus Drive
Geosciences Department, 216 Gearhart Hall
Fayetteville, Arkansas 72701
fredp@cox.net
Office phone: 479–575–3355

Fred Paillet is an Adjunct Professor of Geosciences at the University of Arkansas. He served as the Chief of the USGS Borehole Geophysics Research Project in Denver from 1983 until his retirement in 2002. Since then he has had temporary appointments at the University of Maine, The University of Rennes (France), and the University of Queensland (Australia). His work in karst aquifer characterization included studies in Minnesota, Wisconsin, Illinois, Texas, Tennessee, and Arizona.

Jason D. Payne, Instructor
U.S. Geological Survey
Texas Water Science Center
3745 S. Jackson Street
San Angelo, Texas 76903
jdpayne@usgs.gov
Office: 325–944–4600 x28



Jason Payne is a geophysicist with the USGS in San Angelo, Tex., with more than 10 years of experience in many near-surface geophysical methods and environments. Jason graduated from Angelo State University in Applied Physics in 2006. Since graduation, Jason has been with the USGS as part of the Texas Water Science Center's geophysics team. He has worked on multiple large- and small-scale projects involving a wide range of geophysical capabilities.

Greg Stanton, Instructor
U.S. Geological Survey
Texas Water Science Center
1505 Ferguson Lane
Austin, Texas 78754
gstanton@usgs.gov
Office: 512–927–3558

Greg Stanton is an Associate Director for Science in the USGS Texas Water Science Center in Austin, Texas, coordinating groundwater and geophysics activities in the Center. Greg began his USGS career 25 years ago as a volunteer in the Fayetteville Project Office and subsequently spent 10 years as a Hydrologist in the Arkansas Water Science Center and 14 years in Texas as Groundwater Specialist and Associate Director. During that time Greg has worked on many groundwater and geophysics projects ranging from contaminant studies at Department of Defense sites, to karst studies in the Ozarks and the Edwards aquifers, to groundwater modeling in the Mississippi River Alluvium. Prior to his USGS career, Greg worked 7 years in the petroleum industry collecting and analyzing borehole geophysical data in west Texas, the Southeastern United States, and the Gulf Coast and offshore. Greg holds B.S. and M.S. degrees in Geology from the University of Arkansas.

Jonathan Thomas, Instructor
U.S. Geological Survey
Geophysicist—North Texas
Texas Water Science Center
501 W. Felix Street, Building 24
Fort Worth, Texas 76115
jvthomas@usgs.gov
Office: 682–316–5036

Jon is a geophysicist with the Texas Water Science Center North Texas Program Office in Fort Worth, Tex. Jon earned a B.S in Applied Physics with a minor in Mathematics from Angelo State University in 2008. Jon started in the San Angelo Field Office as a Student Career Experience Program Intern with the Texas Water Science Center in February 2008 and joined the USGS full time after his graduation in December 2008. His experience with the Texas Water Science Center geophysical team consists primarily of borehole geophysics and conceptual model development. Jon is licensed on the USGS Radiation User Permit as Radiation Logging Supervisor. Additional experience includes geodatabase development, geophysical data collection, GIS analyses, data processing, and groundwater/surface-water interaction studies.

Dan Wagner, Instructor
U.S. Geological Survey
Lower Mississippi-Gulf Water Science Center
700 W. Research Center Boulevard, Suite 2411
Mail Stop 36
Fayetteville, Arkansas 72701

Dan is a Hydrologist in the Fayetteville, Arkansas, office of the USGS Lower Mississippi-Gulf Water Science Center. He received his B.S. in Geology from the University of Arkansas in Fayetteville in 2005 and M.S. in Geology from the University of Arkansas in Fayetteville in 2008. Dan started as a Student Career Experience Program Hydrologic Technician in the Arkansas Water Science Center in 2006 and accepted a Hydrologist position in 2008. His work has focused on topics related to surface-water hydrology, including 2D flow modeling, surface-water dye tracing/dilution, seepage runs, bathymetric surveys, and terrestrial light detection and ranging surveys, and statistical work related to trends in streamflow data, regional regression modeling of annual peak flows, and work on the National Skew project.

Sam Wallace, Instructor
U.S. Geological Survey
Texas Water Science Center
501 W. Felix Street, Building 24
Fort Worth, Texas 76115
dswallace@usgs.gov
Office: 682–316–5037

Sam is a Hydrologist with the Texas Water Science Center North Texas Program Office in Fort Worth, Tex. Sam earned a B.S in Environmental Science from Oklahoma State University in 2013 and an M.S. in Environmental Geology from Rutgers University, Newark, New Jersey, in 2015. For his M.S., he studied the benefits of combining geophysical surveys, specifically nuclear magnetic resonance and spectral induced polarization (SIP). As a student, Sam was an Environmental Protection Agency Greater Research Opportunities Undergraduate Fellow and interned with the EPA Region 2 Division of Environmental Science and Assessment in Edison, N.J. Sam became a Pathways Intern with the Texas Water Science Center in 2014 and joined the USGS full time after his graduation in 2015. His experience with the Texas Water Science Center geophysical team consists primarily of borehole geophysical logging and land and waterborne resistivity surveys. Additional experience includes python programming, GIS analyses, peak streamflow frequency analyses, and surface-water modeling.

Devin Galloway, Planner
U.S. Geological Survey—Water Mission Area
Earth System Processes Division
Water Cycle Branch
Indiana Water Science Center
5957 Lakeside Boulevard
Indianapolis, Indiana 46278
dlgallow@usgs.gov
Office: 916–801–2040
https://www.usgs.gov/staff-profiles/devin-lynn-galloway

As of October 1, 2017, Devin is a Hydrologist in the USGS Water Cycle Branch of the Earth System Processes Division but was the Water Science Field Team Groundwater Specialist for the Western Territory, providing technical assistance to groundwater projects in Alaska, California, Hawaii (and other Pacific Islands), Idaho, Montana, Nevada, Oregon, Washington, and Wyoming. He has worked with the USGS since 1978 in the Illinois Water Science Center, the Nuclear Hydrology Program in Colorado and Nevada, the California Water Science Center, the National Research Program, and the Western Region Hydrologist's office. Devin has a B.A. in Biology (Indiana University), M.S. in Environmental Science (Indiana University), and an M.S. in Civil and Environmental Engineering (University of Illinois). He is the author or coauthor of more than 75 hydrogeology publications and currently serves as a member and past chair (2010–15) of the United Nations Educational, Scientific and Cultural Organization Working Group on Land Subsidence, is on the Board of Directors of the U.S. Chapter of the International Association of Hydrogeologists, and is an Associate Editor for the Hydrogeology Journal. Devin has taught the USGS Groundwater Principles and Groundwater Concepts and Modeling courses, as well as USGS-sponsored Time-Series Analysis, Aquifer Hydraulic Testing and Field Methods, and Land Subsidence Monitoring, Analysis, and Modeling courses in several national and international workshops. Devin was helpful in formulation of this course but was in Spain during the week of the course..

Rodney (Rod) Sheets, Planner
U.S. Geological Survey—Water Mission Area
Office of Quality Assurance, Groundwater Specialist
6480 Doubletree Avenue
Columbus, Ohio 43229
rasheets@usgs.gov
Office: 614–430–7710
https://www.usgs.gov/staff-profiles/rodney-a-sheets

Rod currently (October 1, 2017) serves as the USGS National Groundwater Specialist in the Office of Quality Assurance but was a Water Science Field Team Groundwater Specialist for the Northeast/Midwest part of the United States including the Northeast Region and the eastern half of the Midwest Region of the USGS. Rod received his undergraduate and graduate education in Geology/Geophysics and Hydrogeology from The Ohio State University. Prior to and during college, he drilled water and shallow oil/gas wells in eastern Ohio. He began his USGS career as a Geologic Technician/Geologist in 1984 in the Office of Earthquakes, Menlo Park, California, then as a Hydrologic Technician in 1987 at the USGS Ohio District, running field trips, sitting on drilling rigs, and helping the Studies section. After becoming a Hydrologist in 1988, Rod conducted numerous investigations on groundwater quality and quantity, including geophysical studies, simulation of groundwater flow, and surface/groundwater interactions. Rod served as the Ohio Water Science Center Groundwater Specialist for about 10 years and has been in his current position for 10 years. Rod is the author or coauthor of nearly 30 hydrology publications and has given more than 30 technical conference presentations. Rod has been the instructor for several USGS courses, including USGS Groundwater Field Methods, Groundwater Concepts, Surface Geophysics, and Use of Heat as a Tracer, as well as for webinars relating to aquifer testing, well integrity testing, model and geophysical data archiving, and tape calibration. Unfortunately, he had to cancel from participation in the field part of the course.

Appendix 2. Savoy Experimental Watershed Theses, Dissertations, and Papers

[All unpublished theses and dissertations can be obtained from University of Arkansas. Some are available online at https://libraries.uark.edu/.]

Al-Qinna, Mohammed, 2004, Measuring and modeling soil water and solute transport with emphasis on physical mechanisms in karst, Savoy Experimental Watershed, Arkansas: Fayetteville, University of Arkansas, unpublished M.S. thesis.

Al-Rashidy, Said, 1999, Hydrogeologic controls of groundwater in the shallow mantled karst aquifer, Copperhead Spring, Savoy Experimental Watershed, northwest Arkansas: unpublished M.S. thesis, University of Arkansas, 124 p.

Brahana, J.V., Hays, P.D., Kresse, T.M., Sauer, T.J., and Stanton, G.P., 1999, The Savoy Experimental Watershed—Early lessons for hydrogeologic modeling from a well-characterized karst research site, in Palmer, A.N., Palmer, M.V., and Sasowsky, I.D., eds., Proceedings, Karst Modeling, February 24–24, 1999: Charlottesville, Virginia, Karst Waters Institute Special Publication 5, p. 247–254.

Curtis, D.L., 2000, An integrated rapid hydrogeologic approach to delineate areas affected by advective transport in mantled karst, with an application to Clear Creek Basin, Washington County, Arkansas: Fayetteville, University of Arkansas, unpublished Ph.D. dissertation, 121 p.

Dixon, B., 2001, Application of neuro-fuzzy techniques to predict ground-water vulnerability in northwest Arkansas: Fayetteville, University of Arkansas, unpublished Ph.D. dissertation, 262 p.

Hamilton, S., 2001, Survival of E. coli in stream and spring sediments: Fayetteville, University of Arkansas, unpublished M.S. thesis, 48 p.

Hobza, C., 2005, Ground-water quality near a swine waste lagoon in a mantled karst terrane in northwestern Arkansas: Fayetteville, University of Arkansas, unpublished M.S. thesis, 76 p.

Laincz, J., 2011, Investigation of nitrate processing in the interflow zone of mantled karst, northwestern Arkansas, in Kuniansky, E.L., ed., 2011, U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Arkansas, April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, 212 p., https://doi.org/10.3133/sir20115031.

Laincz, J., 2014, Investigation of the flow and fate of nitrate in epikarst at the Savoy Experimental Watershed, northwest Arkansas: University of Arkansas Theses and Dissertations 2248, 149 p., https://scholarworks.uark.edu/etd/2248/.

Leh, M., 2006, Quantification of rainfall-runoff mechanisms in a pasture-dominated watershed: Fayetteville, University of Arkansas, unpublished M.S. thesis, 98 p.

Little, P.R., 2007, Dominant processes affecting groundwater quality and flow in Basin 2, Savoy Experimental Watershed (SEW): Fayetteville, University of Arkansas, unpublished M.S. thesis, 93 p.

Parse, M., 1995, Geomorphic analysis of the role of regolith in karst landscape development Benton County, Arkansas: Fayetteville, University of Arkansas, unpublished M.A. thesis, 177 p.

Pennington, D., 2010, Karst drainage-basin analysis using hydrograph decomposition techniques at the Savoy Experimental Watershed, Savoy, Arkansas: Fayetteville, University of Arkansas, unpublished M.S. thesis, 121 p.

Phelan, T.L., 1999, GIS and 3-D visualization for geologic subsurface static modeling in a mantled karst environment near Savoy, Arkansas: Fayetteville, University of Arkansas, unpublished M.A. thesis, 158 p.

Stanton, G.P., 1993, Processes and controls affecting anisotropic flow in the Boone-St. Joe aquifer in northwestern Arkansas: Fayetteville, University of Arkansas, unpublished M.S. thesis, 212 p.

Ting, T.E., 2002, Development of a bacterial tracer for water quality studies in mantled karst basin using indigenous Escherichia coli labeled with europium: Fayetteville, University of Arkansas, unpublished M.S. thesis, 106 p.

Ting, T.E., 2005, Assessing bacterial transport, storage and viability in mantled karst of northwest Arkansas using clay and Escherichia coli labeled with lanthanide-series metals: Fayetteville, University of Arkansas, unpublished Ph.D. dissertation, 279 p.

Unger, T., 2004, Structural controls influencing ground-water flow within the mantled karst of the Savoy Experimental Watershed, northwest Arkansas: Fayetteville, University of Arkansas, unpublished M.S. thesis, 128 p.

Vaughn, K.A., 2015, Controls on dissolution rate variation at a pair of underflow-overflow springs at the Savoy Experimental Watershed: University of Arkansas Theses and Dissertations 1152, 53 p., https://scholarworks.uark.edu/etd/1152/.

Wagner, D., 2007, In-situ assessment of waste storage effectiveness in karst using stable isotope biogeochemistry: Fayetteville, University of Arkansas, unpublished M.S. thesis, 58 p.

Whitsett, K.S., 2002, Sediment and bacterial tracing in mantled karst at the Savoy Experimental Watershed, northwest Arkansas: Fayetteville, University of Arkansas, unpublished M.S. thesis, 66 p.

Winston, B., 2006, Land use trends in areas underlain by karst and consequences for N source and processing in aquatic ecosystems: Fayetteville, University of Arkansas, unpublished M.S. thesis, 88 p.

Woodstrom, F.A., 1999, The effects of landuse on the spatial and temporal variations in the water quality of selected springs in Washington County, Arkansas: Fayetteville, University of Arkansas, unpublished M.A. thesis, 120 p.

Appendix 3. Planned Agenda for Advanced Groundwater Field Techniques in Karst Terrains, GW2227, November 13–17, 2017

Day 1 – Monday, Nov. 13 Classroom	
Introductions	8:00–9:00 a.m. - Eve Kuniansky
Course objectives	
Facilities	
Savoy field site orientation	
Students talk about their aquifer (Scott Prinos Biscayne 10 min.)	
Karst Hydrogeology/Ozarks	(30 min.) Phil Hays
Hydrogeology of Savoy site	(30 min.) Van Brahana
Break 10:00–10:15 a.m.	
Differential gaging (seepage runs Dan Wagner) for identifying gains and losses: use of standard gaging techniques, flow tracker, weirs, flumes (Dan Wagner)	(1 hr.)
Lunch on your own 12:00–1:00 p.m.	
Borehole dye dilution techniques / flow metering in karst	(30 min.) Fred Paillet
NMR borehole logging	(30 min.) Sam Wallace
Surface geophysics	(30 min.) Greg Stanton
Break 2:30–3:00 p.m.	
Dye tracer testing in karst aquifers	(30 min.) Eve Kuniansky
Geochemical tools used in karst terrain	(1 hr.) Phil Hays
Introduction to temperature tracing, fiber-optic distributed temperature sensing (FO-DTS), vertical FO-DTS (HRTS), and thermal infrared (TIR) imaging	(1 hr.) Marty Briggs
Plans for Tuesday: Group assignments, overview of field stations, and objectives for the day	(30 min.)
Icebreaker dinner (TBD) – Dinner at restaurant next to hotel	
Tracer test starts on Monday evening (10 p.m. to 2 a.m. dumping 2 or 3 different tracers (Rhodamine WT, Fluorescein, eosin) at three wells/sinks known to go to springs (Langle and Copperhead)—Those that want to participate can go with Van, Joshua, Eve, and Dan. Participation is not required.	

Day 2 – Tuesday, Nov. 14 Savoy Field Site	
Students depart hotel; pick up lunch on the way	8:00 a.m.
Class meets at Tree Spring site for initial discussion	9:00 a.m.
Teams rotate among field stations	9:45 a.m.–Noon
Station 1: Tree Spring injection point –salt for dilution, measure specific conductance after each downstream spring	(Marty Briggs and Geoff Delin)
Station 2: Sink point on stream	Phil Hays
Station 3: Langle Spring discharge point	Dan Wagner – grab samples hourly
Station 4: Copperhead Spring discharge point	Eve Kuniansky (Fluor) – grab samples
Station 5: Fluorometer analyses in the field	Eve Kuniansky at Copperhead
Lunch near Tree Spring 12:00–1:00 p.m.	
Teams continue rotating among field stations (it will be determined later who is where in the field)	1:00–4:00 p.m.
Point-to-point tracer test and qualitative sampling of monitoring points:	
Station 1: Tree Spring injection point (?)	
Station 2: Sink point on stream	
Station 3: Langle Spring discharge point	
Station 4: Copperhead Spring discharge point	
Station 5: Flurometer analyses in the field	
Class meets at Tree Spring site for recap of the day's work	4:00 p.m.

Day 3 – Wednesday, Nov. 15 Savoy Field Site	
Students depart hotel; pick up lunch on the way	8:00 a.m.
Class meets at Tree Spring site for initial discussion	9:00 a.m.
Teams rotate among field stations	9:30 a.m–Noon
Station 1: FLIR camera demonstration and usage	Geoff Delin
Station 2: FO-DTS includes field demonstration of data collection, calibration, fiber choices, and splicing	Marty Briggs and Marian Domanski
Station 3: Sink point on stream; HRTS setup	Dan Wagner – grab samples hourly
Lunch near Tree Spring 12:00–1:00 p.m.	
Teams continue rotating among field stations (it will be determined later who is where in the field)	1:00–4:00 p.m.
Station 1: Borehole geophysical logging demonstration – dye dilution at one well	Fred Paillet and Greg Stanton
Station 2: Borehole geophysical logging demonstration – NMR tool	Sam Wallace and Jon Thomas
Station 3: Surface geophysical demonstrations (resistivity, GEM2, GPR)	Jason Payne
Return to hotel	4:00 p.m.

Day 4 – Thursday, Nov. 16 Classroom	
Classroom:	8:00 a.m.–Noon
Seepage-run analysis	(30 min.) Dan Wagner
Dye/Salt-dilution results interpretation- interactive with class.	(2 hrs.) Marty Briggs
Break 10:30–10:45 a.m.	
Results of point-to-point tracer and quantitative testing	(1 hr.) Joshua Blackstock and Eve Kuniansky
Lunch on your own 11:45 a.m.–1:00 p.m.	
Classroom: Temperature analyses	1:00–5:00 p.m.
FLIR Camera results and longitudinal DTS	
1-D heat/flux model theory; 1-D TempPro (version 2) graphical user interface (GUI) for VS2DH numerical modeling approach. Upload of 1-D thermal profiles from Savoy site into 1-D TempPro to determine seepage direction and rates- interactive with class.	(1 hr.)
Introduction to Matlab-based VFLUX analytical modeling programs; analysis of similar 1-D thermal profiles from the Savoy stream as (a) to determine seepage rates – *interactive with class*	(1 hr.)
Group dinner TBD	

Day 5 – Friday, Nov. 17 Classroom	
Classroom:	8:00 a.m.–Noon
Borehole geophysical logging in karst terrain	(1 hr.) Wellcad or Flash
Surface geophysical usage in karst terrain field examples/results	(1 hr.)
Break 10:00–10:30 a.m.	
Open format discussion (1.5 hours): Synthesis of hydraulic, chemical, and geophysical methods for data collection in karst terrain. What are the relative costs and advantages and disadvantages of each method? Which methods are highly complementary? Are any methods duplicative?	(1 hr.) All instructors available
Class ends	Noon

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Kuniansky and others—**Interpretation of Dye Tracing Data Collected November 13–December 2, 2017, at the Savoy Experimental Watershed, Savoy, Arkansas**—Scientific Investigations Report 2019–5016

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