UNIVERSITY OF
ARKANSAS

Department of Geosciences

222 Gearhart Hall ● Fayetteville, Arkansas 72701 ● (479) 575-3355 ● (479) 575-3469 (FAX)

September 10, 2018

Caleb J. Osborne
Associate Director, Office of Water Quality
Arkansas Department of Water Quality
5301 Northshore Drive
North Little Rock, Arkansas 72118-531

Dear Assistant Director Osborne:

I am a 29^+-year citizen of Arkansas, a Research Scientist Emeritus (water scientist) of the U.S. Geological Survey, and a Professor Emeritus at the University of Arkansas (Karst Hydrogeologist), having devoted the last 29^+ years to studying the waters of our Natural State. I have seen Big Creek and the Buffalo National River under a wide range of flow conditions, I have been in the field with many of the scientists who have collected hydrogeologic data, and I feel you are making a major mistake by ignoring the groundwater and dye-tracing data in relation to yur 303 (d) classification of Big Creek and the Buffalo. The studies that support this work have been peer-reviewed and published in professional journals, and by ignoring the groundwater, which forms a major component of the hydrologic cycle in this karst region, you appear to have made a potentially flawed decision.

I feel compelled to add my voice to request strongly that you reconsider this decision, for it flies in the face of Regulation 2, it flies in the face of the science of data collected by the U.S. Geological Survey and the National Park System, and it gives the appearance of political favoritism that ignores the natural environment of our beautiful state. It comes at the expense of negatively impacting tourism that contributes more than $50 million dollars to this fiscally depressed region. Please place Big Creek and the Buffalo National River on the 303(d) list as a category 5 impaired streams, based on the severity of the pollution. Please join all Arkansas citizens in collaborating with science and common sense.

Sincerely yours,

John Van Brahana, Professor Emeritus
Department of Geosciences, University of Arkansas
Research Hydrologist Emeritus

ARKANSAS
DEPARTMENT OF HEALTH

NEWS RELEASE

Meg Mirivel, MA
Public Information Officer
Office of Health Communications
501-280-4768, margaret.mirivel@arkansas.gov

For Immediate Release:
August 1, 2018

Tips to prevent Recreational Water Illness (RWI) this summer

Little Rock, Ark. – The Arkansas Department of Health (ADH) encourages Arkansans to take some simple steps to stay healthy and prevent Recreational Water Illnesses (RWIs) while relaxing at the state's rivers, lakes, streams, and ponds. RWIs are caused when people swallow water that is contaminated with common germs or bacteria, such as E. coli. People can also become sick when swimming during a harmful algal bloom (HAB).

To stay healthy while enjoying the water:

- Do not swallow water.
- Avoid swimming in algae.
- When in doubt, stay out.

You should avoid entering or playing in bodies of water that:

- Smell bad.
- Look discolored.
- Have foam, scum or algal mats on the surface.
- Contain dead fish or animals or if they are nearby (for example, do not enter a body of water if dead fish have washed up on its shore or beach).

Water quality can change quickly. In general, there is a higher risk of getting sick after a rainfall event or in cloudy water. Rainfall can wash contaminates into the water. Cloudy water due to runoff can contain contaminates that may be harmful. Not all of the contaminates can be seen by the naked eye.

Not all algae are harmful but some algae produce toxins that can make people and animals sick. It is not possible to tell if algae are producing toxins just by looking at the water. The size of the bloom is not related to the amount of toxins that could be present. Children and pets are at the greatest risk from swimming or drinking water when algae are present. You should never drink water when algae are present, even if you have filtered it first. Personal filter equipment and treatment options do not eliminate the risks associated with HABs. Never drink, cook or try to filter water affected by HABs.

Symptoms for RWIs include vomiting and diarrhea. If you believe you have gotten sick from recreational water use, contact the ADH Communicable Disease Nurses at 501-537-8969.

The Arkansas Department of Health (ADH) routinely tests designated swim beaches for E. coli levels in the summer months and recommends closure when E. coli levels are too high. Swim beach closures can be found at both the ADH (https://www.healthy.arkansas.gov/programsservices/topics/arkansas-swim-beach-program) and Corp of Engineers (https://www.swl.usace.army.mil/) websites.

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Arkansas Department of Health

4815 West Markham Street ● Little Rock, Arkansas 72205-3867 ● Telephone (501) 661-2000
Governor Asa Hutchinson
Nathaniel Smith, MD, MPH, Director and State Health Officer

3 August 2018

Dear Veterinarian:

Subject: Harmful algal blooms and toxin poisoning in dogs

Harmful algal blooms (HAB) from blue-green algae (cyanobacteria) may be intermittently present in parts of the Buffalo River National Park, specifically the lower river region. These algae can produce toxins, such as microcystins and anatoxins, that affect people, pets, and livestock that swim in and drink from algae-contaminated water. Buffalo River National Park manages multiple high-use recreational swim/float areas where people frequently recreate with their dogs. Though we have received only a few reports of human illnesses possibly associated with HABs, we want to inform you of the current situation and provide additional resources should a potential case present at your clinic.

Though this notice is specific to HAB activity within the lower Buffalo River region, it is important to note that HABs are an issue for many lakes, ponds, and possibly rivers nationwide, and their incidence is on the rise. Please consider water exposure and travel history as elements of a patient's medical history.

Clinical Signs and Diagnosis

Signs of cyanobacterial toxin poisoning depend on the type of toxin (hepatotoxin, neurotoxin, or dermatoxin), toxin concentration, amount consumed, size of the animal, and exposure route. The majority of exposures result in no or self-limiting clinical signs, but ingestion of large amounts of toxin can result in serious illness and presentation for emergency care. Common signs of hepatotoxin poisoning (e.g. microcystins) include vomiting, diarrhea, anorexia, jaundice, abdominal tenderness, and dark urine. Death can occur within days after exposure due to liver failure. Neurotoxins (e.g. anatoxin-a) cause excessive drooling, disorientation, seizures, and respiratory failure. Death follows within minutes to hours after exposure from respiratory paralysis. Additionally, cyanobacteria may produce dermatoxins, which result in rash, hives, or an allergic reaction in the exposed animal.

Diagnosis is based primarily on history of recent exposure to cyanobacteria, clinical signs of poisoning, and necropsy findings. Diagnostic methods include analysis of stomach and fecal content and liver histopathology.

Treatment

Untreated, cyanobacterial toxin poisonings may be fatal in animals. Prompt veterinary care is critical for patients showing hepatic or neurologic symptoms and should include supportive care. There are no antidotes to these toxins, but experimentally, oral cholestyramine has shown promise for treatment in dogs. Inducing vomiting within the first two hours of ingestion may minimize absorption of ingested toxins. Activated charcoal slurry may be of benefit to bind toxins in the gut if cholestyramine is not available. Pet Poison Hotlines may be consulted for additional treatment advice.

To report an illness: contact Arkansas Department of Health at adh.zoonotic@arkansas.gov or 501-280-4136.

To report suspect nuisance or harmful algal blooms: contact Arkansas Department of Environmental Quality at https://www.adeq.state.ar.us/complaints/forms/nuisance_algae_complaint.aspx or https://www.adeq.state.ar.us/complaints/forms/harmful_algae_complaint.aspx or 501-682-0923.

For additional information:
Laura Rothfeldt, DVM, DACVPM
State Public Health Veterinarian
Arkansas Department of Health
Zoonotic Disease Section
Office: 501-280-4136
Laura.Rothfeldt@arkansas.gov

http://www.merckvetmanual.com/mvm/toxicology/algal_poisoning/overview_of_algal_poisoning.html?qt=cyanobacteria&alt=sh

http://www.mdpi.com/2072-6651/5/6/1051/htm

http://www.health.state.mn.us/divs/idepc/diseases/hab/vet/index.html

http://www.dec.ny.gov/docs/water_pdf/habspets.pdf

https://www.nps.gov/buff/learn/news/buffalo-river-water-quality.htm

Utilizing Fluorescent Dyes to Identify Meaningful Water-Quality Sampling Locations and Enhance Understanding of Groundwater Flow Near a Hog CAFO on Mantled Karst—Buffalo National River, Southern Ozarks

By Van Brahana[1], Carol Bitting[2], Katerina Kosic-Ficco[3], Teresa Turk[4], John Murdoch[5], Brian Thompson[6], and Ray Quick[7]

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Abstract

The karst area of the Springfield Plateau in the southern Ozarks of north-central Arkansas is subject to numerous and varied land-use practices that impact water quality. In this region of the U.S., animal production and human activities have concentrated wastes within environmentally-sensitive karst hydrogeologic settings. Groundwater flow in this region includes aquifers covered by a thin, rocky soil, and a variable thickness of regolith. The karst groundwater system is underdrained by relatively-pure carbonate-rock aquifers that have been dissolved to form an open network of caves, enlarged fractures, bedding planes, conduits, sinkholes, swallets, sinking streams, and springs. Flow in these aquifers is typically rapid, flow directions are difficult to predict, interaction between surface and ground water is typically extensive, and processes of contaminant attenuation that characterize many other ground-water settings are not easily visible. Herein, we show dispersive groundwater flow from multiple injection sites; groundwater basin boundaries vary with groundwater level. Although the geologic framework appears simple, the results of tracing with fluorescent dyes during 2014 indicates that a meaningful conceptual model is indeed complex, yet essential to use when sampling water quality and fully understanding the movement of groundwater and its close interaction with surface streams and recharge..

INTRODUCTION

The hydrogeology of the mantled karst in the southern Ozarks (figure 1) is not typically apparent from topographic features on the land surface, yet the region is underlain by a system of well-developed fast-flow pathways and voids which pass water and entrained contaminants downgradient to resurgent springs and streams quickly and with little attenuation of the pollutants. Karst scientists have long been aware and are fully knowledgeable about this and related areas of mantled karst, covered by insoluble debris weathered from the original carbonate bedrock (White, 1988; Quinlan, 1989; Ford and Williams, 2007).

Unfortunately, consultants unfamiliar with mantled karst have difficulty in recognizing the vulnerability of groundwater that underlies the land surface, and with the close interaction of that groundwater with surface water of such areas (Murdoch et al., 2016). This is the case of Big Creek basin, the third largest tributary of the Buffalo National River (BNR), an area of mantled karst was permitted for a 6,500-head concentrated animal feeding operation (CAFO) for hogs in 2012 using documents that did not discuss groundwater or karst (Pesta, 2012).

There are two objectives for conducting this research and writing this paper. The first is to present the results of five tracing events using three separate fluorescent dyes in Big Creek in the vicinity of the CAFO and its spreading fields,

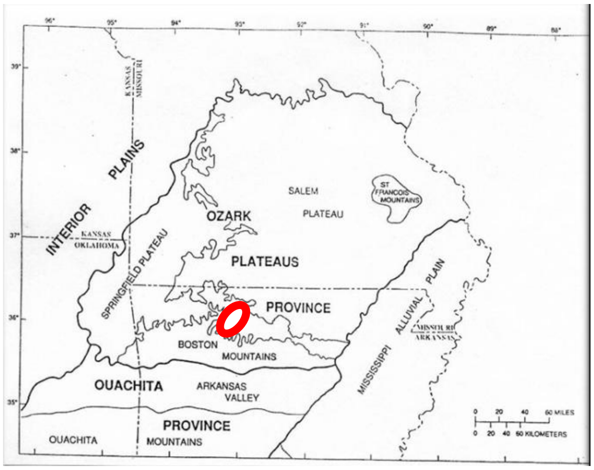


Figure 1. General physiographic regions of the Ozark Plateaus, including the Springfield Plateau, a chert-rich limestone that develops mantled karst. The red elipse shows the approximate area of Big Creek and the Buffalo National River, a unique and extraordinary resource waterway that is administered by the National Park Service. (modified from Imes and Emmett, 1994).

focusing on point to point groundwater flow connections, and time of travel. The long duration of the traces was intended to show natural variation of the groundwater flow system in the karst for varying recharge, and establish that the rates of flow do indeed characterize the fast-flow conditions of conduit transport. The second objective is to provide an explanation of why the groundwater moves in the manner that was measured, and to do so in terminology that will enlighten and educate laypeople and other stakeholders, especially those who have the responsibility of promulgating regulations based on the established karst science. Documenting these karst attributes in peer-reviewed publications represents an important means to further educate these unenlightened consultants.

Hydrogeologic and Karst Characterization of the Study Area

Big Creek is one of the largest tributaries to the Buffalo National River, encompassing about 8% of the total drainage of the entire Buffalo River basin. Topographically, tributaries head in uplands on terrigenous sediments of Pennsylvanian age of the Boston Mountains Plateau (figure 1) and flow generally toward the north and east with relatively steep gradients, typically in the range of .003 to .005.

The stratigraphic unit of concern to this study is the Boone Formation (Braden and Ausbrooks, 2003), an impure limestone interval Figure 2) that contains as much as 70% chert (Liner, 1978). The chert is hypothesized to have formed from atmospheric deposition of volcanic ash that was periodically ejected and carried by prevailing winds. In northern Arkansas, the setting was a shallow carbonate shelf (Brahana, 2014). The carbonate factory operating in this shallow marine setting at that time was hypothesized to have been overwhelmed by massive amounts of silica, which in the study area formed thin but fairly continuous layers of silica gel that typically ranged in thickness from 5 to 30 cm. During periods of volcanic quiescence, carbonate sediments were deposited onto the thin layers of silica gel, and with successive sedimentation from these two sources, a sequence of approximately 80 m of couplets were laid down, compressed, and diagenetically altered and indurated into limestone and chert of the middle portion of the Boone Formation (Brahana, 2014).

Structural uplift resulting from compressive closure of the Ouachita orogeny , which created a foreland bulge. This uplift acted concurrently with the volcanism, caused jointing, faulting, and tilting that allowed and facilitated pathways of weathering and karstification (figures 3 and 4) of the carbonate intervals of the middle Boone. It is onto this landscape that the CAFO and its spreading fields were sited, and which our dye tracing was conducted.

Big Creek and its major tributary, Left Fork of Big Creek, flow in alleviated valleys on bedrock. Alluvium is composed of nonindurated sediments, primarily chert and terrigenous rock fragments from younger, topographically higher formations. The alluvium in these valleys varies in thickness from a feather-edge to about 8 meters (m). Outcrops of the Boone Formation are common in the streambed and bluffs along Big Creek and the Buffalo. Springs are common along the entire reach of Big Creek, ranging from relatively small discharges in the tens of liters per minute range to large discharges in the tens of

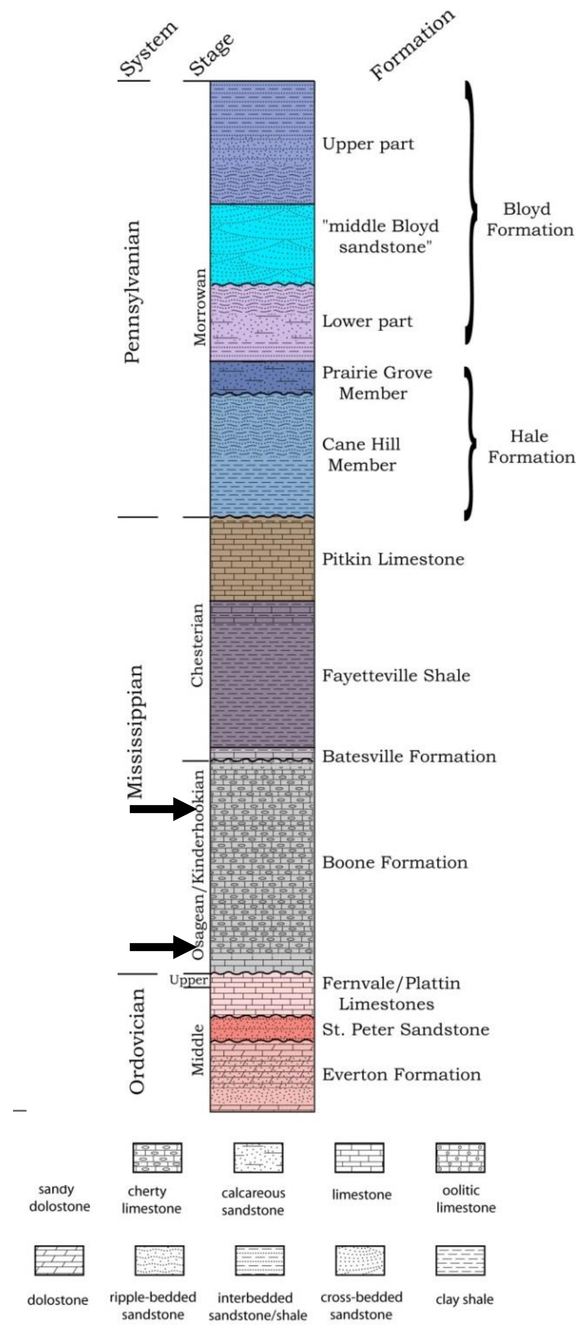


Figure 2. Stratigraphic column of the Big Creek study area, showing the stratigraphic extent of karst where the Boone Formation (light grey color) occurs at land surface. Arrows on the column bracket approximately 80 m of the chert-rich interval of the chert/limestone couplets of the Boone. Total thickness of the Boone is about 110 m. Figure modified from Braden and Ausbrooks (2003).

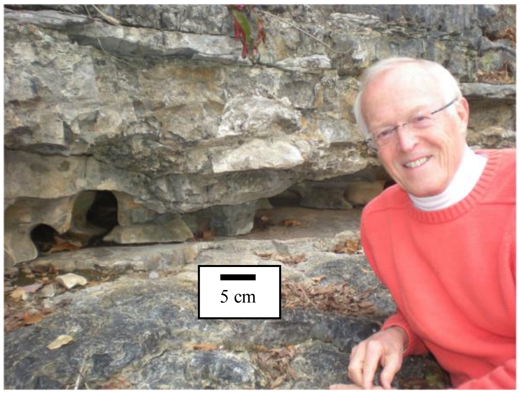


Figure 3. Karst dissolution features in limestone interbedded with chert from the middle Boone. The chert acts as an insoluble confining unit for the upper and lower dissolution zone. The scale of these voids typically ranges from 2 to more than 5 cm.

liters per second. These larger discharges resurge from relatively pure limestone lithologies, with caves) more commonly found in the lower Boone or in Ordovician aged limestones and dolomites (Mott et al., 2000).

METHODOLOGY

Qualitative dye tracing was conducted from April 2014 through October 2014 in Big Creek and contiguous basins using three nontoxic, fluorescent dyes, fluorescein, rhodamine WT, and eosin. A single dye was injected into flowing groundwater at sites that included hand-dug wells, a sinking stream in alluvium, and a swallet (figure 6). The latter feature was a sinkhole that captured all of the flow of Dry Creek, a tributary that lies upgradient from Big Creek and nearby spreading fields in limestone of the upper Boone (figure 5); fluorescein dye was introduced into a dug well with groundwater flowing on the epikarst overlain by Big Creek alluvium over lower-middle Boone about 500 m downgradient from the CAFO; and eosin was injected into a dug well that was surrounded by waste-spreading fields.

Passive dye receptors similar in appearance to a tea bag were constructed by placing approximately 10 grams of coconut charcoal in a permeable packet that allowed flowing groundwater to contact the charcoal. In most cases, the permeable external layer of the packet was a “milk sock”, whose manufactured purpose is to filter milk from automatic milking machines used by dairy barns. This fabric enjoys recent popularity among dye tracers, especially for flow velocities about 2 km/d or less. For greater flow velocities, such as surface streams, an additional packet was made with larger fabric openings approximately one-forth the size of window screen. This mesh is greater than the mesh of the milk sock, yet small enough to retain all the charcoal. From previous experience, use of screen with full-sized openings was subject to charcoal breakage, and the charcoal would be washed from the packet, leaving an empty dye receptor. In high velocity streams, the milk sock receptor was often too fine a mesh to allow full contact of the flowing groundwater with the charcoal, and thus did not yield meaningful positive dye detections.

Figure 4. Karst conduit in pure limestone of the Boone Formation showing stain from sediment and water that moved through this void previously. Because groundwater can move so rapidly in karst openings, there is little chance for contaminants to be filtered or attenuated. Flow and transport does not occur continuously in a conduit like this, owing to their great hydraulic conductivity.

Passive dye receptors were placed in flowing groundwater and surface water throughout the study area, based on a previous karst inventory and discussion with local landowners. Receptors were placed in all available springs, wells, streams, and flowing water where we had been granted permission. Inasmuch as groundwater flow directions were not known at the start of the study, such a conservative approach is required (Quinlan, 1989).

If fluorescent dye were in the water, it was sorbed onto the charcoal of the receptor. These were left in place for periods of time varying from one day to one month, and were replaced by new receptors when the original receptors were retrieved. Receptors were identified by plastic tags with station number, date placed, and date retrieved noted in black permanent marker (Sharpie), and placed into ziplock bags with additional information as appropriate recorded on the bag. Chain-of-command forms were prepared and updated for the receptors through each transfer responsible for all remaining actions.

Upon receipt from the field, the receptors were rinsed with distilled water in the Hydrogeology Laboratory at the University of Arkansas to remove sediment and related debris (Room 240 Gearhart Hall). They were allowed to air dry for at least 24 hours, and analyzed on a calibrated Shimadzu scanning spectrofluorophotometer (Model RF 5000). One half of the dried charcoal was placed into plastic containers and an elutant of isopropyl alcohol and potassium hydroxide was added to mobilize any dye present on the charcoal into the residual solution (eluant). This eluant was transferred by disposable polyethylene pipette into a single-use cuvette, and analyzed for the wavelength of any fluoresce. All analyses were made using the scanning spectrofluoromphotometer. Wavelength maxima of fluorescein were centered at 515 nm; for eosin at 540 nm; and for rhodamine WT at 572 nm.

DATA VERIFICATION

Verification of the accuracy of dye tracing is essential, and is documented by a process called quality assurance/quality control (QA/QC). QA/QC is a major component of all dye-tracing studies, and it provides unquestioned verification that the information gained from the passive detectors is accurate and represents only dye that was injected into the flowing groundwater. For this study, it involved verifying that: 1) the hydraulic head of the groundwater is higher at the point of injection that at the point the dye receptor was placed; 2) that the injection point is part of a dynamic groundwater flow system; 3) that positive attributes of the dye at specific locations are duplicated by other dye analysists through a series of blind testing; 4) that the

Figure 5. This spliced-multiimage photo shows karstified zones in a sequence of limestone/chert couplets in a bluff along Big Creek. The dark, near-horizontal features are incompletely dissolved zones in the limestone, which Figure 3 represents a close-up view. Vertical fractures allow water from above to enter the karst and exit through Big Creek. The gentle dip of the layers reflects slight tilting, typically less than several degrees.

Figure 6. Swallet in Dry Creek in Ozark National Forest capturing all streamflow upgradient from CAFO spreading fields. In karst, surface water and groundwater interact as a single resource, with streams typically being pirated into groundwater as shown here, later resurging from downgradient groundwater springs back to the surface.

concept of clean hands/dirty hands is honored strictly and that receptor retrieval is done by different personnel than those that injected the dye; 5) that cross-contamination of receptors is avoided by means of gloves and ziplock bags; and 6) that duplicate receptors reflect the same hydrogeology.

As a final note on QA/QC, all dye injections were accomplished using liquid dyes, inasmuch as the powdered dyes (fluorescein and eosin) are easily caught up by air currents, and cause severe cross-contamination if they are not in liquid form during injection. The liquid dyes were kept in impermeable containers, and dye receptors and personnel were isolated from incidental contact which would give false positive results (Aley, 2003; Quinlan, 1989).

TRACING RESULTS

Five dye traces were undertaken in the study area in 2014, and a summary of specifics of each is summarized in table 1. Dye injection sites are shown in figure 7 overlain on a shaded relief map, and a summary of point-to-point dye connections are shown in figure 8. Important details of each trace are described in the following section.

On April 22, five kilograms (kg) of fluorescein dye were injected into BS-39, a hand-dug well 13.17 m deep that had flowing groundwater on an epikarst perched on chert of the lower Boone Formation. BS-39 lies on an alluvial surface between the CAFO and Big Creek, about equidistant from both (figure 6).

On April 27, two kg of rhodamine WT were injected at BS-78, a sinking stream at the intersected Sycamore Hollow and a county road (figure 7). The dye was emplaced into alluvial gravel that overlaid limestone of the upper part of the middle Boone (figure 7). No positive instrumental observations of dye were confirmed from this trace. Insofar as passive dye receptors were only placed along Dry Creek and Big Creek for this test, all that can be taken from this test is there was no discernable eastern groundwater flow for the low-flow conditions measured at the

Table 1. Selected dye injections events in the study area during 2014. Locations of injection sites are shown on figures 7 overlying topography and 8 overlying geology.
[FL, fluorescein; RWT, rhodamine WT; EO, eosin; v, velocity of groundwater; ~, approximately; m, meters; d, day; outside tracers providing verification of positive traces included Tom Aley, Ozark Underground Lab, Protem, Missouri, and Geary Schindel, Edwards Aquifer Authority, San Antonio, Texas. Instrumental confirmation was conducted with Shimadzu Scanning Spectrophotometers; visual confirmation was assessed by fluorescent color in the resurgence by observers]

Injection Date	*Site Number*	*Hydrologic Setting*	*Geology*	*Tracer*	*GW Flow*	*Generalized Results*
4/22/14	BS-39	Dug well perched	lower cherty Boone epikarst	FL	moderate	multiple visual and instrument confirmations; v ~660 m/d
4/27/14	BS-78	Sinking stream	alluvial gravel over middle Boone	RWT	low	no observable confirmation; likely perched ; v not calculated
5/12/14	BS-36	Dug well perched on chert	middle cherty Boone	EO	very high	widespread instrument and outside tracer confirmations; cross-basin and crpss-formation flow; radial flow; v ~800 m/d
7/10/14	BS-71	Swallet perched	upper Boone limestone	RWT	moderate	Visible and instrument confirmation; v ~7000 m/d with surface flow part of way
8/5/14	BS-36	Dug well	middle cherty Boone	FL	very low	no observable confirmation; dye density caused it to sink to lower reservoir; stagnant no recharge; v ~0 m/d

time of this test. Positive traces were visually and instrumentally confirmed in an alluvial well downgradient, and and multiple springs that resurged from below a chert layer in the bottom of Big Creek, upwelling about 660 m from the injection site at 24 hours after injection. As with many of the other positive dye traces in the study area, the springs in the middle part of the Boone had multiple orifices that flowed from a discrete karstified layer of a single limestone/chert couplet. This trace established that groundwater flowed from BS-39 to springs in Big Creek at a velocity of at least 660 m/d. Springs associated with this resurgence would be an excellent place to sample for potential contamination from the CAFO , including feeding, waste-handling, and pond leakage.

On May 12, eight kg of eosin dye were injected into BS-36, a hand-dug well 12.23 m deep in the middle Boone with visible groundwater flow along several zones near the water table that has been intensively studied (Murdoch et al., 2016). One day following dye emplacement, more than 15 cm of rainfall caused a water-level rise of more than one m, mobilizing much of the dye into permeable zones above the pre-injection water level. The dye was dispersed in a radial pattern (figure 8), with 36 confirmed positive eosin traces (figure 9) extending to springs and surface streams in different basins than Big Creek. One positive trace to Mitch Hill Spring,

on the opposite side of the Buffalo River from injection reflected how complex the karst flow system is and how far flow from the study area could be measured. This positive Mitch Hill Spring trace (Figure 9) was reconfirmed by both of the external dye tracers using split receptor samples provided in a blind test. Obviously, some of the flow from the ground-water resurfaced and moved downgradient in Big Creek and other surface channels, but this test documented that groundwater flow from the area of the spreading fields surrounding BS-36 is mobilized under intense rainfall events, and sampling sites at springs along Left Fork, the Buffalo River, and surface streams in contiguous basins would be excellent sites for water quality sampling at high-flow conditions. The radial pattern of flow resulting from this storm (figure 8) is a common feature observed in other dye traces in the middle Boone (Aley, 1988; Mott et al., 2000). The solid arrows of this positive trace with a northwest trend from BS-36 to Left Fork (figure 8) showed receptors at 7 days, yielding a conservative straight-line velocity of about 800

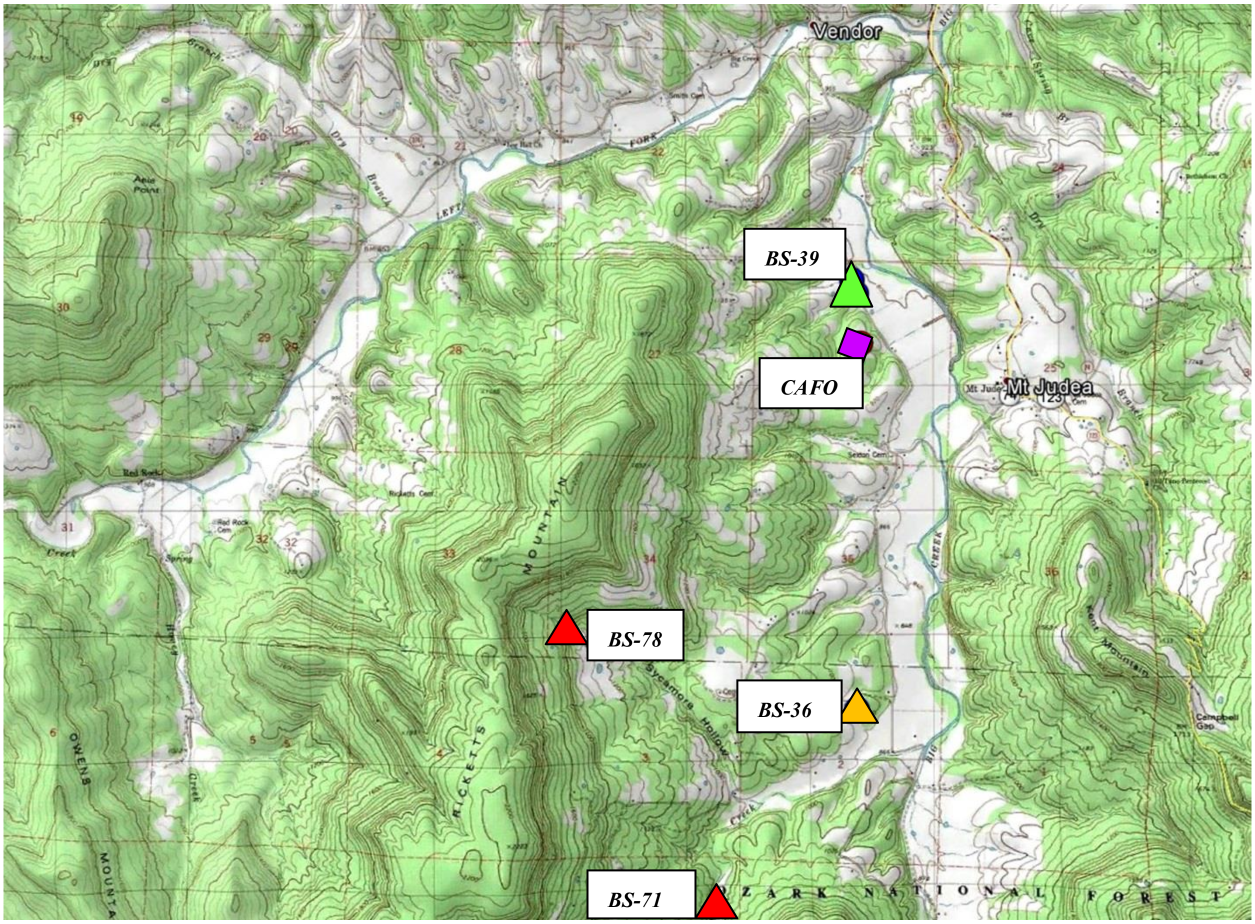


Figure 7. Topography of Big Creek near Mt. Judea, in the area of the CAFO, including the locations of dye injection, type of dye injected, location of structures housing 6,500 hogs and waste lagoons. Symbol colors for the injection sites is red for rhodamine WT, green for fluorescein, and orange for eosin. The eosin site, BS-36, also was used to inject fluorescein 3 months later, but no dye was recovered except from deep within the injection well. Table 1 summarizes the important aspects of each dye- tracing test.

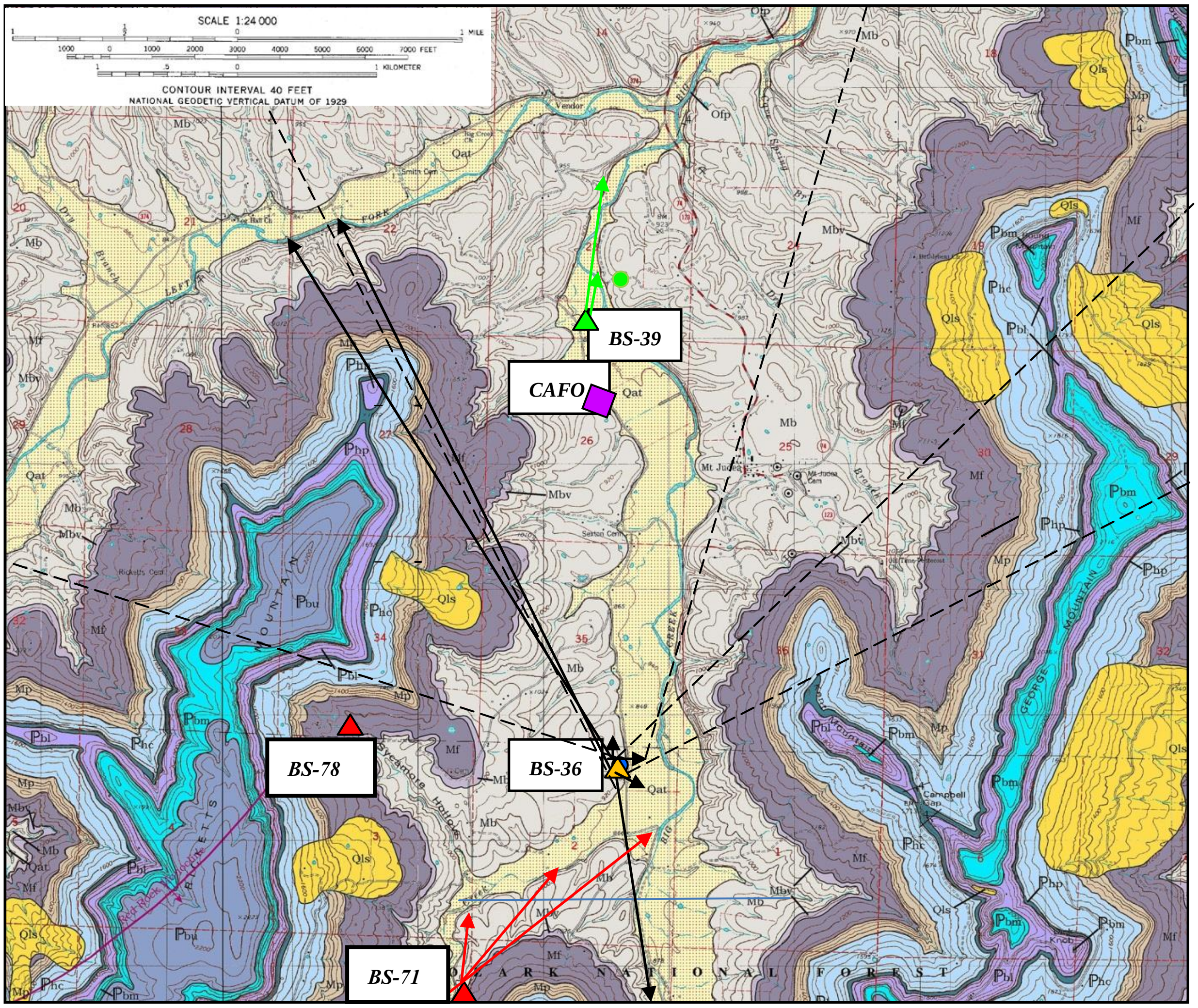
m/d. These values, along with those from the BS-39 injection site, are comparable to the fluorescein trace from BS-36 in the same geologic interval. As a comparison of velocity, later recovery of dye receptors from BS-36 showed a static zone of very little groundwater movement that served as a storage reservoir in the lower part of the well. The remaining dye, which was denser than water, was not flushed from the deeper part of the well for more than three months, and during that time was trapped with a velocity of 0 m/d.

On July 10, five kg of rhodamine WT were injected in to a swallet in the upper Boone that captured the entire discharge of Dry Creek upstream from BS-71 (Figure 7). This site had visual confirmation of dye at the confluence of Dry Creek and Big Creek, as well as positive instrumental confirmation from dye receptors at springs along Dry Creek, and the fastest groundwater velocity, nearly 7000 m/d, based on visual observation at the confluence of Dry and Big Creeks,. This is consistent with the nature of the open conduits found in karst of the upper Boone limestone (Stanton, 1994), which is chert free. Flow velocity based on this test is much greater than determinations made from the karst in the middle Boone, and can be explained by less frictional flow from conduits in the pure-phase upper limestone of the upper Boone and significant portion of the flow path occurring on the surface in Dry Creek.

On August 5, two kg of fluorescein were injected into BS-36, this time under extremely low-flow conditions. As with the trace at BS-78, no positive confirmation at any dye receptor except within the injection well was observed. The variation of stage in BS-36 at the time of this test was significantly lower than the eosin trace of May 5 and the conditions of groundwater flow were essentially as different from the May 12 test as they possibly could be. The May 13 test had 36 confirmed positive eosin traces. The August 5 fluorescein trace had no confirmed traces (figure 9). This result provides good insight for the water-level control on the flow in the middle Boone, and helps explain the possible reasons for what we have observed. Transport during low-flow conditions are manifested in insignificant flow,

DISCUSSION AND CONCLUSIONS

Based on the results of the dye tracing described herein, the following observations of groundwater flow in the Boone Formation in the



Modified from Braden and Ausbrooks, 2003

Figure 8. Geologic map overlain by point-to point dye-tracing results in the area of the CAFO and its spreading fields. Injection points are shown by triangles, and the arrows that emanate from the injection points show the groundwater sites of recovery based on positive dye traces, but not the full extent of the surface water sites. Actual flow paths in the subsurface are significantly more complex than the straight lines shown. Dashed lines from injection well BS-36 extend beyond the area shown in this figure, with the full observed extent shown in Figure 9. Tracing results shown here are groundwater-level dependent.

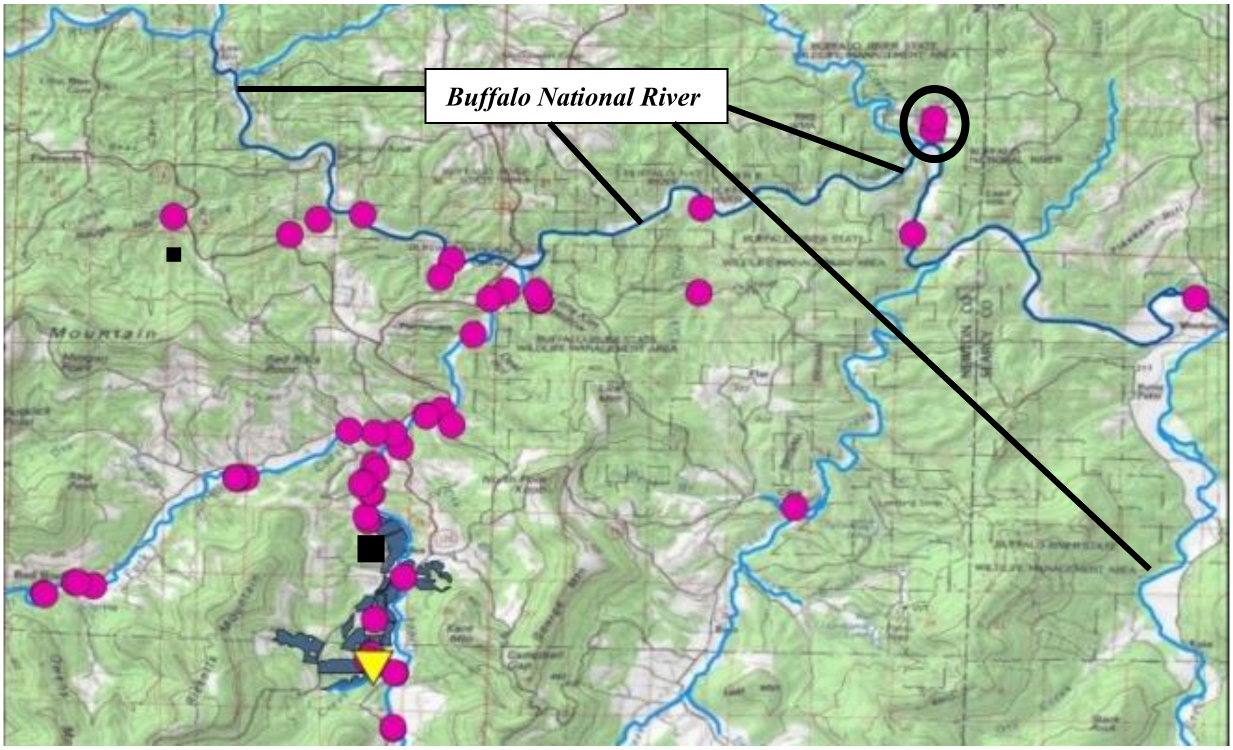


Figure 9. Flow from BS-36 where eosin input was positively traced to outflow springs and streams. This trace shows the full dispersive extent of karst flow in the subsurface into other surface water basins, the Buffalo National River, and even beneath the river to Mitch Hill Spring, identified by the black circle in the northeast quadrant. The yellow triangle is dye input well BS-36, blue shapes are hog-waste spreading fields, and the black rectangle is the CAFO. The Buffalo Nation River is the blue irregular sinuous feature that extends from the northwest to the southeast corner of the map. Pink circles are positive dye detections, five of which were retrieved from the rivet

Big Creek study area can be used for designing a more reliable and relevant water-quality sampling network to assess the impact of the CAFO on the karst groundwater and to gain further understanding of the karst flow.

1. Although the study area is mantled karst, subsurface flow is very important, and forms a significant part of the hydrologic budget.
2. Groundwater velocities in the chert/limestone portion of the middle Boone Formation were conservatively measured to be in the range of 600-800 m/d.
3. Conduits in pure-phase limestones of the upper and lower Boone have flow velocities that can exceed 5000 m/d.
4. Groundwater flow in the Boone Formation is not limited to the same surface drainage basin, which means that anomalously large springs should be part of the sampling network (Brahana, 1997).
5. Because the Buffalo National River is the main drain from the study area, and the intensive contact of the river water by uses such as canoeing, fishing, swimming, and related activities, large springs and high-yield wells should be included in the sampling network.
6. Maximum potential transport times of CAFO wastes from the land surface appear to be greatest during and shortly after intense precipitation events. Minimum groundwater flow occurs during droughts. Sampling should accommodate these considerations.

The chert obviously plays a role as confining layer, and adds to the complexity of the flow systems of the karst. Interbasin transport of the dye is consistent with groundwater following faults, which are common in the study area, with many not mapped. Faulting and uplift were the result of the closure of the Ouachita orogeny, and in the subsurface in karst, the insoluble material can typically be washed into the fault plane and deflect groundwater flow along the fault. The appearance of linear patterns truncating topography (Figure 7) and geology (Figure 8) are consistent with this interpretation, and can be further tested with additional dye traces.

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