KARST GEOLOGY AND THE BIG CREEK WATERSHED

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Background

The Big Creek Watershed below the C&H Farm and application field locations, lie within a karst hydrologic system of great complexity exhibiting intimate connection of surface-water and groundwater regimes. These characteristics endow the hydrologic system as an important recreational resource locally and regionally, but also render the system vulnerable to contamination. The complexity of karst prevents easy understanding of flow regimes, challenging effective protection and management. Karst hydrologic systems are defined by the heterogeneous distribution of high-permeability solution channels that have developed in soluble, carbonate rock and the connectivity of these channels with the land surface (Figure 2).

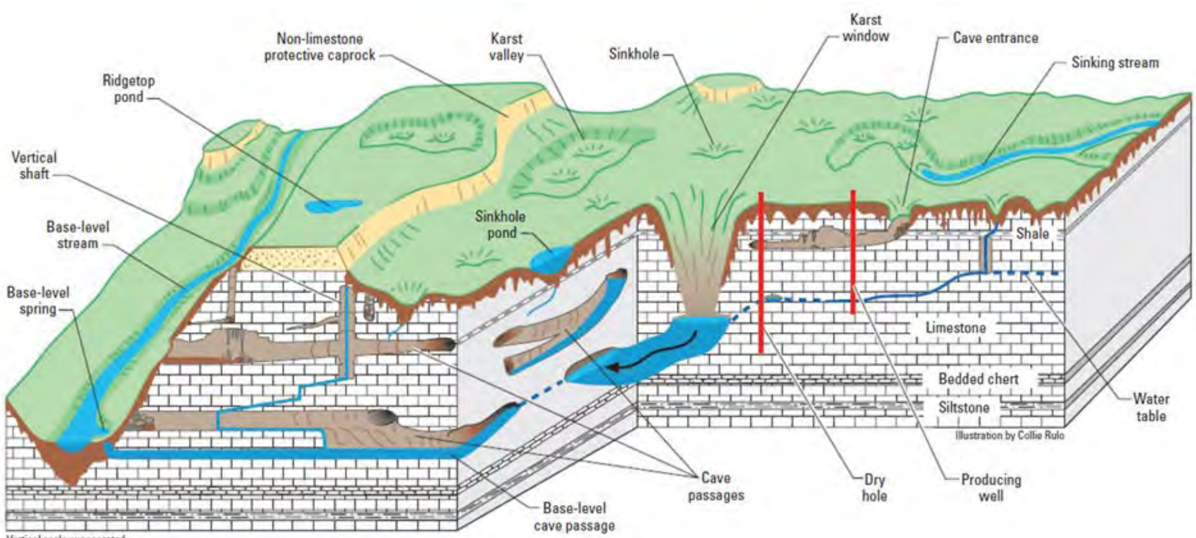

Figure 1. Schematic representation of karst features that influence the fate and transport of nutrients in the landscape; and which can increase the speed and unpredictability of nutrient flows (from Currens, 1995).

This connectivity results in rapid transport of surface water, as well as surface-derived contaminants, into the groundwater environment, bypassing soils, regolith, and granular rock strata, where any attenuation of contaminants may occur. Karst groundwater flow paths often cross surface topographic divides and are dynamic, frequently changing dominant conduits and flow direction, as well as changing recharge-area boundaries with changing hydrologic conditions. Karst terrane is often typified karst features representing locations on these solution-channel paths; e.g., sinkholes, springs, caves, and losing streams. In the Big Creek Watershed, these surface expressions of karst are often subdued or covered by a regolith mantle. Mantled karst is characteristic of the Springfield Plateau, the physiographic section in which the Big Creek Watershed is largely located.

Geologic Framework

The weathered regolith mantle overlying the karst bedrock of the Big Creek area is a key hydrogeologic framework component affecting hydrology in the Big Creek Watershed. The regolith varies greatly in thickness across short distances, from near zero (one example area is where bedrock is exposed at the surface, excluded from application of manure,) to 60 ft or more (as observed in the area of swine barns). The regolith tends to be thicker in more flat-lying valley floors, and thinner in steep areas.

The regolith is a clay-rich, typically low-permeability unit that contains variable amounts of chert; this material is derived from weathering of the original Mississippian and Pennsylvanian units. The regolith generally is present as a silt loam surface soil overlying a clay loam subsoil, which can vary from being well-drained and exhibiting moderate permeability, to very tight with low permeability. Chert constitutes up to 90% of the regolith in some areas, and is present from sand to boulder size, as well as being present as laterally continuous remnant layers that remain in autochthonous soils. These chert layers present permeability contrasts along which water flows, often acting as barriers to infiltration.

The variable thickness and composition of the regolith mantle, imparts heterogeneous and anisotropic hydraulic characteristics and resultant spatially variable flow rates through the unsaturated zone (Al-Qinna et al., 2014). Where present in considerable thickness, the regolith is a strong impediment to infiltration of precipitation and surface water, protecting the underlying karst aquifer from rapid input of surface-derived contaminants. However, the variable thickness of the regolith and the variable clay and chert distribution render the protective qualities of the regolith somewhat spatially sporadic. Big Creek valley is generally covered in alluvial sediments that range up to more than 20 ft in thickness.

Relatively horizontal sedimentary rocks of Ordovician through Pennsylvanian age are exposed and underlie the Big Creek watershed. Pennsylvanian clastics--sandstones, shale and siltstones—are present at the surface at higher elevations—ridges and plateaus. At lower elevations, in the foothills and valleys, the Mississippian Boone Formation, a cherty limestone, is exposed and is the predominant geological formation in the study area. The Ordovician Ferndale, Plattin, St. Peter Sandstone, and Everton Formations are exposed at low elevations in the Big Creek Watershed near the confluence with the Buffalo National River (Figure 3).

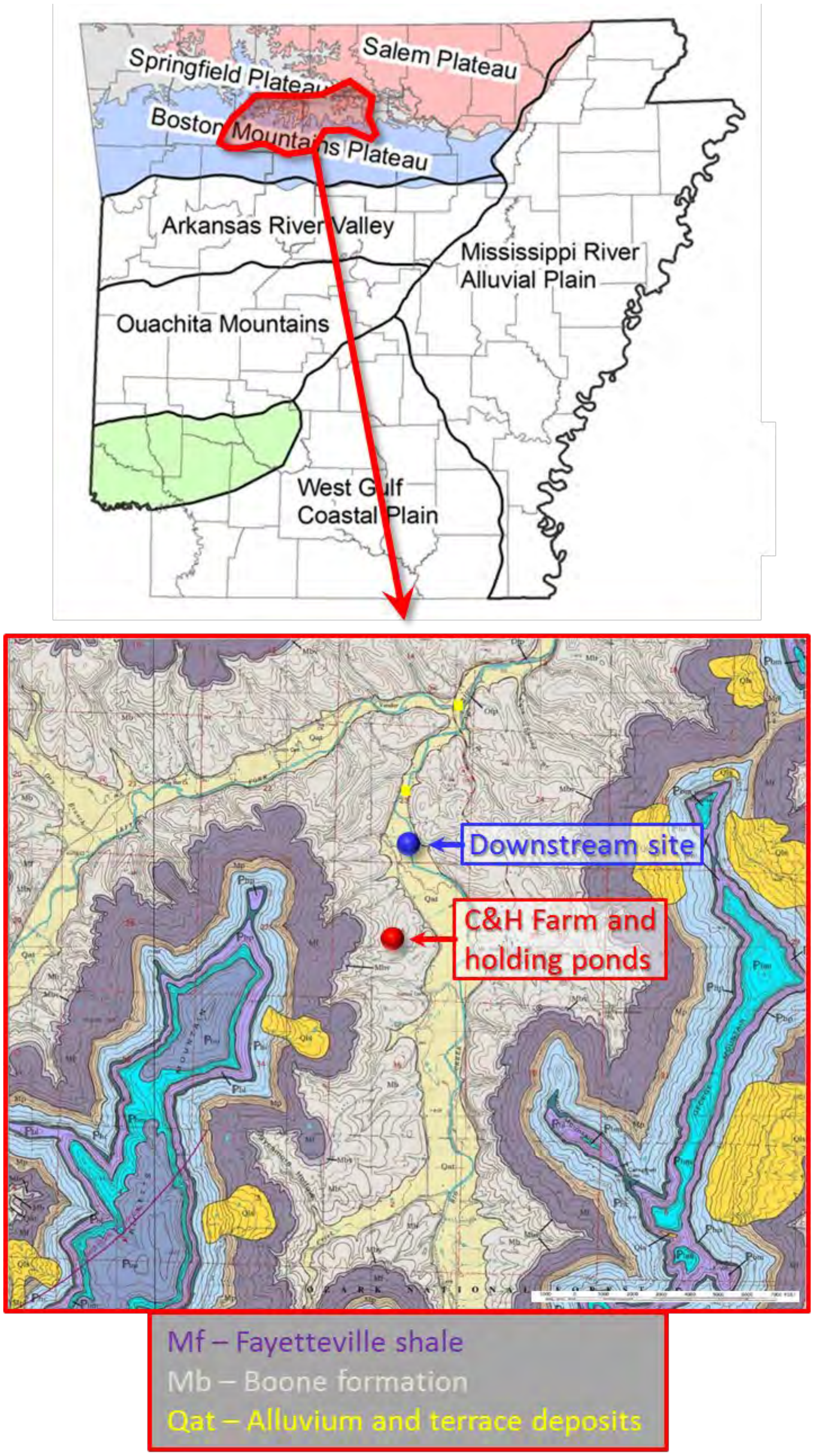

Figure 2. Physiographic map of Arkansas showing the areas containing rocks susceptible to karst formation with location of the Buffalo River Watershed (top map) and geology of the area encompassing the monitored Big Creek Watershed, C&H Farm, and BCRET sampling site on Big Creek downstream of the C&H Farm operation (bottom map adapted from Braden and Ausbrooks, 2003).

The Boone Formation is the main rock unit in the study area as it underlies C&H Farm and the application fields and is exposed at the surface or is present in the subsurface across most of the Big Creek Watershed. The Boone Formation consists of approximately 330 ft of interbedded limestone and chert. The basal St. Joe Member of the Boone Formation and the upper 20 ft of the Boone Formation, are generally represented by relatively pure limestone. Soluble limestone of the Boone contrasts with the highly insoluble, brittle chert, which constitutes 50 to 70% of the entire thickness of the Formation (Liner, 1979). Limestone layers form numerous couplets with the aerially extensive chert layers through much of the middle and lower sections of the Boone Formation (Hudson and Murray, 2003). Limestone layers are soluble and prone to karstification; the chert layers are relatively insoluble and present permeability contrasts, which separate and bound groundwater flow paths.

Karst Development and Hydrologic Characteristics

The highly soluble nature of the carbonate rocks of the Boone Formation has given rise to karst development resulting in conduits, springs, and other karst features in the Big Creek watershed. The older, deeper Ordovician carbonates—the Ferndale, Plattin, and Everton Formations—have also experienced karst development. Karst-development processes and history are important aspects of the geology controlling groundwater hydrology in the Big Creek Watershed and broader Ozark region. Multiple episodes of karst dissolution are evident in the carbonate strata, culminating in the karst development that is currently ongoing with exposure of these soluble carbonate strata to meteoric water and surface-weathering conditions. Paleokarst development occurred in Ordovician units at the Ordovician-Mississippian unconformity and in Mississippian units at the Mississippian-Pennsylvanian unconformity (Webb, 1994; Kresse et al., 2014). Additionally, hypogene karst development, predating recent epigenetic karst, occurred as lead and zinc ore-bearing fluids moved from the Arkoma Basin during Permian time and deposited the Mississippi Valley Type ores in northern Arkansas

In the Boone Formation, high hydraulic conductivity values (up to 3−10 ft/s; Stanton, 1993) are a result of development of secondary porosity through karst-forming diagenetic processes, particularly dissolution of bedrock along joints, fractures, and bedding planes, rather than from primary, matrix-type porosity. Enhancement or enlargements of fractures, bedding planes, and conduits by carbonate dissolution is an active, ongoing process. Hydraulic conductivity values of matrix porosity blocks are much lower, on the order of 10^{-12} ft/s or even less (Van den Heuvel, 1979; Peterson et al., 2002). Development of secondary porosity has produced anisotropic and heterogeneous hydraulic characteristics for the aquifer.

The presence of smaller-scale matrix, small-aperture fracture, and small-conduit porosity combined with the dissolution-enhanced conduits result in a bimodal permeability distribution and in water movement that may be described relative to two flow end members—diffuse flow and focused (conduit) flow. Because of the low rock-matrix hydraulic conductivity, a large fraction of groundwater transfer is through the focused-flow component, and rapid input of surface water, rapid flow velocities (often in the range of at velocities of 10s to 1,000s of ft/d; e.g., Hudson et al., 2007, 2011; Mott et al., 2000;

Funkhouser et al., 1999), rapid mass transfer, and minimal attenuation of contaminants are associated with this component of flow. More time-averaged flow, maintenance of stream flows during dry periods, low flow velocities, and effective attenuation of contaminants are behaviors associated with the diffuse component of flow.

Wells yields in the study area reflect the porosity types: where wells intersect highly porous and permeable zones, yields of 10 gal/min and more are observed; where wells are completed in zones with little secondary development of porosity and permeability, well yields are typically less than 10 gal/min. An important phenomenon caused by karst development is inter-basin transfer of water. Dye-tracing studies and observations of drainage-area-discharge relations show the abundant occurrence of transfer of groundwater across surface-water drainage basin divides in subwatersheds along the Buffalo River (Brahana et al., 2016; Brahana, 1997; Sullivan, 1974; Mott et al., 2000). Consideration of inter-basin movement of water is an important point for protection and management of groundwater, because contributing zones are not apparent at the surface and contaminants can be introduced into groundwater from unexpected locations.

Groundwater recharge in the study area occurs through infiltration of precipitation and is strongly controlled by the karst development of the system. Recharge occurs as both diffuse and focused recharge. Diffuse recharge occurs by infiltration of precipitation through the overlying soils and regolith. Focused recharge occurs through karst features such as sinkholes, fractures and conduits, and losing stream reaches. Karst features and focused-flow avenues allow rapid recharge by precipitation falling on the surface, thus allowing influx of surface-derived contaminants into groundwater systems with little attenuation and results in higher susceptibility to surface-derived contamination.

Karst Features in the Buffalo River and Big Creek Watersheds

Turner et al. (2016) recently mapped karst features of the Ozark Physiographic Province, northern Arkansas. Those features mapped in the Buffalo River and Big Creek Watersheds are presented in Figure 3. The level of resolution of mapped features is too coarse to identify known observed surficial karst features on fields permitted to receive slurry from the C&H Farm.

Although on-farm nutrient management planning occurs at the field scale, there is a lack of consistent and well-maintained GIS databases of karst features and geologic mapping at this scale. As an example, in Arkansas, the AGS topographic-scale geologic mapping (which includes an inventory of karst features), usually maps 1- 3 quads a year; other states map at a similar rate. Thus, NMP development and risk assessment at a State level (where policy is made) would be greatly aided by consistent karst feature databases and geologic mapping.

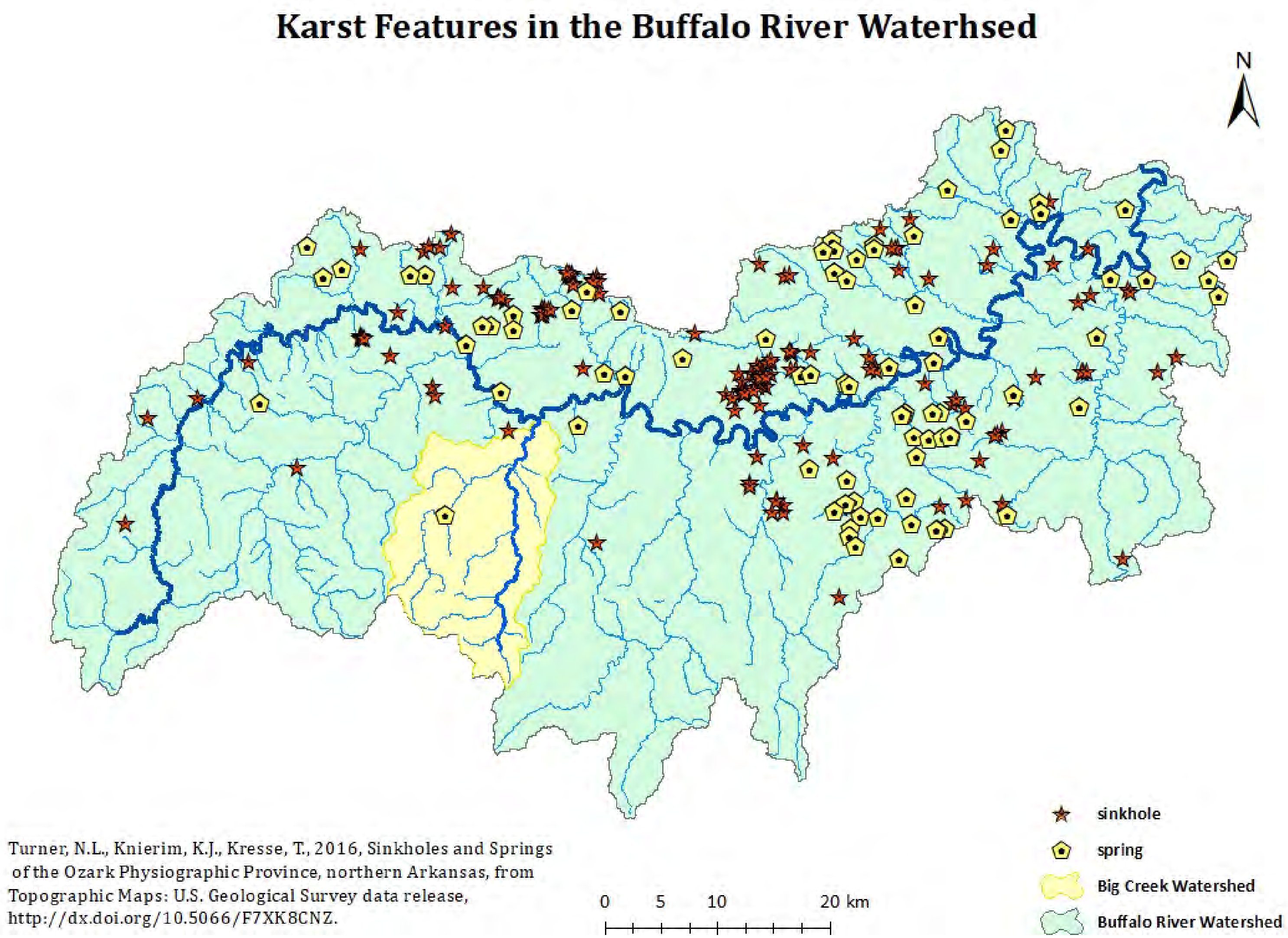

Figure 3. Karst features in the Buffalo River Watershed, derived from Turner et al. (2016).

Implications of Karst on Nutrient Fate and Transport

The effective connection of surface with groundwater environments by high-permeability, dissolution-enhanced conduits, create rapid groundwater velocities and high volume and mass-transport capacities. This coupled with groundwater recharge bypassing the overlying soil and regolith, limit any filtration, and processing capacity within the karst framework, combine to render groundwater in karst hydrologic systems, very susceptible to contamination from various land uses. Studies of various agricultural land uses including CAFOs in karst terrain have shown that waste lagoons and manure application fields can be sources of groundwater contamination (Brahana et al., 2014, 2016; Chapman et al., 2015; Ham, 2002; Kelly et al., 2009; Hutchins et al., 2012). Contaminants include nutrients N and P, bacteria, steroid hormones, heavy metals, antibiotics, and pharmaceuticals (Hong et al., 2013; Mallin and Cahoon, 2003; Lapworth et al., 2012; Roland, 2016).

Dye-trace Studies Conducted in Big Creek Watershed

A series of dye-trace studies in the monitored Big Creek Watershed were conducted by Drs. Kosič and Brahana in 2014 after the C&H Farm became operational. As mentioned in our plan of work, in order to conserve resources, we chose not to conducted additional dye-trace studies and refer to Kosič (2019) and mimicked the surface application of slurry to our monitored, permitted fields. A general map of area geology and dye-trace studies conducted in the Big Creek Watershed is shown in Figure 3 (from Brahana et al., 2016). Additionally, we were not able to devise an appropriate dye-trace study that would simulate potential for movement with surface applied slurry.

Kosič (2019) used three dyes fluorescein, rhodamine, eosin and to trace groundwater flow paths in April and August 2014 at several sites in the Big Creek Watershed (Table 1). Dye injection points were chosen based on the hydrogeological setting of the area, direct accessibility to the aquifer, and proximity to the C&H Farm production area and its spray fields (Kosič, 2019 and Kosič et al., 2015). Dye receptors were placed at selected monitoring points in private or National Park Service springs, wells and caves. Several monitoring points were also located in the stream beds of Big Creek and Buffalo National River.

Sampling utilized active charcoal dye receptors which enabled the time-integrated monitoring of a large number of locations. For example, the eosin dye was injected in a field adjacent to Field 12 monitored by BCRET. Here 3 kg of eosin, previously diluted with 5 L of water, were injected on May 12, 2014 and flushed with 20 L of water. Two days later an 89 mm rainfall occurred.

Dye receptors were collected periodically over a period of four months, with a sample frequency of days to weeks depending on hydrological conditions. Receptors were cleaned, dried, and eluted with a mixture of 70 % of isopropanol and 5 % potassium hydroxide. The resulting eluent was analyzed after 5 hours, using a scanning Shimadzu spectrophotoflurimeter at the University of Arkansas. The resulting detects in springs, caves, and creeks in the Big Creek Watershed for fluorescein, rhodamine, and eosin are shown in Figures 4, 5, and 6, respectively. Arrows on these figures assume straight-line groundwater flow directions between injection and detection points.

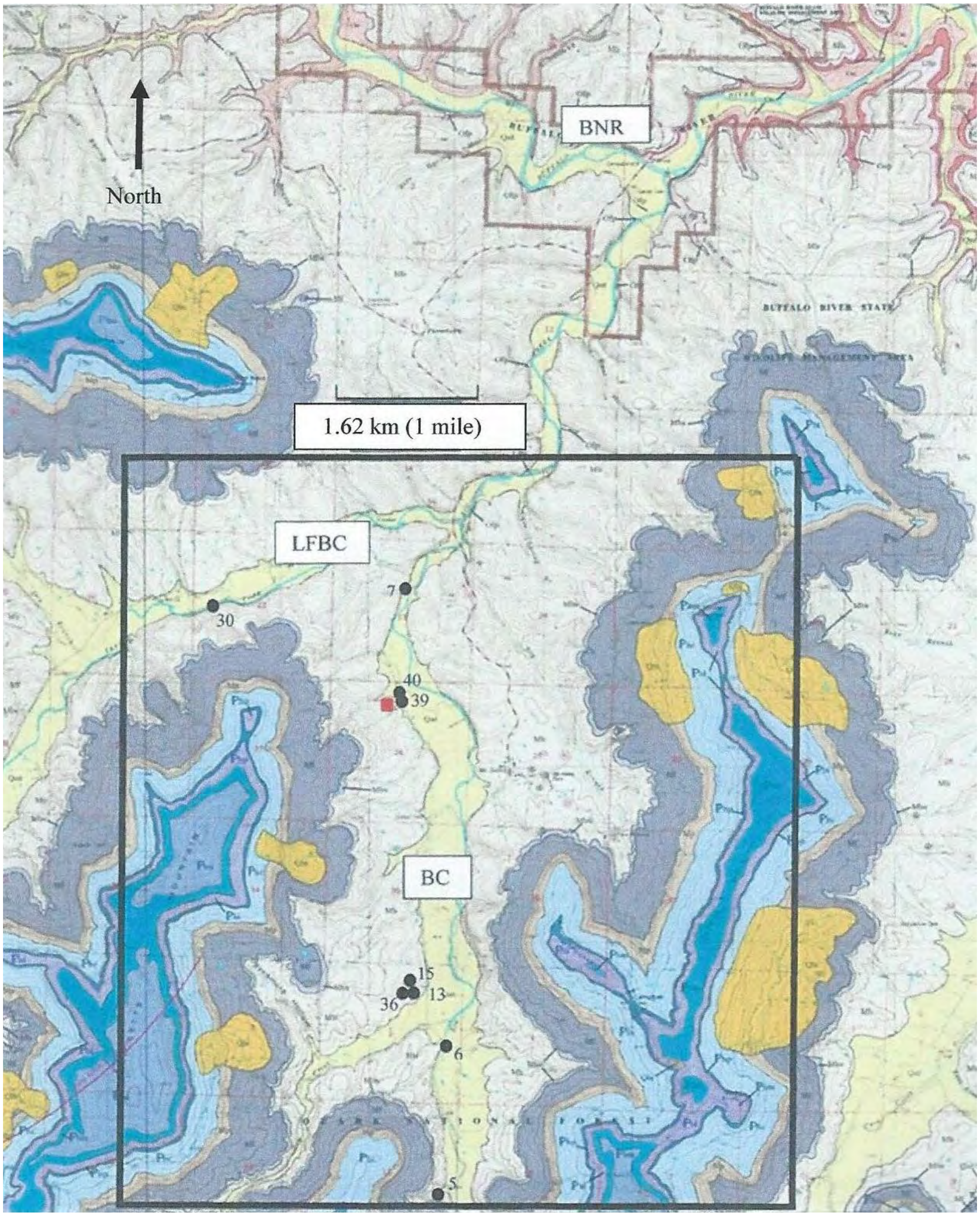

Figure 4. Geologic map of the study area, indicating the extent of karst where the Boone Formation (light grey color) occurs at land surface. BNR is Buffalo National River; BC is Big Creek and LFBC is Left Fork of Big Creek. The CAFO is shown by the red square, and the spreading fields for waste mostly lie between 7 & 6 on the west side of Big Creek. The study area is outlined by the black rectangle. Numbers 5 & 30 are the furthest extent of groundwater tracing in the study area from dye input at 36, which has an altitude greater than any of the dye-receiving sites. Map reproduced from Brahana et al. (2016) with the permission of Dr. Brahana.

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The dye-trace studies of Kosič (2019) and Kosič et al. (2015) demonstrate the high velocity with which groundwater flows can occur in the Boone karst setting of Big Creek Watershed (Table 1 and Figures 4, 5, and 6). It was evident from the eosin-dye injection that subsurface flows traversed surface drainage basins, with detects from the field adjacent to BC12 occurring in Left Fork sub-watershed (Figure 6). The overall conclusions of the dye-trace studies of Kosič (2019) demonstrate the complexity of subsurface flows in the karst system in this area of the Boone formation.

Table 1 . Qualitative trace tests conducted in 2014 in Big Creek Watershed and adjacent watersheds using three fluorescent dyes; fluorescein (F), rhodamine (R), eosin (E). Information adapted from Kosič (2019) with permission from Dr. K. Kosič.

Injection date	Site	Injection point	Geology	Trace material	Groundwater flow	Detection comments
April 22	BS-39	Dug well, perched	Lower cherty Boone epikarst	F	Moderate: velocity about 600 m/day	Multiple visual and instrumental confirmation
April 27	BS-78	Sinking stream	Alluvial gravel over middle Boone	R	Low velocity, not calculated	No observable confirmation, likely perched
May 12	BS-36	Dug well, perched on chert	Middle cherty Boone	E	Very high velocity, about 800 m/day	Multiple instrumental confirmation; cross-basin and cross formation flow; radial flow
July 10	BS-71	Swallet, perched	Upper Boone	R	Moderate velocity, about 700 m/day	Visual and instrumental confirmation; surface flow part of the way
August 5	BS-36	Dug well, perched on chert	Middle cherty Boone	F	Very low, no velocity	No observable confirmation; dye sunk to lower reservoir, ,which was stagnant with no flow

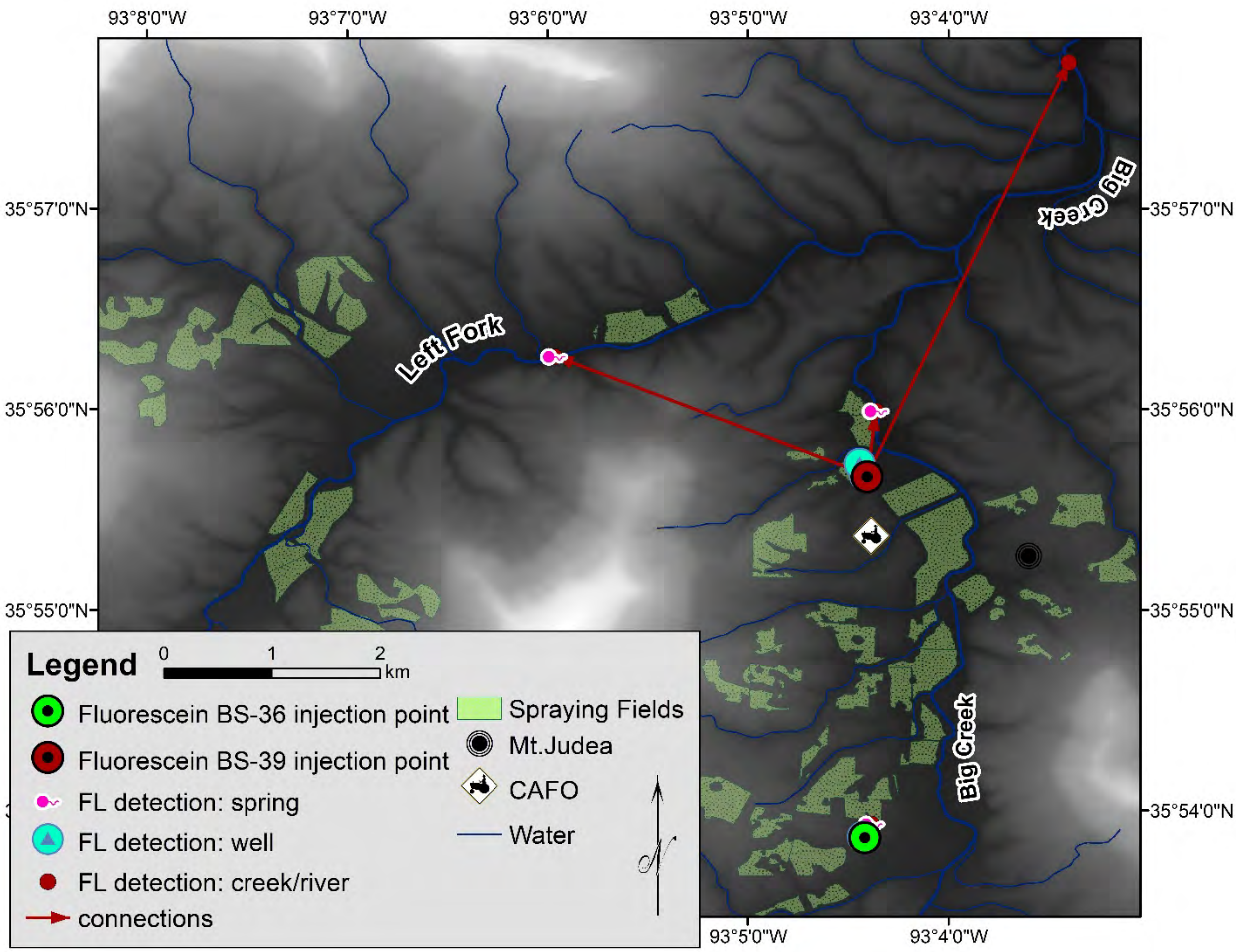

Figure 5. Map of dye-tracing results for fluorescein injections on April 22, 2014. No positive detects were obtained for tracing performed on August 5, 2014. From Kosič (2019) reproduced with permission of Dr. K. Kosič.

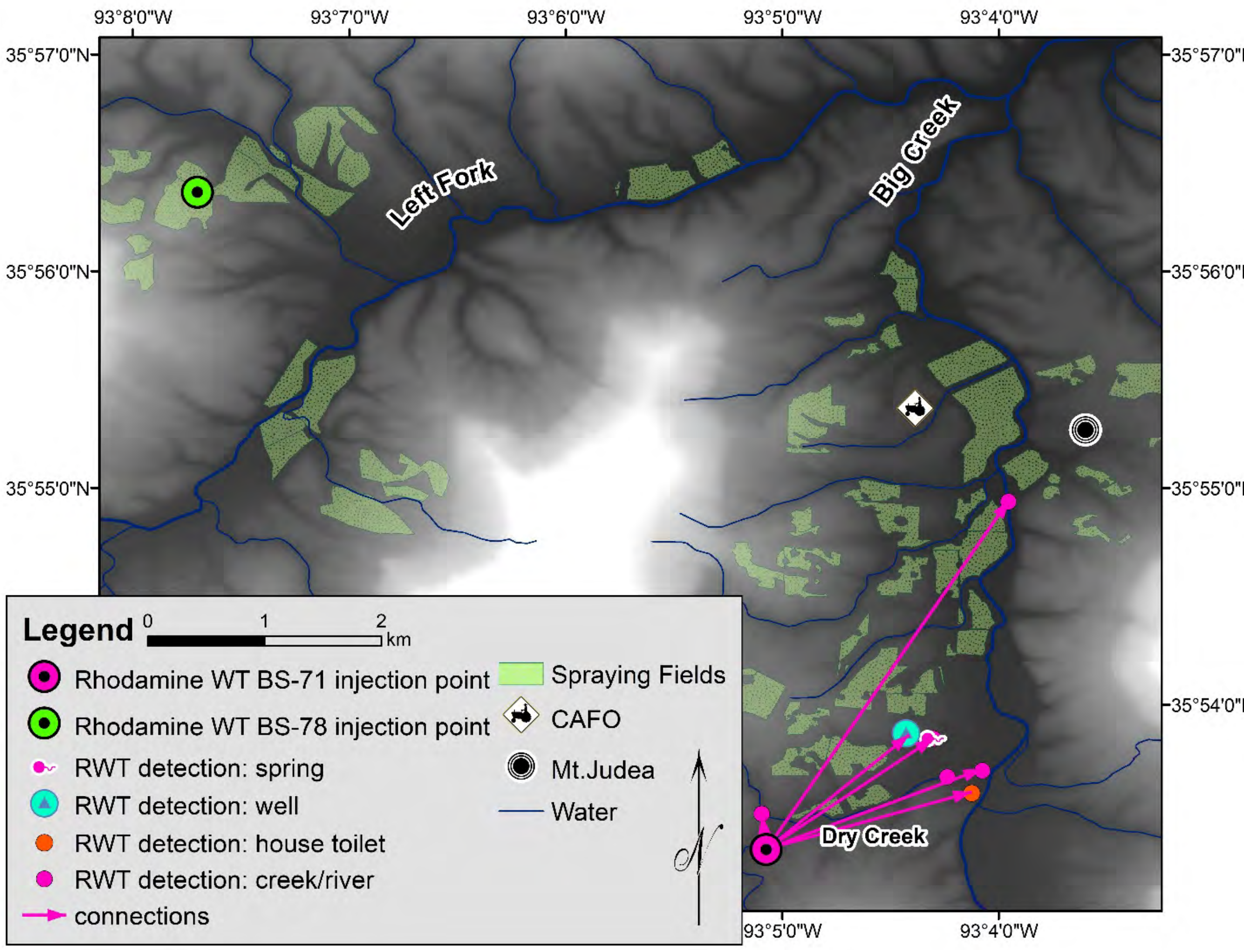

Figure 6. Map of dye-tracing results for rhodamine injections on July 10, 2014. No positive detects were obtained for tracing performed on April 27, 2014. From Kosič (2019) reproduced with permission of Dr. K. Kosič.

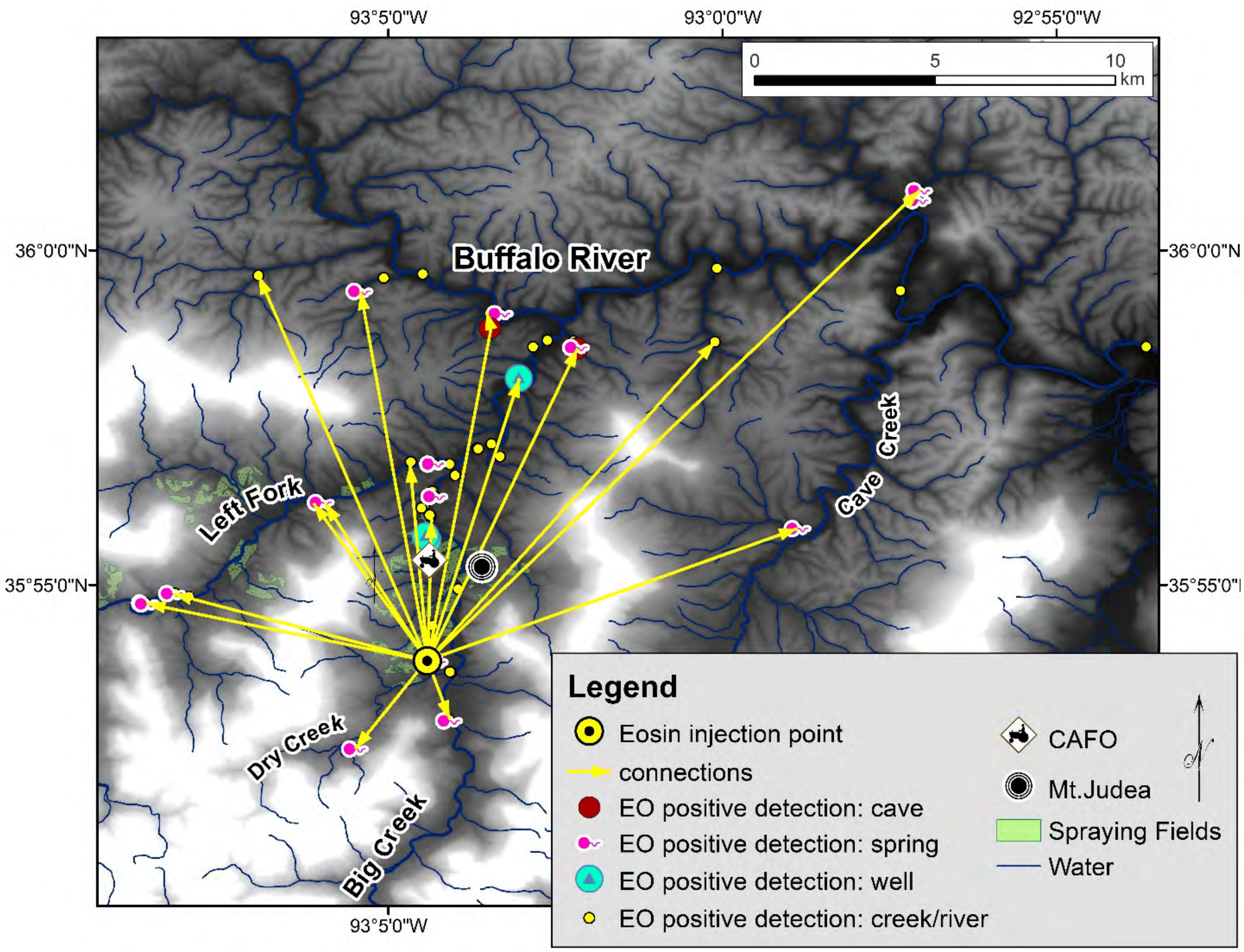

Figure 7. Map of dye-tracing results for eoscin injections on May 12, 2014. From Kosič (2019) reproduced with permission of Dr. K. Kosič.

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