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Margaret White Springs Recharge Study
Buffalo National River, North-central Arkansas USA

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Geology

by

Ashlon Leonard
Arkansas Tech University
Bachelor of Science in Geology, 2014

December, 2018
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

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Abstract

Margaret White Springs (MWS) is one of the largest springs in the middle section of the Buffalo National River (BNR) and contributes several tens of cubic feet per second of flow to river discharge on average, yet the source of the water has not been fully studied or documented. The spring is located approximately 4 miles downstream from Robertson Hole, a losing reach of the river. At Robertson Hole the river loses a significant amount of flow to groundwater, which during the dry season (summer) can be as much as 100%. Flow in the main channel is re-established at MWS; interestingly, the resurging discharge has been measured as exceeding that lost at Robertson Hole. Determination of recharge areas to MWS is critical for understanding the hydrology of the spring and management of water resources along the BNR middle reaches. The majority of the river watershed lies within the karst terrain of the Springfield and Salem Plateaus, and surface to subsurface flow is complex. Flow directions are difficult to predict, and groundwater flow paths often cross surface-water divides. Dye-tracing methods were performed during three storm events to try to determine flow paths and delineate the recharge area to MWS. The three dye-tracing tests took place in areas outside the local surface watershed for MWS to determine if flow paths were moving beneath topographic divides. The results of the dye-tracing tests provided no indication that the areas chosen for dye injection contribute water to MWS. Specific conductance measurements also were also taken at MWS and springs in the surrounding area, as well as the BNR at Robertson Hole. Mixing models using these data show a seasonal change in conductance values and indicate that not all MWS recharge originates at Robertson Hole, consistent with previous discharge measurement comparisons.

Acknowledgments

First, I would like to thank Dr. Phillip Hays, my advisor, for all the knowledge, and guidance he gave me during my time at the University of Arkansas. I appreciate the freedom and trust you had in me during this project, and the many opportunities you provided me with.

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To all my fellow students who helped out on the project, thank you, this was really a team effort. I could not have completed this without your help. A special thanks to Joshua Blackstock who not only got in the river with me in February but was excited to do so. Thank you for all of your pep talks and brainstorming meetings, this project would not have been so much fun without you!

I would like to thank all of my family and friends who helped along the way. I absolutely could not have done it without your support. A special thank you to my dad. I am so lucky to have a father who not only believes in me but is also willing to help with field work. Thank you for hiking mountains with me. Lastly, I would like to thank my best friend and husband, Justin. I would not be here if it wasn’t for your support, encouragement and love along the way. Thank you for doing field work with me and driving the 3 hours to Searcy county on countless occasions. I could never have done any of this without you. Thank you for keeping me laughing and sane along the way. I can’t wait to see where our future adventures take us!

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1. Introduction

The Buffalo National River (BNR) was the first National River in the United States and is one of the few remaining free-flowing rivers in the country (Benke, 1990). Public Law 92-237 established the BNR on March 1, 1972, “for the purpose of conserving and interpreting an area containing unique scenic and scientific features, and preserving as a free-flowing stream an important segment of the Buffalo River in Arkansas for the benefit and enjoyment of present and future generations…” The park consists of 150 square miles and 135 miles of the 151-mile-long river (Mott and Laurens, 2004). Only 11% of the river’s 857,607-acre watershed lies within National Park Service administration and 29% is in federal or state ownership, leaving the remaining 60% in private ownership (Mott and Laurens, 2004) (Fig. 1 & 2). Not only is the BNR considered a valuable natural resource in Arkansas and one of the last significant natural rivers in the conterminous U.S., it also greatly contributes to the local economy. In 2016 the park reported 1,785,358 visitors who enjoyed hiking, fishing, viewing various types of wildlife, camping, canoeing, and swimming. These visitors spent $77,556,600 in communities in and near the park, which supported 1200 local jobs (Thomas and Koontz, 2017).

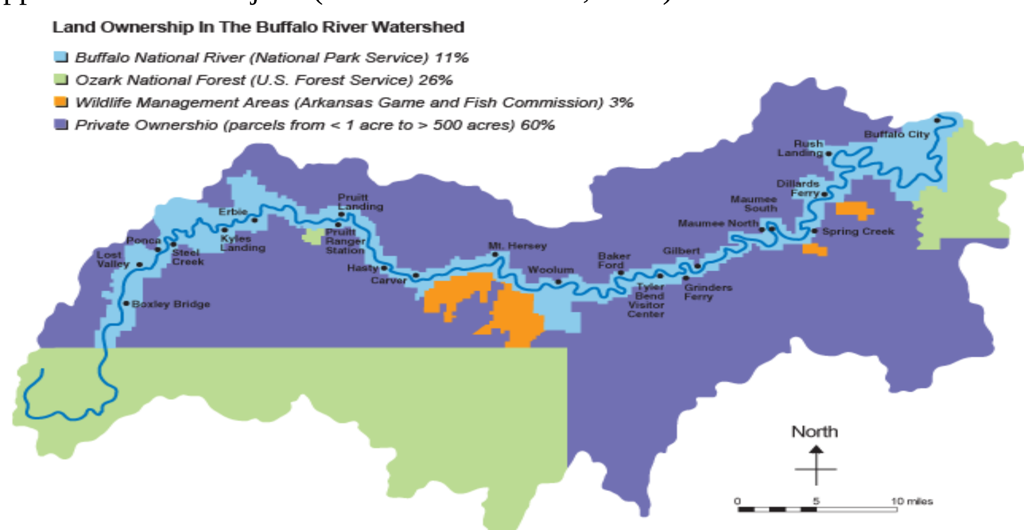

Figure 1: Image from Buffalo River Foundation showing the land ownership in the Buffalo River watershed.

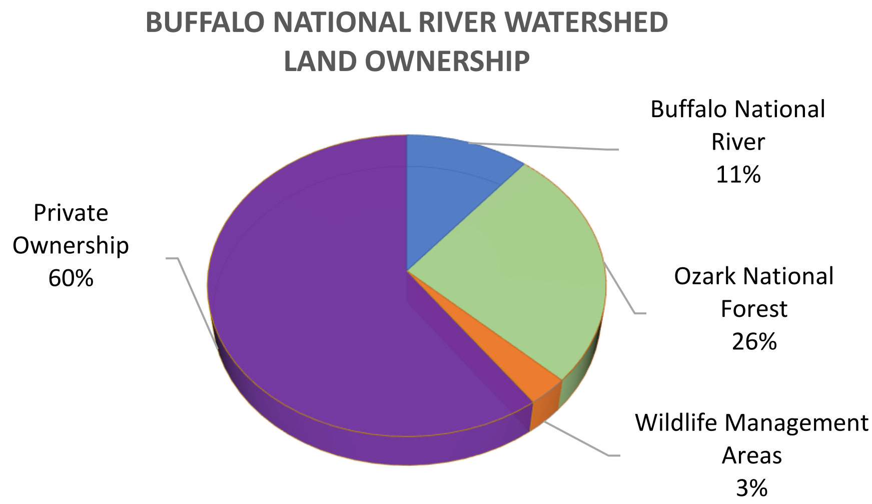

Figure 2: Pie chart illustrating the percentages of land ownership within the Buffalo National River watershed.

The BNR is located in one of the largest karst regions in the midwest United States and has been the focus of various scientific studies which have assessed many aspects of the river such as: geology, geomorphology, water quality, nutrient loads and transport, ecosystems, and land use (Springer et al., 1977; Guccione, 1993; Scott and Smith, 1994; Adamski et al., 1995; Scott and Hofer, 1995; Peterson et al. 1998; Mott et al., 1999; Petersen et al., 2002). Despite the many scientific investigations that have taken place at the BNR, MWS has remained essentially a feature that has not been adequately characterized, either hydrogeologically or geochemically. It is one of the largest springs in the middle section of the BNR, and one of the largest in the area of outcrop of the Boone Formation in northern Arkansas, contributing several tens of cubic feet per second of flow to river discharge, yet the source of the water is a point of debate. The spring is located at mile marker 83.5 which is 4 miles downstream of Robertson Hole, a swimming hole at the Woolum campground on the BNR (Smith, 2004) (Fig. 3). At Robertson Hole the river loses a significant amount of flow to groundwater, up to 100% during the summer. Flow is re-established at MWS; interestingly, the resurging discharge has been measured as exceeding that lost at Robertson Hole (Smith, 2004). Determination of recharge areas to MWS is critical for protecting water quality along the middle reaches of the BNR and understanding the interaction of groundwater and surface water in the Springfield Plateau karst region of northern Arkansas (Hays, 2014).

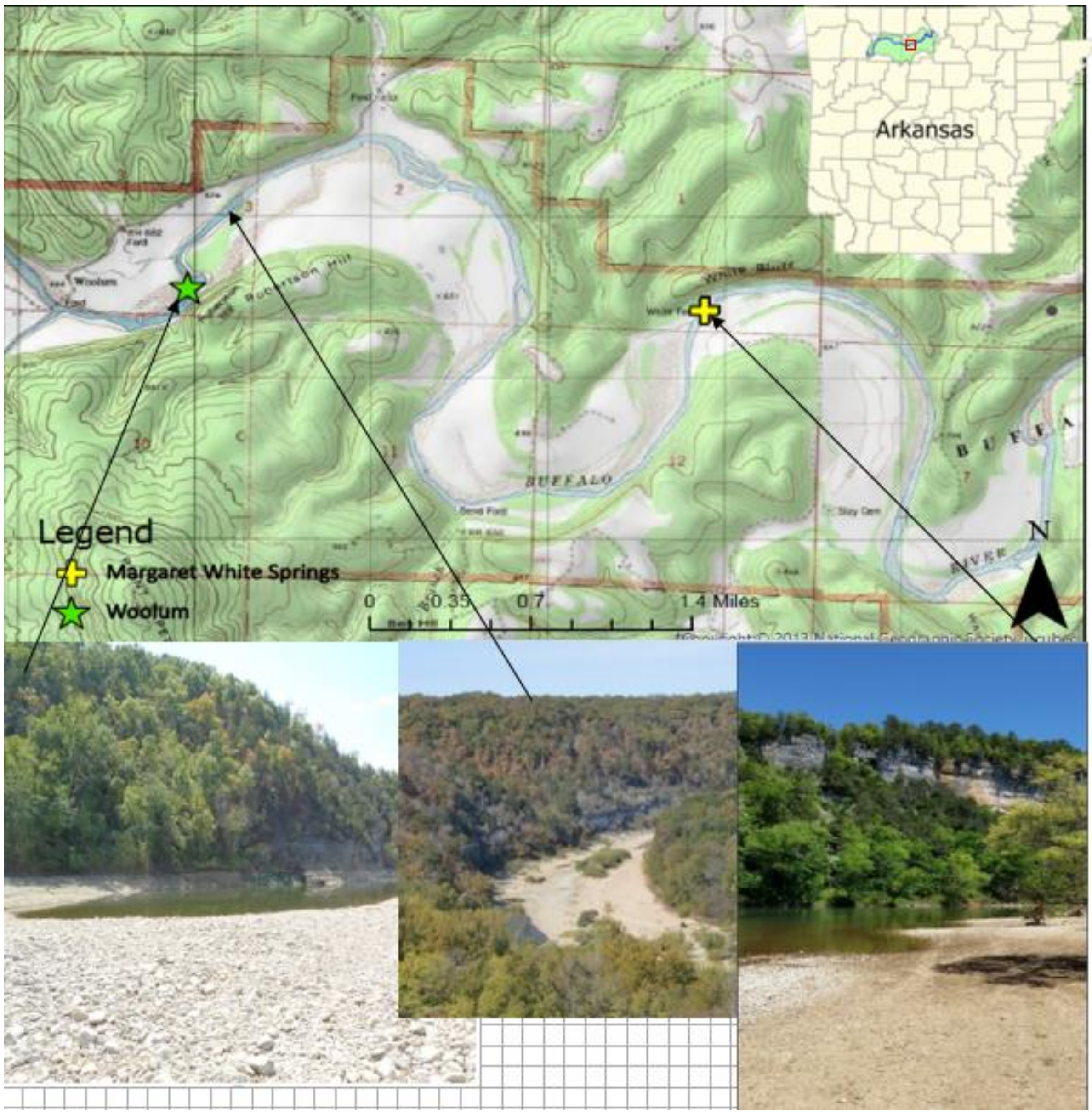

Figure 3: Margaret White Springs location and Robertson Hole at Woolum on the Buffalo National River (left and middle photos by: (Chamberlin, 2016)).

Seventy percent of the 857,607 acres of the surface watershed of the BNR is underlain by soluble carbonate bedrock of the Springfield and Salem Plateaus (Scott and Hofer, 1995). Karst landscapes are formed from the dissolution of soluble rocks, creating dissolutional features such as sinkholes, springs, caves, and losing and gaining streams which provide a direct connection between surface water and groundwater. Karst landscapes area highly susceptible to groundwater contamination because natural attenuation of contaminants are less effective in karst than in other groundwater systems. This is due to multiple factors, most notably rapid flow through large voids, recharge bypassing soils in very thin soil zones, and the conduit nature of karst secondary porosity (Mott et al., 2000). MWS resurges from the Boone Formation, a cherty limestone, which forms the predominant outcrops along the middle portion of the BNR. The Boone Formation contains abundant karst features (Hudson et. al, 2011). An initial investigation found that the discharge volume of MWS exceeds that lost by the river upstream at Woolum (Hays, 2014). This observation suggests that a considerable component of groundwater emerges at the spring in excess of what is initially lost at Robertson Hole (Hays, 2014). Because this is a karst groundwater system, intimate connection between surface water and groundwater exists, causing groundwater to be vulnerable to contamination. The complex nature of karst also makes defining flow paths very difficult, because of the heterogeneous permeability distribution and because groundwater flowpaths commonly move beneath surface-water divides. In addition, groundwater flow directions in the Boone Formation have been documented to vary with changing hydrologic conditions (Aley and Aley, 1989; Brahana et al., 2017). Many studies of the BNR have shown that oftentimes a large amount of recharge for springs comes from outside their surface watersheds (Table 2).

Preliminary flow and hydrologic data suggest that the recharge area for MWS likely includes all of the local surface drainage area upstream from Robertson Hole, as well as groundwater from other subsurface areas outside the local surface-drainage area (Hays, 2014). This project applied groundwater-tracing techniques, and water-chemistry data to determine the groundwater-recharge zones lying outside of the surface-drainage area that contribute to MWS. Point-to-point groundwater-flow connections focusing on MWS and springs in the surrounding area were tested by performing a series of groundwater dye-tracing tests to determine potential flow paths originating outside of the surface-water drainage and to gain a better understanding of groundwater flow paths. Groundwater tracing using dyes is a proven method for characterizing flow paths in karst terrains and has successfully been used in the BNR watershed in past studies (Table 2).

1.1 Importance

Although protection of water quality is the main priority for BNR Park managers and scientists, water quality of the BNR is degrading, predominantly in the middle reaches of the river (Mott and Laurens, 2004; Moix and Galloway, 2004; ADH, 2018, ADEQ, 2018). Agricultural land use in this area is intense, and has caused temporally increasing levels of nutrients in the stream (Mott and Laurens, 2004), and has continued to increase throughout the years. High levels of nutrients in the river can lead to algal blooms which can interfere with a number of recreational activities. In July of 2018 the Arkansas Department of Environmental Quality (ADEQ) recommended that 14 miles of the BNR be considered impaired due to an excess in pathogens, and the Arkansas Department of Health (ADH) advised visitors to not swim in algal blooms or swallow water because certain types of algae can be harmful to humans and animals (Walkenhorst, 2018,) Table 1 from Scott and Hofer with recent data from the USDA shows that an agricultural land use increase of 103,163 acres, a 157.2% increase, occurred between 1965 and 2012 This increase in agricultural land use can impact the water quality on the BNR. Pasture runoff effects on the water quality of the BNR were investigated by Mott and Steele (1991) by sampling the river upstream and downstream from a pasture. Pasture runoff had an average fecal coliform concentration 50 times greater than the river upstream. Land-use changes are also linked to alterations in the relative abundance of many fish species (Mott and Laurens, 2004). High levels of nutrients in the river can lead to algal blooms which can interfere with a number of recreational activities (ADH, 2018). This can also lead to a decrease in oxygen, which will greatly impact the aquatic life in the BNR (Mott and Laurens, 2004; ADH, 2018).

Table 1: Modified table from Scott and Hofer, 1995 with data from USDA showing land use changes in the Buffalo River watershed in Searcy County

Land Use Change of the Buffalo River Watershed in Searcy County, Arkansas					
Land Use:	**1965**	**1979**	**1992**	**2007**	**2012**
----------Acres----------					
Agricultural	65,632	91,452	101,042	194,963	168,795
Forest	249,909	223,710	211,843	-----	94,136
Urban/barren	1,701	2,342	4,684	-----	-----
Water	1,084	1,084	1,084	-----	-----
Transportation	1,052	1,052	1,052	-----	-----

Studies (Table 2) have found that interbasin transfer of water from streams outside of the BNR's topographic watershed boundary is occurring, and this is negatively impacting water quality along the river (Aley and Aley, 1989; Aley and Aley, 2000; Soto, 2014; Brahana et al., 2017). Delineating true watershed boundaries is difficult in karst areas, but dye-tracing tests conducted on the BNR have provided much needed information about the karst system. Areas of interbasin transfer can significantly influence water quality and need to be correctly delineated for effective water-resource management (Mott et al., 2000; Brahana et al., 2017). The information obtained from this study adds to our understanding of groundwater flow paths and groundwater contributions specifically to MWS. The knowledge gained will help water conservation groups assist land owners within the watershed with the implementation of Best Management Practices (BMPs), and the understanding of groundwater processes can be applied to other karst terrains (Mott and Laurens, 2004).

1.2 Objectives and Scope

1) Perform dye-tracing tests to characterize groundwater flow paths in the area;
2) Determine the areas outside of the surface-water drainage area that may be contributing groundwater to MWS; and
3) Utilize mixing models to approximate the amount of groundwater contribution that mixes with BNR surface water captured at Robertson Hole using specific-conductance measurements;

Scope of work: the study area is limited to the potential area of recharge of MWS. The study is based on a compilation of previous studies and the wisdom they provide; field investigation of dye-tracing study; and theoretical investigation of two- member modeling.

1.3 Study Area

The study area is located in north-central Arkansas in Searcy County. MWS is located at mile marker 83.5 (Smith, 2004) in the middle portion of the BNR and is the focus of this study. The study area was chosen to include potential recharge boundaries that lie outside the

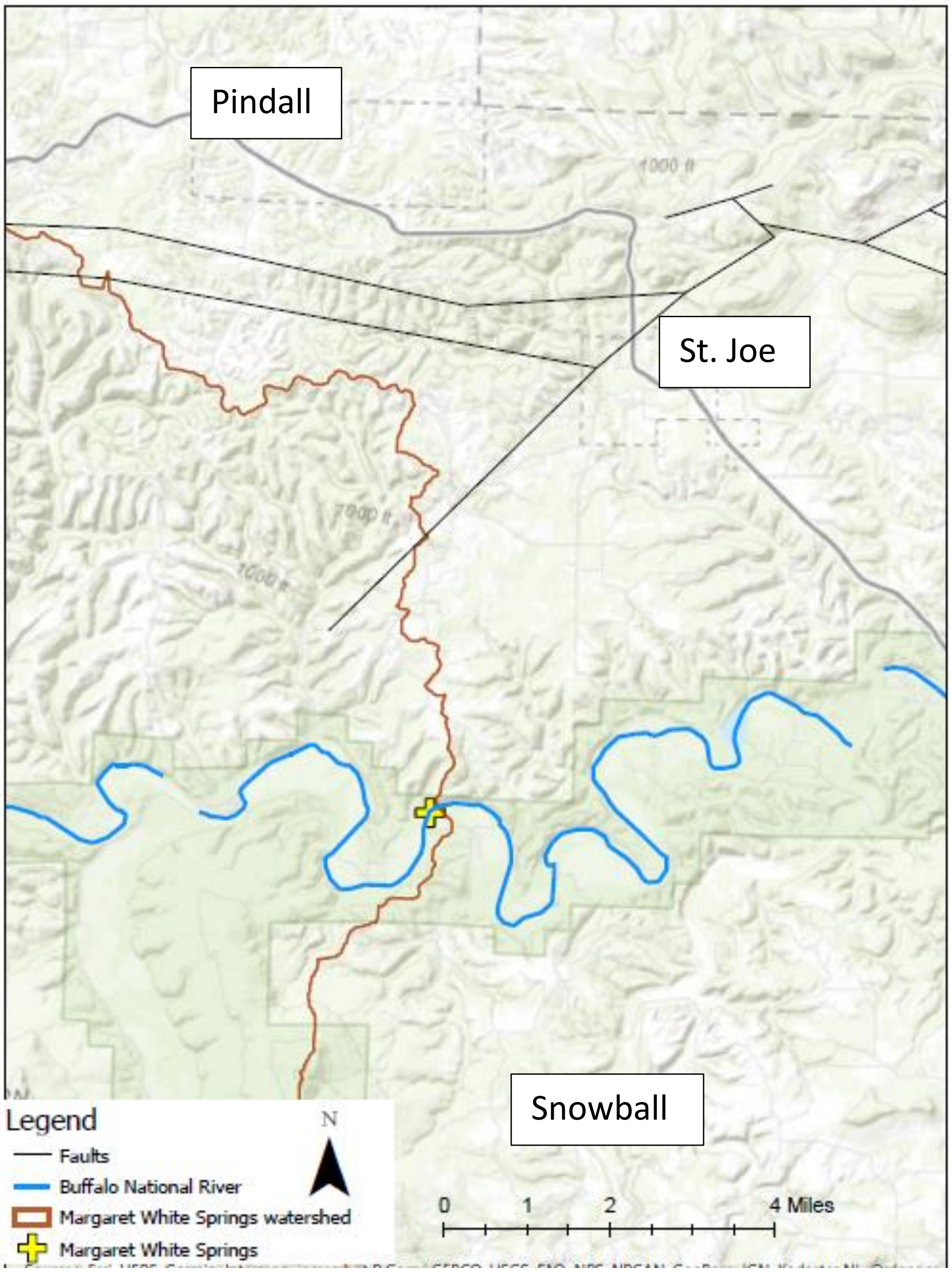

Figure 4: Map of study area showing the locations the dye-tracing tests took place and Margaret White Springs watershed.

known surface watershed to MWS. These areas included three towns in Searcy County: St. Joe, Pindall, and Snowball. The study area includes the 7.5-minute topographic quadrangles Western Grove, St. Joe and Snowball (U.S. Geological Survey).

2. Previous Work

Despite the large flow that MWS contributes to the BNR, no investigations have been conducted on the recharge area to MWS. However, a compilation of numerous groundwater tracing studies (Soto, 2014) have been documented for different watersheds around the park, and these can be related to this study and provide better understanding of local karst hydrogeologic flow systems (Table 2).

In 1986-1987, Aley and Aley (1989) conducted a dye-tracing study to delineate and characterize the recharge area for Mitch Hill Spring, a large spring flowing to the BNR. The work was conducted for Citizens Against the Landfill (CALF), a citizen's group concerned about contamination from a proposed landfill in the area. The landfill was located 4.5 miles from Mitch Hill Spring. This study documented the complex groundwater flow in this region and revealed interbasin transfer of groundwater along previously undetected faults. The proposed landfill was found to be within the recharge area for Mitch Hill Spring. This new information led to the permit for the landfill being rescinded due to the potential negative groundwater impacts. The study revealed that a large amount of land outside the topographic basin of the BNR contributes groundwater to Mitch Hill Spring. This study demonstrates how important determining recharge areas in karst systems are for protecting water quality (Aley and Aley 1989; Soto, 2014). A later study (Brahana et al., 2017) documented a greater extent to the complexity of the karst; dye injected south of the BNR actually was found in Mitch Hill Spring, which lies on the north side of the Buffalo.

In 2000 Thomas Aley and Catherine Aley conducted a dye-tracing study to understand the recharge areas for Upper and Lower Dogpatch Springs. Using the results from the dye-tracing study they were able to delineate that the total area contributing water to Upper Dogpatch Spring was 4.82 square miles. Upper Dogpatch Spring is located in the Mill Creek topographic basin, but up to 71% of the recharge area was found to be located in the Crooked Creek topographic basin. They discovered similar results for the area contributing water to Lower Dogpatch Spring; it, too, is located within the Mill Creek basin, but 80% of the recharge was found to be contributed from the Crooked Creek topographic basin (Soto, 2014).

In 2002 Mott et al. conducted a series of dye-tracing tests in and around Davis Creek. Davis Creek is one of the major surface tributaries to the BNR. They recovered dye that was introduced within the Crooked Creek basin in the Davis Creek basin and determined that 2,285 acres of land from the Crooked Creek basin contributes water to Davis Creek (Soto, 2014).

Mott et al. (2002) completed 13 dye-tracing tests to determine the recharge area for John Eddings Cave and Elm Spring both of which are located on the south side of the BNR. From this study they determined that the recharge area for John Eddings cave was 231 acres and 156 of those acres lie outside of the topographic basin where the cave is located. The recharge for Elm Spring was found to be 1,772 acres and 1,017 of those acres lie outside the topographic basin in which the spring is located.

Mott et al. (2002a) conducted 30 groundwater tracing tests in the community of Gilbert. This study took place because homes in the town rely on individual on-site septic systems for waste-water treatment. Water-quality monitoring shows that Gilbert Spring, a large spring along the BNR, is the most contaminated spring in the park due to the septic fields in the town which are located over karst with thin soils. After testing the 22 septic systems they discovered that two of the systems rapidly contributed dye to Gilbert Spring. The other systems were efficient in removing the dye (Soto, 2014).

Brahana et al. (2017) performed a series of dye-tracing tests from April to October of 2014 in the Big Creek basin which is the second largest tributary of the BNR. Located in the Big Creek basin is a hog factory, housing 6,500 swine in a concentrated animal feeding operation (CAFO) and its waste spreading fields. Waste from the CAFO was permitted to be spread onto 0.965 mi^2 of onto 0.97 mi^2 of mantled karst. The Brahana (2017) project conducted point-to-point groundwater dye-tracing tests near the CAFO to help explain groundwater movement in karst terrains. Numerous positive detections of dye were recorded during the five dye-tracing tests. One of particular interest was the dye-tracing test initiated on May 12, 2014, where 17.6 pounds of eosine were injected into a hand-dug well located in the southernmost CAFO waste spreading fields. The dye spread in a radial pattern with 36 positive dye detections, at springs and streams in the Big Creek basin, and was also recovered in other, adjacent basins. One important positive detection was at Mitch Hill Spring on the opposite side of the BNR, showing that under high-flow conditions the waste spreading fields may be contaminating the BNR. Results from this project will be useful for designing water-quality sampling to determine the impact of the CAFO on the groundwater in the area. Many more dye-tracing tests have been conducted near the BNR, each of which demonstrate how important the delineation of watersheds are for protecting water quality along the BNR, because of the interbasin transfer of water from streams outside the BNR topographic basin (Table 2) (Soto, 2014).

Table 2: A summary of the previous dye-tracing studies done in and around the Buffalo National River

Previous Dye-tracing Studies in the area of the Buffalo National River

Authors:	Publication Date:	Project Title:	Publication Source:
Thomas Aley, et al.	1989	Delineation and characterization of the recharge area for Mitch Hill Spring, Buffalo National River, Arkansas	Ozark Underground Laboratory Publication
David N. Mott, et al.	1999	Nutrient Loads Traced to Interbasin Groundwater Transport at Buffalo National River, Arkansas	Proceedings of the 10th Conference on Research and Resource Management in Parks and on Public Lands
Thomas Aley, et al.	2000	Inventory and Delineation of Karst Hydrology Features, Buffalo National River, Arkansas	Phase II Report from the Ozark Underground Laboratory
David N. Mott, et al.	2000	Hydrogeologic Investigation Reveal Interbasin Recharge Contributes Significantly to Detrimental Nutrient Loads at Buffalo National River, Arkansas	Proceedings of the Arkansas Water Resources Center Annual Conference: Environmental Hydrology
David N. Mott, et al.	2002	Delineation and Characterization of Karst Groundwater Recharge in the Vicinity of Davis Creek and John Eddings Cave, Buffalo National River, Arkansas	Report for the National Park Service
David N. Mott, et al.	2002	The Impacts of On-Site Septic Systems to the Water Quality of the Buffalo River near Gilbert, Arkansas	Report for the National Park Service
Van Brahana, et al.	2017	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	U.S. Geological Survey Karst Interest Group Proceedings, San Antonio, Texas, May 16–18, 2017

3. Geology

The geology and hydrogeology of north-central Arkansas and the BNR have been described in numerous publications, most notably (McKnight, 1935; Odgen et al., 1979; Goodman and Odgen, 1980; Adamaski et. al, 1995; McFarland, 1998; Kresse et. al, 2014). Relevant mapping has recently been completed for the St. Joe area by Hudson and Turner, (2009) and the Pindall area (Fig. 4 by Hudson et al, 2006). The geology of the Snowball area was mapped by (Braden et al., 2003). These maps were used extensively during this investigation.

3.1 Physiography

The study area is located in the southern Ozark Mountains of north-central Arkansas. This area is a part of the Ozark Plateau physiographic province, which is subdivided into three broad plateau surfaces based on age and elevation: the Salem Plateau, the Springfield Plateau, the Boston Mountains Plateau (Fenneman and Johnson, 1946; Chandler, 2014; Fig., 5). The study area of this thesis lies within the karst terrain of the Springfield Plateau (Fig. 5). The Springfield Plateau occupies an area greater than 10,000 square miles in parts of Missouri, Kansas, Oklahoma and Arkansas (Adamski et al., 1995). In north-central Arkansas the Springfield Plateau makes up the southern flank of the asymmetrical Ozark dome, with the dome center being the igneous rocks of the St. Francois Mountains of southeast Missouri (Croneis, 1930; Adamski et al., 1995; Chandler, 2014).

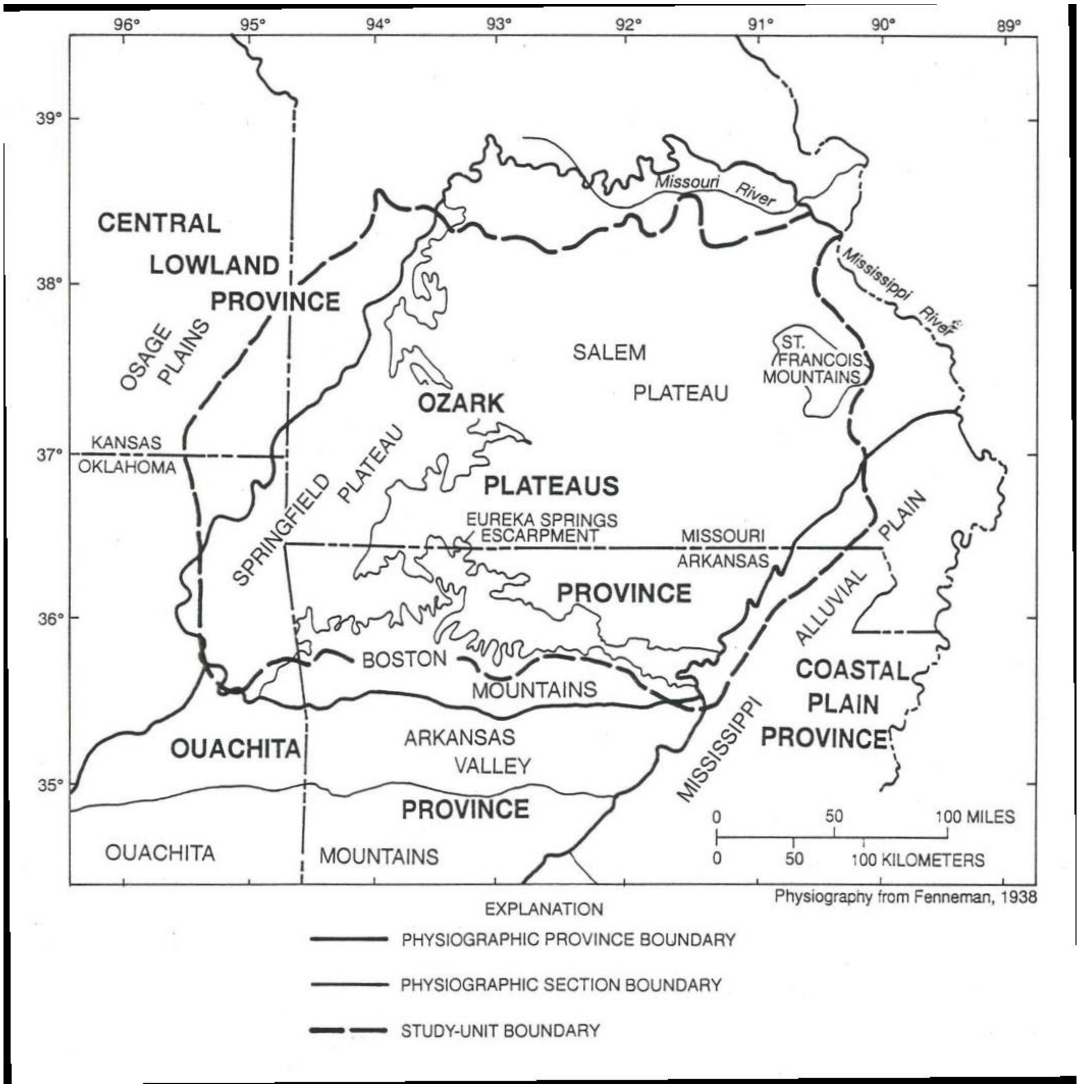

Figure 5: Ozark Plateau physiographic provinces, (Fennemen, 1964)

The rocks of the area were lain down in a shallow marine environment during the Paleozoic era (Mott and Laurens, 2004, Brahana, 2014). Over the region's 300-million-year history, it has been uplifted, slightly tilted, eroded, and resubmerged numerous times to form what is now the Ozark Mountains (Mott and Laurens, 2004). The uplift and associated tilting, which is only a few degrees, was a response to the Ouachita orogeny, and caused many fractures, faults, and joints in the area and resulted in the down-cutting of the BNR (Chandler, 2014).

3.2 Tectonics and Structure:

The strata of northern Arkansas are generally nearly horizontal (less than a five-degree dip), but areas of increased dip can be seen near local disturbances such as faults, down-dropped blocks and monoclines (McKnight, 1935; Hudson, 2000). This structural deformation occurred during middle-to-late Paleozoic and was related to the oblique closure of the Ouachita orogen (Kresse, 1983; Hudson, 2000). Many regionally extensive faults lie within the study area, which are of particular interest because solution conduits often form upgradient and along fractures and faults (Ford and Williams, 2007). Structural features in the study area include: the St. Joe fault, Mill Creek fault, Mill Creek Graben, and the St. Joe Monocline (Hudson and Turner, 2009; McKnight, 1935) (Fig. 6)

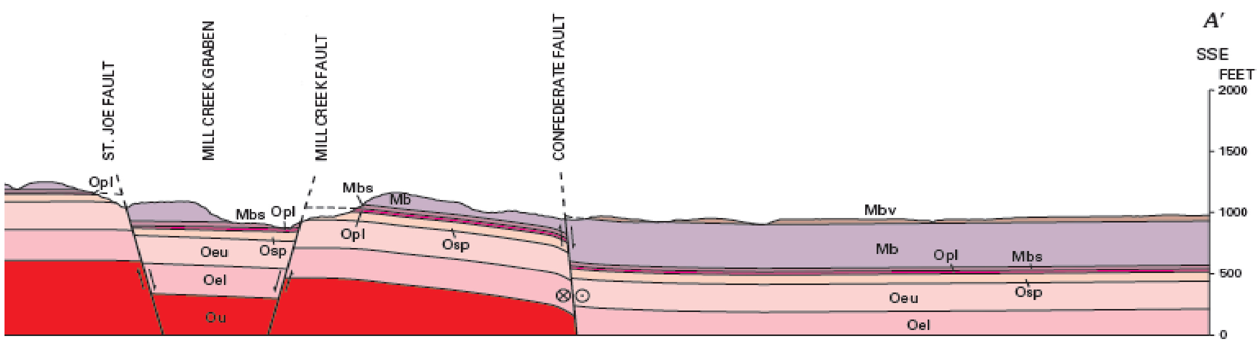

Figure 6: Portion of a cross section from the geologic map of the St. Joe 7.5-minute Quadrangle showing the St. Joe Fault, the Mill Creek Fault, the Mill Creek Graben and the Confederate Fault (Hudson and Turner, 2009)

Within the study area, the St. Joe fault is an east-west trending normal fault that extends for 15 miles. The down-dropped block of the St. Joe fault is to the south, with a vertical displacement of 500 feet (Fig. 6). Mill Creek fault is a normal fault with displacement down to the north that parallels the St. Joe fault; Mill Creek fault is about 1,500 feet to the south. Together, these faults form the boundaries of the east-west trending Mill Creek graben (McKnight, 1935; Fig. 6). The Mill Creek graben was found to be an important groundwater recharge area for Mitch Hill Spring (a large spring in Searcy County that was determined to flow into the BNR) during the dye tracing study of Aley and Aley (1989). The Mill Creek graben is part of a graben system that extends 15 miles to the west, where it is labeled the Braden Mountain graben (Hudson et. al, 2006; Hudson and Turner, 2009). Vertical joints are abundant in the study area, and the dominant set strikes north (Hudson and Turner, 2009). Joints that occur in the carbonate rocks are typically enlarged by dissolution and create preferred pathways for

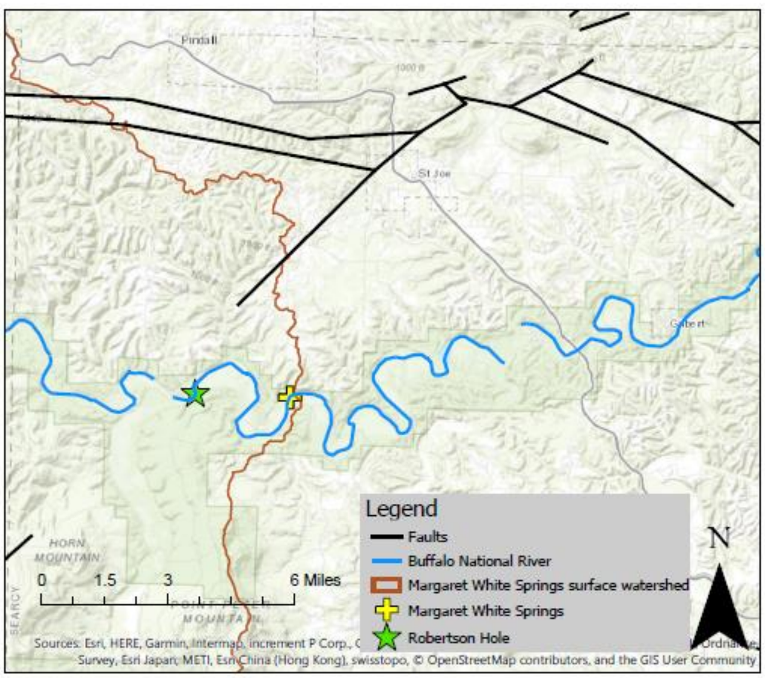

Figure 7: Map of study area displaying faults crossing the surface watershed for Margaret White Springs.

groundwater flow. Figure 7 showing the Confederate fault crossing the surface watershed for MWS, which is of particular interest for this study as faults often facilitate stream loss.

3.3 Stratigraphy

The Springfield Plateau is composed of sedimentary rocks that range in age from Ordovician to Quaternary and are composed of limestone, chert, dolostone, shale and sandstone. Ordovician-age strata comprise the Everton, St. Peter, Plattin, and Fernvale Formations

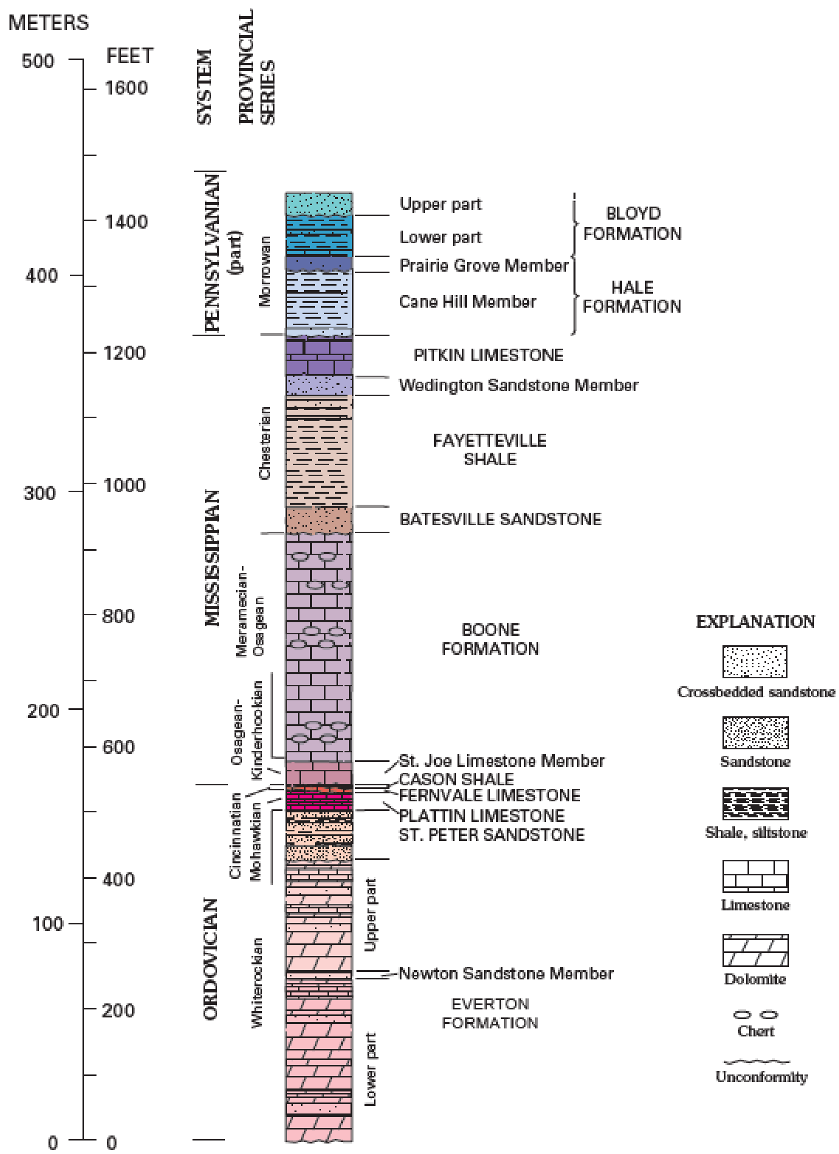

Figure 8: Stratigraphic section of the study area (Hudson and Turner, 2009)

(McKnight, 1935; Caplan, 1957). The Boone, Batesville, Fayetteville, and Pitkin Formations constitute the Mississippian-age strata, and the Bloyd and Hale Formations make up the Pennsylvanian age strata (Hudson and Turner, 2009). Quaternary-age strata are characterized by alluvium and terrace deposits consisting of unconsolidated clay, silt, sand and gravel (Hudson and Turner, 2009). McKnight (1935) noted that several formations are missing as a result of periods of erosion and periods of non-deposition. Eleven sedimentary formations are documented in the study area.

3.3.1 Bloyd, Hale, and Pitkin Limestone Formations

The Bloyd and Hale Formations are not significant in areal extent and are limited to the St Joe and Pilot Mountains in the study area (McKnight, 1935; Braden et. al, 2003; Hudson and Turner, 2009). The Bloyd Formation consists of a sequence of interbedded sandstone, siltstone, shale, and limestone beds. The upper part of the Bloyd forms the prominent cliffs of the St. Joe and Pilot Mountains (Hudson and Turner, 2009). The Hale Formation is an interbedded sequence of siltstone, sandstone, shale and limestone and is 100 to 180 feet thick (McFarland, 1998). The Pitkin Limestone is a fine- to coarse-grained, oolitic, bioclastic limestone (McFarland, 1998). Many of the sinkholes in the St. Joe area formed in the Pitkin Limestone

3.3.2 Fayetteville Shale & Batesville Sandstone

The Fayetteville Shale is a black, fissile, clay shale with interbedded fine-grained limestones. The Fayetteville Shale is divided into the Weddington Sandstone Member, which is a fine-grained calcareous sandstone, and the main body of black fissile shale. Fossils are common in the Fayetteville Shale; thickness in the study area ranges from 130 to 160 feet (Hudson and Turner, 2009). Below the Fayetteville Shale lies the Batesville Sandstone which is described as fine- to coarse-grained, tan to brown sandstone with thin shales. Aley (1989) described the Batesville Sandstone in the community of Pindall (Fig. 4) to be a “medium-grained, reddish-brown micaceous slabby sandstone,” and is about 80 to 100 feet thick (Fig. 8). Many sinkholes can be observed in the Batesville Sandstone caused by the dissolution and collapse of the underlying Boone Formation (Kresse, 1983, Fig.11).

3.3.3 Boone Formation

The Boone Formation is composed of fine-to coarse-grained, micritic limestone interbedded with chert. In some areas the chert may constitute as much as 70 percent of the rock (Aley and Aley, 1989). The Boone Formation is the most predominant formation in the study area, and contains many of the dissolutional karst features such as sinkholes, caves and enlarged fissures that can be seen throughout the region (McFarland, 1998). The chert layers in the Boone Formation have a very low permeability compared to the limestone layers which can cause isolation of the groundwater flow (Murdoch et al. 2016). Groundwater is often perched on the chert layers and feeds low discharge springs (Murdoch et al., 2016). In 1989, Aley estimated the thickness of the Boone Formation in the Pindall area to be greater than 250 feet. An inventory of caves in the BNR shows that more than fifty percent occur in the Boone Formation (Hudson et. al, 2011; Chandler, 2014).

3.3.4 St. Joe Limestone

The St. Joe Limestone Member, the basal unit of the Boone Formation, is the oldest of the Mississippian-age strata that occurs in the study area and consists of fine-grained limestone (Hudson et. al, 2011). The limestone commonly is gray, but can also be red or pink on fresh surfaces due to hematite matrix (McFarland, 1998). This red coloration is due to the oxidation state of the iron present during deposition (Kresse, 1983). The contact with the Boone Formation is often discernable by an increase in chert, and the lower part of the limestone contains greenish shale interbeds (Hudson and Turner, 2009). In the Mill Creek sub basin of the BNR, springs often occur near the contact of the St. Joe Limestone Member and the Boone Formation. (Hudson et. al, 2011).

3.3.5 Fernvale & Plattin Limestone

The Fernvale Limestone is a massively-bedded, coarsely crystalline, light grey to pink, crinoidal limestone. Fossils are very common and include: orthoconic nautiloids, brachiopods, bryozoans, and crinoids. The Plattin Limestone is a fine-grained, light-to-dark grey micritic limestone that is very dense and breaks with conchoidal fractures. Where present in the study area, it is generally about 40 feet thick (McFarland, 1995; Hudson and Turner, 2009). Both of these formations are karst formers, and several large caves along the BNR are known from this stratigraphic interval.

3.3.6 Everton Formation & St. Peter Sandstone

The Everton Formation of Ordovician age is the oldest rock unit cropping out in the study area. The Everton Formation shows considerable lithologic differences from one location to another, and it may be composed of sandstone, dolostone, or limestone (McFarland, 1998). Outcrops of the Everton Formation observed in the study area are composed of medium-grained, well-rounded quartz sandstone, and are almost indistinguishable from the overlying St. Peter Sandstone (Kresse, 1983). Because of the difficulty in distinguishing these two formations, they will be considered one rock unit for this study. Although the Boone Formation contains the majority of the karst features, the largest spring in the park, Mitch Hill Spring, resurges from the Everton Formation. In the Pindall area many of the springs emerge at the contact of the Everton and Boone Formations.

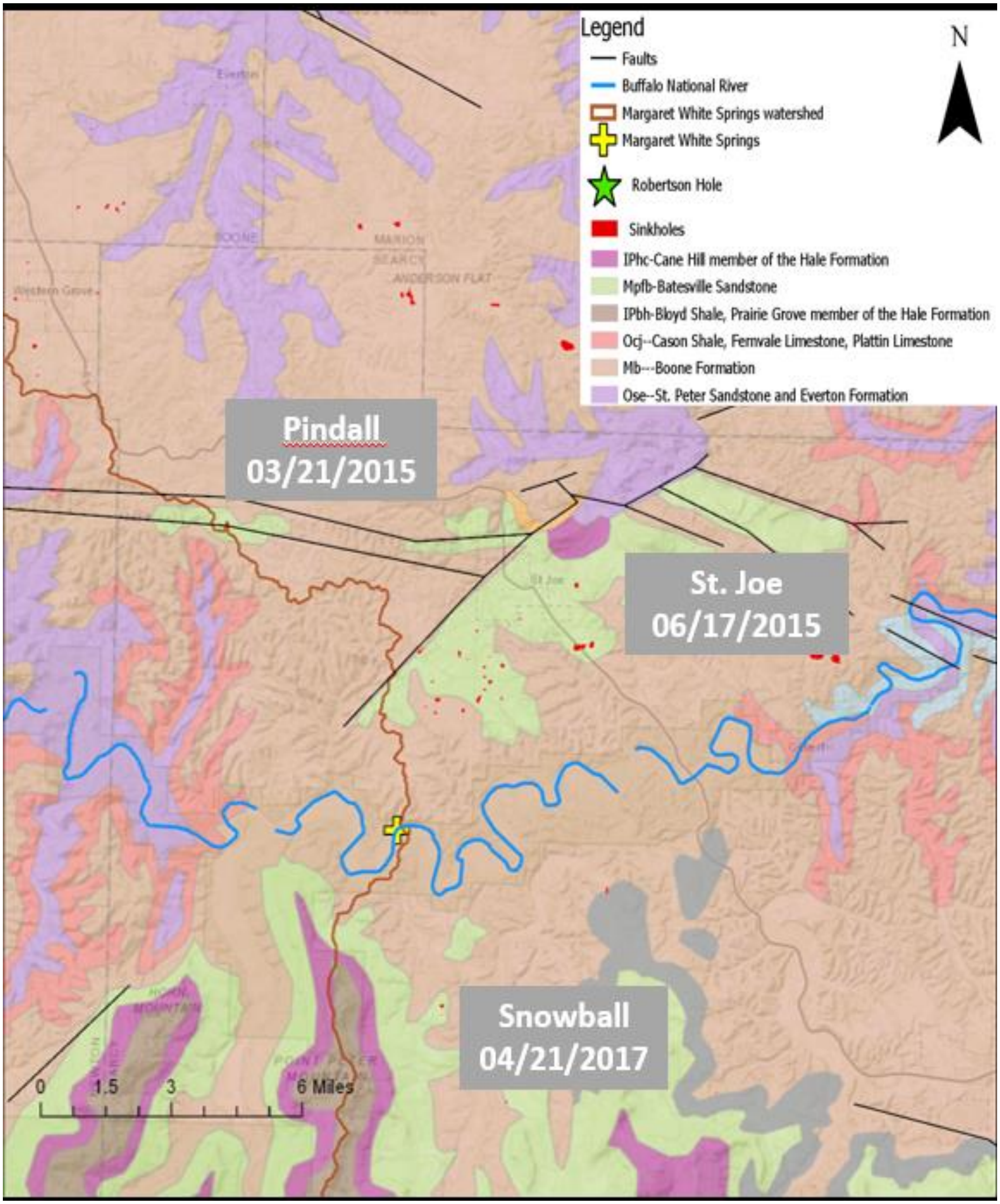

Figure 9: Geologic map of the study area. The Boone Formation (light brown) covers the majority of the area.

3.4 Karst Hydrogeology

The BNR headwaters begin in the Boston Mountains in land controlled by the National Forest, and flow eastward onto rocks of the Springfield and Salem Plateaus before eventually joining the White River in Buffalo City. Nearly 70 percent of the BNR watershed is underlain by karstified rocks of the Springfield Plateau and Salem Plateaus (Mott and Laurens, 2005). The middle portion of the BNR, the focus of this study, lies within the Springfield Plateau physiographic province. The Springfield Plateau aquifer is the uppermost aquifer of the Ozark Plateaus aquifer system which has a complex hydrogeology predominantly characterized by mantled karst (Czarnecki, 2009; Kresse et al 2014). This aquifer generally ranges from 200 to 400 feet thick (Renken, 1998).

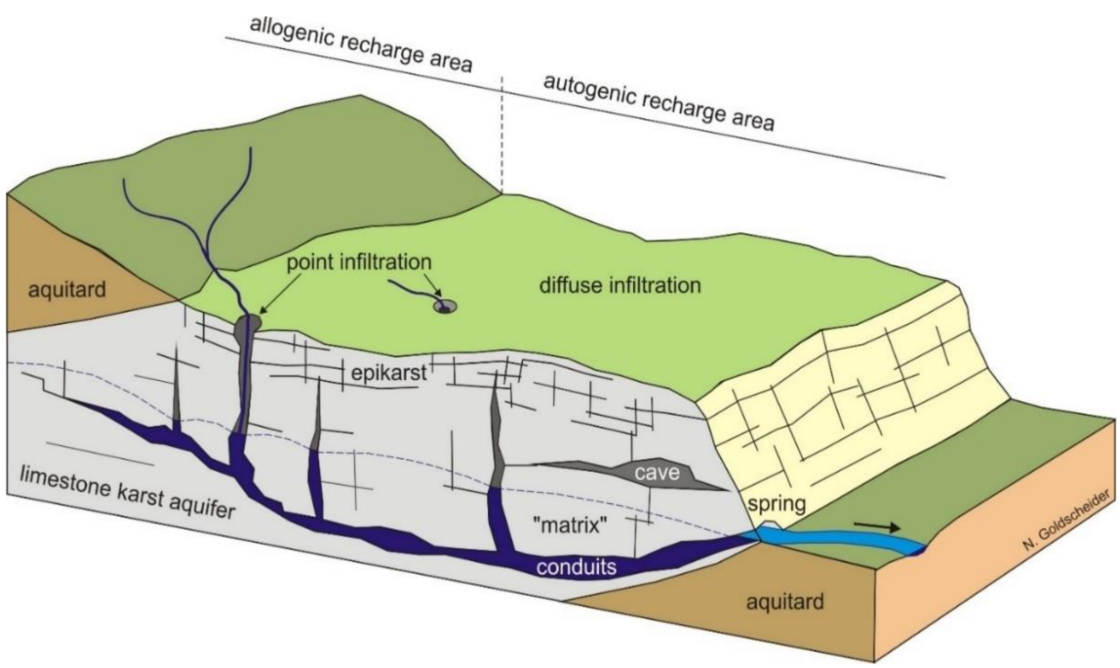

Figure 10: Block diagram of a generalized karst aquifer showing the types of recharge point or discrete vs diffuse infiltration, and conduit flow (Goldscheider & Drew 2007)

Groundwater systems in karst terrains are unique and often difficult to characterize using conventional hydrogeologic methods (Taylor and Greene, 2008). Two main end-member types of groundwater recharge typify karst terrains, discrete recharge and diffuse recharge (Fig. 10). Because the study area is a karst groundwater system, much of the carbonate rock has dissolved in areas to form a network of caves, conduits, sinkholes, losing streams, gaining streams, and springs. Sinkholes, and losing streams provide a direct and rapid connection between surface water and groundwater, and are responsible for the discrete groundwater recharge. Discrete recharge is rapid, and bypasses natural attenuation processes which filter and sorb contaminants carried in the flow. This attribute causes the hydrologic system to be more vulnerable to contamination than porous-media systems, and complicates an easy understanding of characterizing the groundwater basin boundaries and defining groundwater flow paths. Ultimately, the lack of homogeneity and high anisotropy of karst aquifers can make water-quality protection difficult. Diffuse recharge is the slow percolation of precipitation into the subsurface through matrix porosity, and receives natural attenuation processes as water passes through the soils.

Sinkholes, springs, and losing streams are very common karst features found in the study area. One of these karst features is the focus of this project: MWS, which is a large, multi-aperture spring located at mile marker 83.5 in the middle portion of the BNR (Smith, 2004), and contributes several tens of cubic feet of flow to river discharge. The majority of the other known springs in the area are located in Pindall (Fig. 4). Sinkholes in the study area were mostly concentrated near the town of St. Joe (Fig. 11 & 4). Sinkholes are the surface expression of underground drainage, and these are formed by dissolution of limestone and collapse.

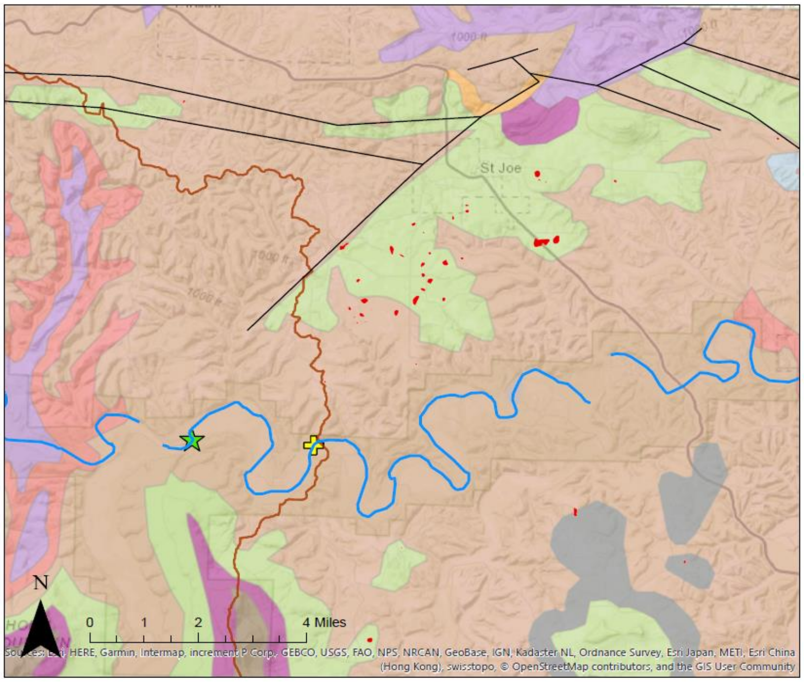

Figure 11: Sinkhole (red) swarm in St. Joe portion of the study area with geology. The majority of the sinkholes are located in the Batesville Sandstone. These are formed when Batesville Sandstone collapses into a void in the underlying Boone Formation (Turner et al. 2016)

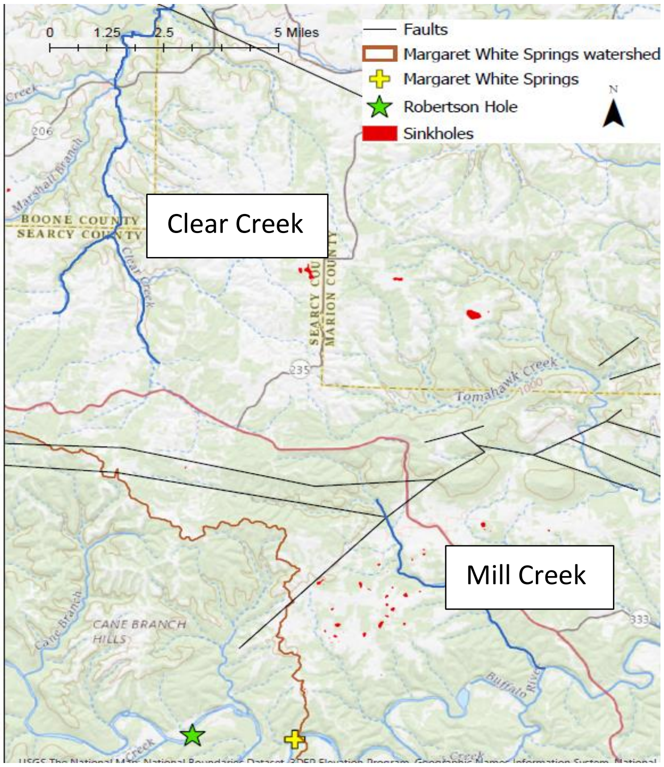

Figure 12: Map of study area with Mill Creek and Clear Creek in dark blue.

Nearly all the streams found in the study area are considered losing streams, meaning they lose surface flow to the groundwater. Both Mill Creek and Clear Creek are two of the major losing streams in the study area (Fig 12). Many of the streams only have surface flow for a short period after a major rainstorm.

A complication of the intimate interaction of groundwater and surface water in karst terrains is determining recharge areas. In most geologic settings, recharge for an area is contained within the topographic divides which outline the watershed boundaries. However, in karst settings, recharge for a spring basin often flows beneath surface-watershed boundaries (Mott et al., 2000; Murray and Hudson, 2002; Soto, 2014). Hydraulic conductivity values for the karstified Boone Formation range from 0.1 to 2000 feet per day (Reed and Czarnecki, 2006). This large range of values is due to the local zones of high hydraulic conductivity caused by solution openings within the subsurface as compared with low hydraulic conductivity values in dense matrix blocks. Likewise, local groundwater flow paths and flow directions may be very different from what might be predicted based on topography (Davis et al., 1985). Determining the local direction of water flow in karst settings is difficult due to the local differences in hydraulic conductivity. Pirating of water from one groundwater basin to another during large storm events takes place frequently in karst systems (Aley and Aley, 1989). Several studies (Soto, 2014), have demonstrated that the BNR groundwater watersheds do not correspond to the overlying surficial drainage watersheds (Table 2).

3.4.1 Local aquifer investigation

Goodman and Odgen (1980) conducted an investigation into the groundwater resources for northern Searcy County, and identified two main aquifers, the Boone-St. Joe, and a group of sandstones, limestones and dolomites located below the Chattanooga Shale, where it is present or the St. Joe. The Everton is the most significant unit in this aquifer, but overlying units often contribute water to wells so the aquifer was termed the Sylamore-Everton. These are utilized by local residents for domestic water supplies (Kresse, 1983). The most widely used of the two is the shallower, Boone-St. Joe, which yields from 0.5 to 75 gallons per minute (gpm), with an average yield of slightly less than 10 gpm. The Boone-St. Joe aquifer is unconfined where it is exposed at the surface. Wells in this aquifer are typically drilled to a depth of 350-360 feet. The less-extensively used Sylamore-Everton aquifer has yields reported from 1 gpm to 80 gpm, with an average yield of 17 gpm; well depths from the Sylamore-Everton generally average 570 ft. This aquifer is below the Chattanooga Shale, which acts as a confining layer between the two.

4. Methods

4.1 Groundwater Tracers

Determining recharge areas, movement, and discharge locations of groundwater is important in karst regions, inasmuch as karst groundwater basins do not often follow topographic divides (Goldscheider and Drew, 2007). A groundwater tracer can be any type of material, solutes, or actual physical property of water that can be used with flowing water to determine the direction, paths, and rates of groundwater flow. Tracers can include attributes such as stable isotopes, radionuclides, water temperature, and specific conductance, and substances as diverse as corn cobs, rice hulls, ducks, hydrocarbons, unique contaminants, spores, organic dyes, ionized substances, and fluorocarbons (Davis et al., 1980; Goldscheider and Drew, 2007). Obviously, unsafe or hazardous substances are not deliberately used because of their negative impacts on ecology and human health, but safe, reliable substances can be valuable in ascertaining karst groundwater flow.

Fluorescent dyes have become the tracer of choice for karst hydrogeologists, and been used extensively to determine possible sources of contaminants in the BNR (Table 2), and nationally and internationally these have become established as an essential tool to characterize the hydrogeology of karst landscapes (Smart and Laidlaw, 1977; Crawford, 1979; Quinlan and Ewers, 1985; Wilson and Skiles, 1988; Mull, 1993; Hunt et al, 2005; Spangler and Susong, 2006; Christiansen, 2009). Fluorescent dyes are among the most popular water tracers due to their ease of detection and cost effectiveness.

Groundwater tracing using fluorescent dyes is a very reliable method for understanding groundwater flow in karst regions and has been used since the late 1800's (Davis et al. 1985, Ford & Williams, 2007). Qualitative dye-tracing can identify point-to-point connections between groundwater recharge points, such as losing streams, caves, and sinkholes, and groundwater discharge points, such as springs or gaining streams (Mull, 1993). While qualitative dye-tracing methods can determine point-to-point connections a quantitative dye tracer test can provide dispersion rates, breakthrough curves, and dye concentrations. Quantitative dye tracer tests are more labor intensive and require specialized equipment (Mull et al, 1988). This study will apply qualitative dye-tracing methods.

When selecting a fluorescent dye, the dye must meet certain criteria such as: water solubility, detectability in low concentrations, separability from background conditions, low toxicity, and cost effectiveness (Mull et al, 1988). For this particular study the fluorescent organic dyes, fluorescein, eosine, and rhodamine WT were used to determine the size and boundaries of the groundwater recharge area to MWS. These dyes fluoresce when exposed to light which allows them to be detectable in very small quantities (Sabatini & Austin, 1991). Different fluorescent dyes can be detected during the same field experiment because each dye has different wavelength range and different emission which will be detailed below.

4.2 Fluorescent Dye Properties:

4.2.1 Rhodamine WT:

Rhodamine WT (CAS # 37299-86-8) is a red liquid that is made for the use of dye-tracing. The color index name for rhodamine WT is acid red 388 and is also commonly sold as fluorescent red, or red fluorescent dye (Aley, 2002). Rhodamine WT has an emission range between 561.7 to 568.9 nanometers, with the peak typically being 565.0 nanometers (Aley, 2002). Some common man-made fluorescence interference sources for rhodamine WT include: storm water runoff from major roads, automotive coolants, hydraulic fluids, leak tracer dyes used by plumbers, agricultural chemicals, plastic manufacturing plants, and colored paper and colored felt tip pens (Aley, 2002). Rhodamine WT does not degrade in sunlight and is therefore able to be used to trace surface waters (Aley, 2002). The resistance to adsorption onto inorganic matter is not as good for rhodamine WT as it is for fluorescein and eosine; and it has shown a high adsorption rate on many different types of soils (Kasnavia et al., 1999). Despite having a high adsorption rate and many fluorescence interferences, rhodamine WT is still a very common dye used for water tracing because it is non-toxic at low concentrations, water soluble and, and fluoresce in apart of the spectrum that is far removed from fluorescein and eosine (Wilson et al., 1986; Mull et al., 1988).

4.2.2 Fluorescein

Fluorescein (CAS # 518-47-8) was first invented in 1871, and was first used as a groundwater tracer in 1877 when it was injected into a sink in the Danube River and later recovered from a spring more than twelve kilometers away (Bradley, 1970; Goldscheider and Drew, 2007)**.** Fluorescein is a synthetic compound that is sold as a reddish-orange powder. Fluorescein powder is water soluble and becomes a bright fluorescent green when it comes into contact with water. Fluorescein is also commonly referred to as Uranine, Uranine C, Sodium Fluorescein, Fluorescein LT and D&C Yellow 8 (Aley, 2002). The peak emission range for fluorescein is between 510.7 and 515.0 nanometers (Aley, 2002). With each dye, various compounds can interfere with the emission spectrum. Fluorescein has a high rate of photochemical decay in sunlight, which causes it to be a poor choice for many surface-water tracing applications (Bradley, 1970; Aley, 2002). Other common man-made fluorescence interferences for fluorescein include: storm water runoff from major roads, automotive coolants such as anti-freeze, discharge from sewage treatment plants, wood treatment plants, dyes used by plumbers to detect leaks, and colored paper and colored felt-tip pens (Aley, 2002). Certain organic materials such as algae will also affect the fluorescence which can result in a fluorescence peaks near the expected wavelength for fluorescein., thereby giving a false positive dye reading (Aley, 2002). Despite the common fluorescence interferences with fluorescein, it remains one of the most common water-tracers for karst systems due to its safety, resistance to adsorption on soils and sediments, availability, and its ready adsorption onto active charcoal samplers (Aley, 2002).

4.2.3 Eosine

Eosine (CAS # 17372-87-1) is a water soluble, reddish orange powder that turns bright orange when mixed with water. Eosine is also commonly sold as Acid Red 87, Eosin, Eosine OJ, and D&C Red 22 (Aley, 2002). Eosine has many less-common fluorescence interference sources than the previous discussed dyes, although it does have some. Interferences include: wood treatment plants, waters in contact with high-sulfur coal, and colored paper and colored felt tip pens (Aley, 2002). The emission range for eosine is between 533.0 to 539.0 nanometers, with a peak fluorescence at 536.0 nanometers. Eosine has a good resistance to adsorption onto inorganic matter, but will photodegrade when exposed to sunlight (Aley, 2002).

4.3 Field Techniques

4.3.1 Site Selection for Passive dye detectors:

Prior to each dye-tracing test, all available groundwater resurgences (springs) were located near each planned dye injection point in the St. Joe, Pindall, and Snowball areas, as well as in MWS and at locations downstream and upstream of MWS in the BNR . This placement allowed p determination of groundwater flow paths. Activated-charcoal samplers, formally called passive dye receptors, and informally referred to as bugs, were used to collect the fluorescent dye. The activated-charcoal samplers consist of permeable filters with small-opening s that are filled with activated charcoal and sealed (sold as Break Proof 45 milk filter socks to dairy farmers). These allow water and dye to pass into the passive receptors, and if dye is present, to be sorbed onto the charcoal, for later diagnosis in the lab. Dye that comes into contact with the charcoal in the passive detector is sorbed, and remains so until it is eluted in the lab after washing with deionized water to remove dirt and debris. enabling later elution of the dye, and determination of hydrologic connection with the dye-input point. Landowners were interviewed to find many of the springs that were not recorded on the topo maps of the area. Coordinates for the sites were recorded using the GAIA gps app which uses the World Geodetic System of 1984 (WGS84) coordinate datum. Several methods were used to install the packets securely in the springs. After trial and error, the best method for this study was to secure the charcoal samplers onto rocks using wire.

4.3.1.1 St. Joe Area

Two springs, Church Spring and Antler Spring and one seep near St. Joe were used as locations for dye monitoring using the passive dye receptors. (Fig. 13). Church Spring located at 35° 59’ 47.12” N, 92° 51’ 14.96” W (Fig. 13) was being pumped for water use, and had an estimated discharge of xx gallons per minute, or cubic feet per second, or some specific value of Q for most of the duration of the test .The second spring used was referred to as Antler Spring (35° 58’ 11.7” N, 92° 49’ 27.99” W (Fig. 13). Neither of these two springs or the seep were identified on the topographic map for St. Joe. The last feature used for charcoal packet placement was referred to as Woolum Seep, located at 35° 58’ 41.77” N, 92° 53’ 31.48” W (Fig. 13), and had very low discharge.

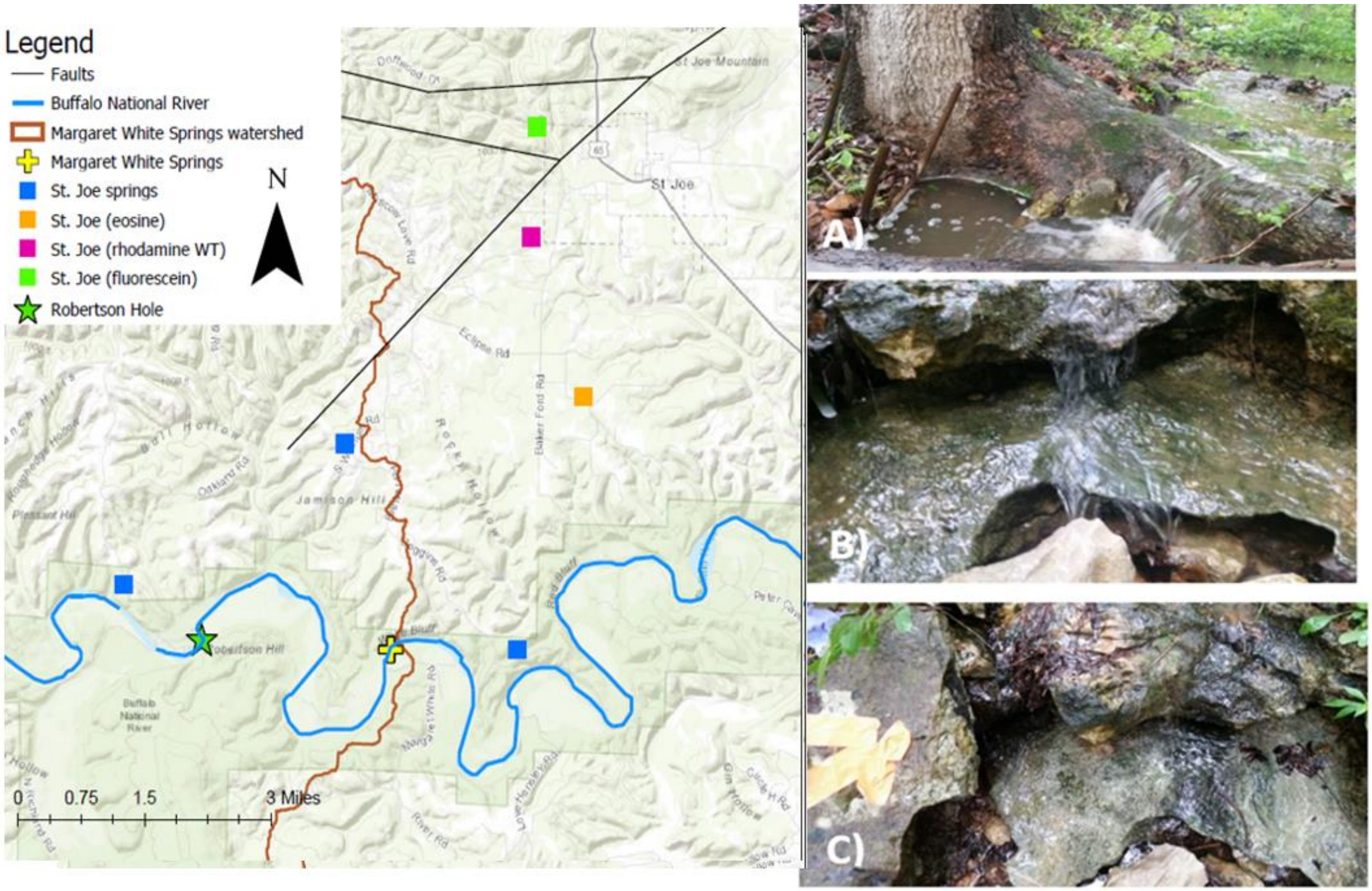

Figure 13: Site map of the St. Joe area dye trace indicating the spring locations. Pictures are of A) Church Spring, B) Antler Spring and C) Woolum Seep.

4.3.1.2 Pindall Area

Four springs were chosen for placement of charcoal samplers in the Pindall area: Jack Keith Spring, Glencoe Spring, Hatchery Spring, and East Spring (Fig. 14). Charcoal samplers were also placed in the Buffalo River upstream from MWS (35°58'44.97"N, 92°52'5.51"W). Jack Keith Springs, location 36°4’32.844” N, 92°53’ 22.99” W was one spring monitored and discharges from a cave formed at the contact of the Boone and Everton Formations (Aley and Aley, 1989). Aley (1989) noted that this spring discharges 5- 10 cubic feet per second (cfs) during the wetter periods of the year and then ceases to flow during dry periods. The flow from the spring joins into Clear Creek. Glencoe spring, at 36°6’2.448” N, 92°53’14.856” W is also located at the contact of the Boone and Everton Formations. Hatchery Spring, location 36° 7’ 10.056” N, 92° 54’ 12.024” W, emerges from the contact of the upper and lower Everton Formation. This spring is being pumped, and from field observations appears to flow year-round. East spring (36° 7’ 45.156” N, 92° 51’ 58.896” W) emerges from the Boone Formation and also is reported to flow year-round.

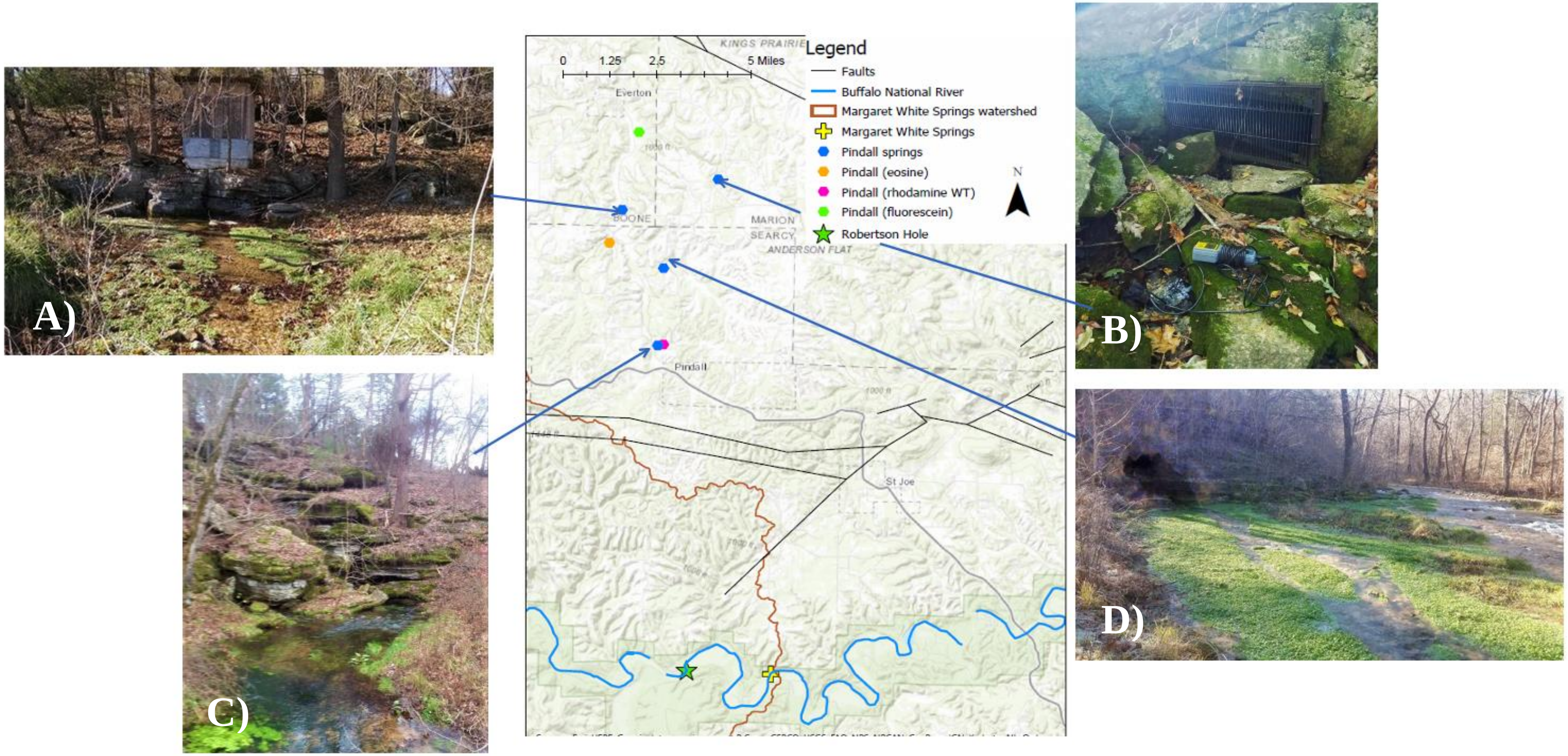

Figure 14: Site map of the Pindall area dye trace map indicating locations of springs at which passive dye receptors were placed. The show A) Hatchery Spring, B) East Spring, C) Jack Keith Spring, and D) Glencoe Spring

4.3.1.3 Snowball Area

Five springs-- Alexander Spring, Calf Creek Spring, an unnamed spring, Road Spring, and Ledbetter Spring, and two streams--Calf Creek, and a location downstream from MWS on the BNR were used as monitoring locations at which passive dye receptors were installed for the Snowball area test (Fig. 15). Alexander Spring (35° 56’ 21.156” N, 92° 49’ 15.82” W) is reported to flow continuously year-round. This spring emerges from the Boone Formation. Calf Creek spring (35° 56’ 12.98” N, 92° 48’ 47.376” W) emerges from the Boone Formation and flows into Calf Creek. An unnamed spring (35° 56’ 16.368” N, 92° 48’ 50.544” W) was found near the Calf Creek spring after the dye injection and a sampler was placed in it. No background fluorescence information was collected for this spring, and it only flowed for a short period of time after the precipitation event. Road Spring (35° 56’ 59.856” N, 92° 50’ 38.94” W) was very close to MWS, and flow had been diverted using pipes to flow under the road and into a stream that joins the BNR. Leadbetter Spring (35° 56’ 4.416” N, 92° 46’ 40.368” W) emerges from the contact of the Boone formation and the Batesville Sandstone. Samplers were also placed in the mainstream of Calf Creek (35° 56’ 17.376” N, 92° 48’ 40.716” W), and in the BNR downstream of MWS (35° 57’ 44.856” N, 92° 49’ 27.48” W).

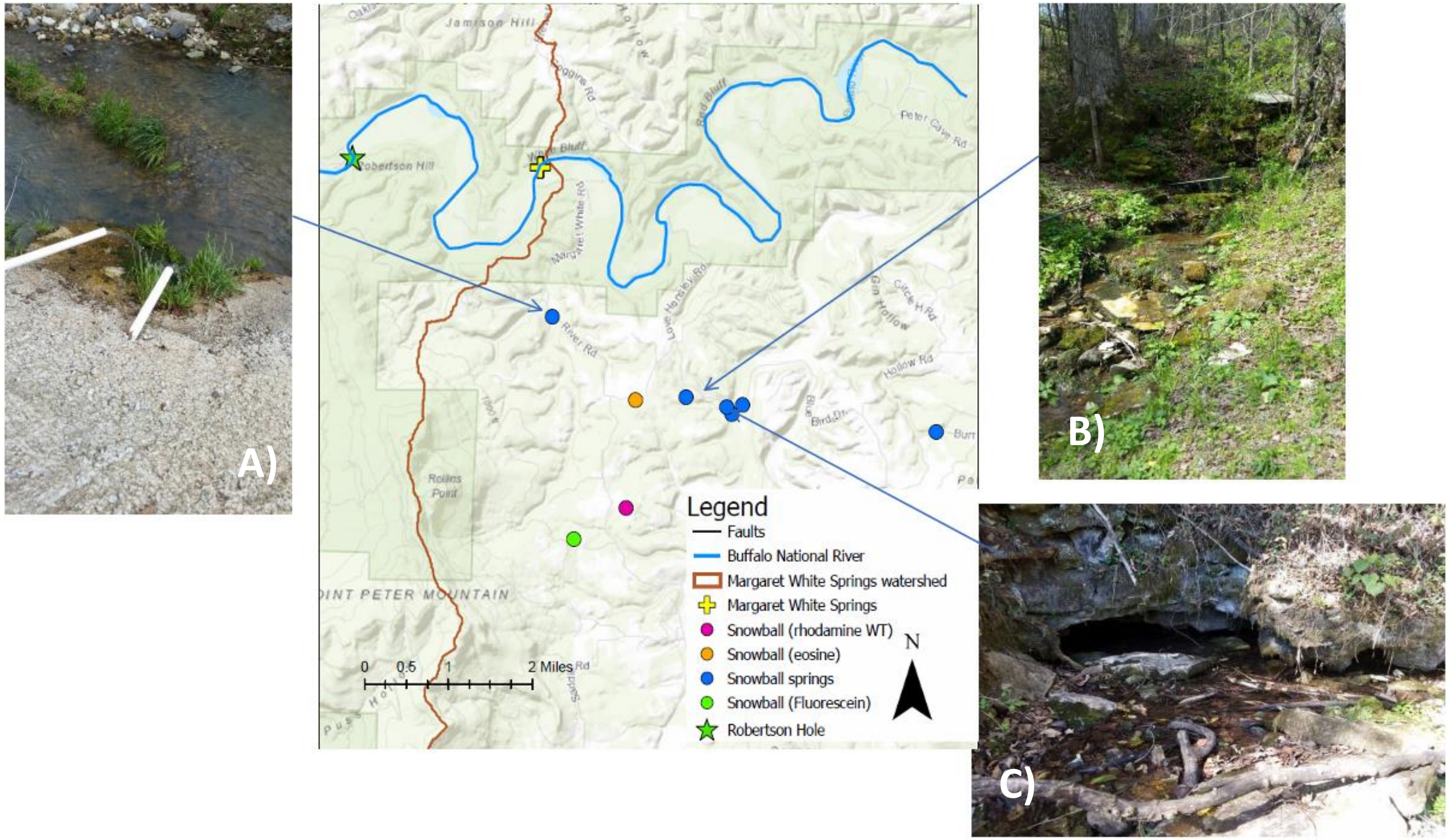

Figure 15: Site map of the Snowball area dye trace indicating locations of springs. Pictures are of A) Road Spring, B) Alexander Spring, and C) Calf Creek Spring.

4.3.1.4 Margaret White Springs

MWS is a multi-aperture spring emerging within the stream channel of the BNR, and is the main focus of this study (Fig. 16). Up gradient of this spring is a four-mile losing reach of the river that typically goes completely dry during the months of summer. Multiple emergences of the spring were chosen for placement of the charcoal packets and were generally located along joints in the bedrock. Several methods were used to secure the packets in place. One method was to hammer angle iron with a charcoal packet attached between openings in the bedrock. Another method included wrapping wire around large, heavy rocks, attaching a charcoal packet using a carabiner, for easier replacement, and placing them at the spring resurgences. Because many charcoal samplers were lost due to river turbulence during the background investigation, generally six to seven charcoal packets were placed in the at well-mixed sites in the BNR during each cycle of replacement of the passive dye detectors.

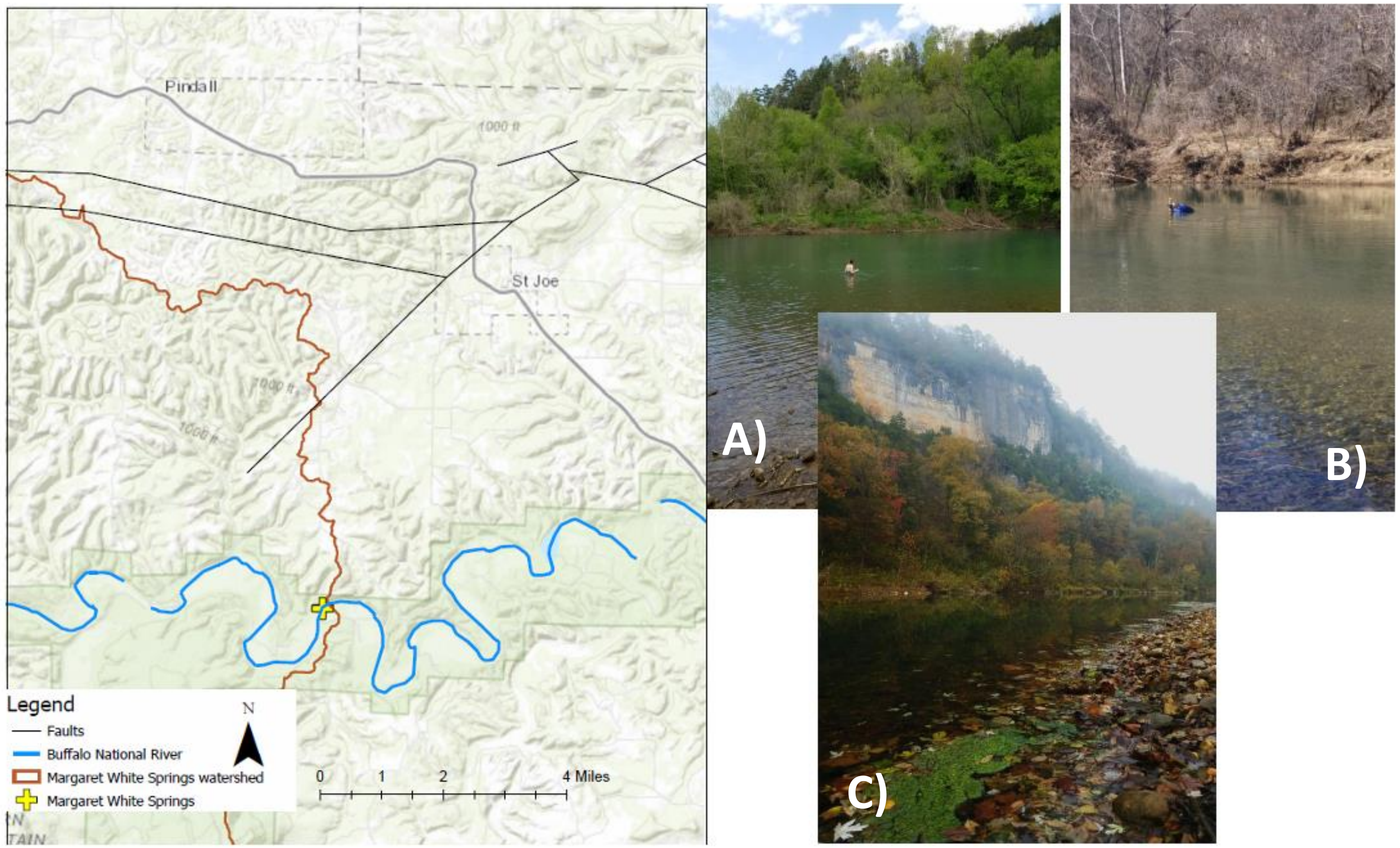

Figure 16: Study area map showing Margaret White Springs (yellow) and the partial watershed (brown). Photos show: A) searching for samplers at Margaret White Springs under moderate flow conditions, B) Searching for spring emergences under moderate flow conditions, C) looking downstream from Margaret White Springs under low-flow conditions.

4.3.2 Site Selection for Dye Introduction

Three dye-injection areas were chosen within a 6-mile radius of MWS and outside its surface-drainage area, and named for the nearest town, St. Joe, Pindall, and Snowball based on the hydrogeologic framework of each area with the goal of elucidating the size and boundaries of any recharge area to MWS lying outside the surface-drainage area. Sinkholes and losing sections of streams were the two karst features selected for dye-injection because these features typically have a direct connection to the groundwater, and are considered a point source of infiltration. Available map data were reviewed, and local landowners were interviewed to determine the location of unmapped sinkholes.

Coordinates for potential dye-injection sites were recorded using the GAIA global positioning system (gps) software (app) which uses the World Geodetic System of 1984 (WGS84) coordinate datum (Table 3). Although the dye-injection sites were concentrated in the three areas (Fig. 4), the sites were relatively far apart to ensure that the potential drainage basin to MWS is well characterized.

4.3.2.1 St. Joe Area

The town of St. Joe is located approximately 4.6 miles northeast of MWS, and outside of the surface watershed (Fig. 4 and 17). Field reconnaissance was necessary to locate and gain access to sinkholes and determine the usefulness of sinkholes for dye injection. The St. Joe area contained many more sinkholes than any other region in the entire study area (Fig.11). This is a typical observation in northwest Arkansas, because the area around St. Joe has easily karstified pure-phase upper Boone Formation overlain by Batesville Sandstone, which acts as protection against surface erosional processes (Davis et al., 2000).

Two sinkholes, referred to as Baker sinkhole and Scott sinkhole for this thesis and a section of Mill Creek were chosen as dye injection locations in the St. Joe area. Scott sinkhole was located near 36° 1’ 30.5” N, 92° 49’ 20.93” W, and was associated with several small sinkholes, indicating good karst development. None were shown on any U.S. Geological Survey 7.5-minute topographic maps. The sinkhole chosen was roughly five feet in diameter, not identifiable on a map of 1:24,000 scale; the sinkhole was about one foot deep. Soil and vegetation growth were noted within portions of the sinkhole, but a 1-foot diameter open throat provided direct access to the subsurface. The open-throat was determined to be an effective input for dye as air could be felt coming out of it. Baker sinkhole (36° 0’ 8.57” N, 92° 48’ 47.52” W) was located in a large field used for cattle grazing. This sinkhole was about ten feet in diameter and two feet deep. Soil, leaves, and thorn bushes covered much of the interior of the sinkhole, but several small open throats were observed where air could be felt coming up; these were used for the input of dye. The third location for dye injection in St. Joe was located in Mill Creek (36° 2’ 13.344” N, 92° 49’ 15.996” W) which is a large tributary to the BNR. A large fault cuts across Mill Creek, a portion of the creek above the fault was chosen to place the dye in to determine if the fault zone was a possible source of connection to the springs.

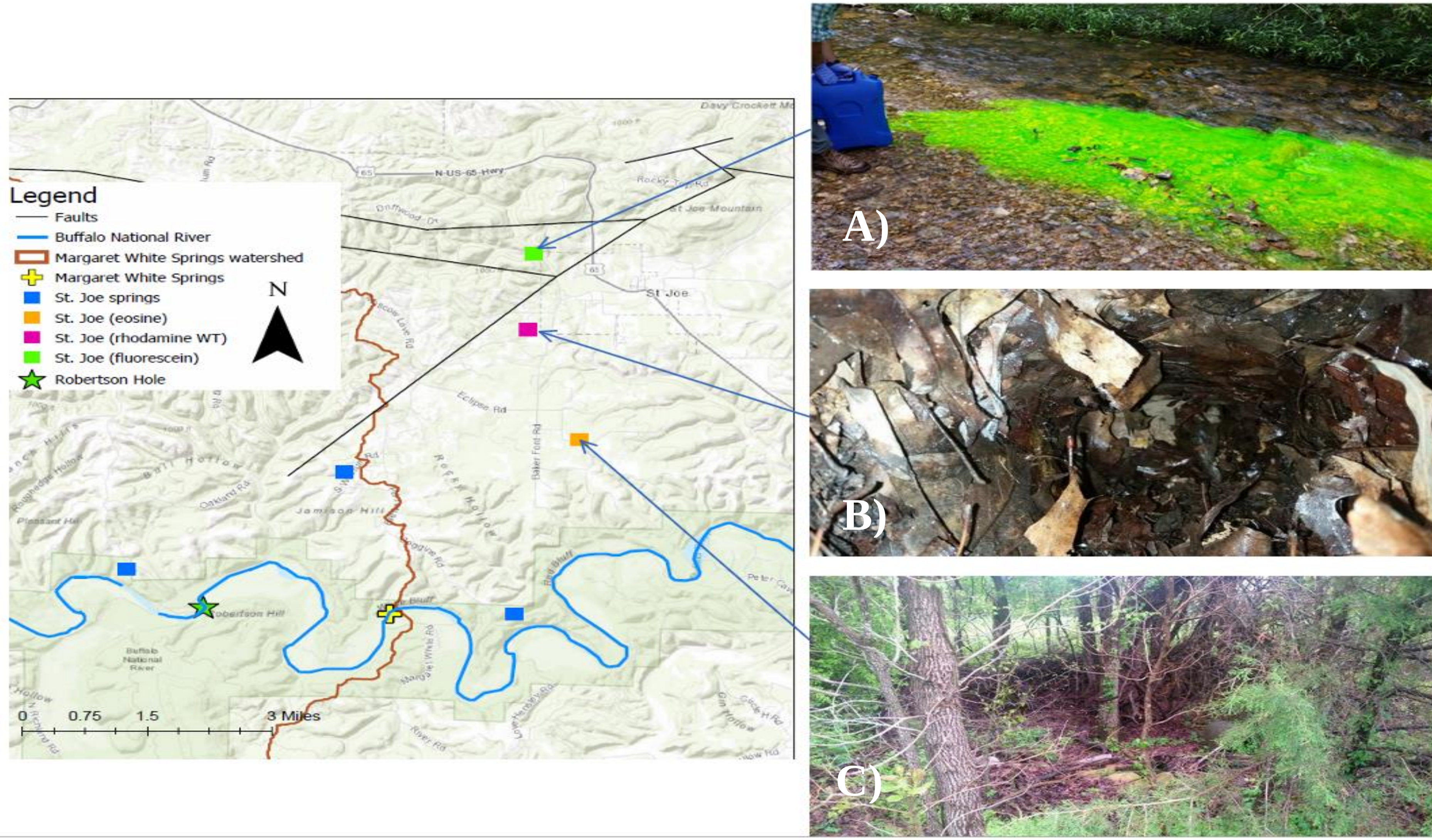

Figure 17: Site map of the St. Joe area dye trace indicating locations of springs. Pictures are of A) Fluorescein in Mill Creek, B) Open-throat in Scott sinkhole, and C) Baker sinkhole

4.3.2.2 Pindall Area

The town of Pindall is located approximately 6.8 miles north of MWS and tracing from this area is the furthest away from the spring (Fig. 4 & 18). A previous dye-tracing study was done in this town in the 1980’s by Tom Aley. After several weeks of background field work fully utilizing topographic maps and intensive field karst inventorying, three sections of small, losing streams were chosen as the dye injection locations. The first location (36° 8’ 33.996” N, 92°53’15” W) was a small losing section of an unnamed tributary to Clear Creek and was the most southern location chosen, and the nearest of these injection points to MWS. This location was chosen for dye injection because water could be seen going into the subsurface, and the stream became completely dry downstream from this point in the channel. The second location (36° 6’ 32.112” N, 92° 54’ 29.772” W) chosen for dye injection was another losing reach of an unnamed stream tributary to Clear Creek. Water flowed in this stream up until the point where all surface flow went into the subsurface. The last location for dye injection for the Pindall dye-tracing test was a larger losing stream in Jones Hollow and was the most northern location (36° 8’ 40.092” N, 92° 53’ 48.804” W) of the dye-tracing test. No water was present in this creek, even when Jones Hollow was observed during a precipitation event of 3.15 inches of rainfall from 03-08-16 to 03-14-16

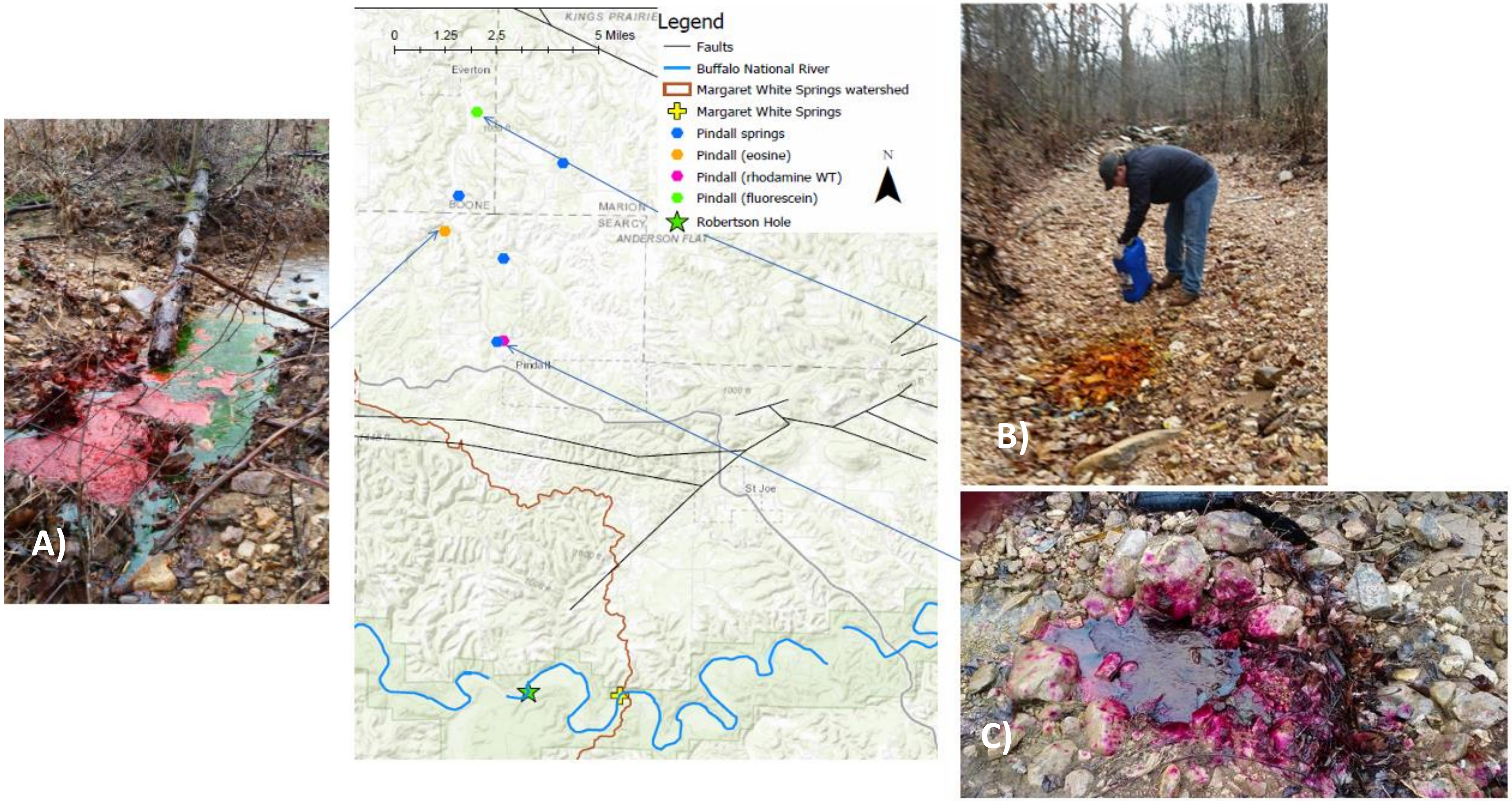

Figure 18: Site map of the Pindall area dye trace indicating locations of springs. Pictures are of A) Eosine in Clear Creek tributary, B) Fluorescein in dry reach of Jones Hollow, and C) Rhodamine WT in losing reach of an unnamed tributary near Jack Keith Spring.

4.3.2.3 Snowball Area

The town of Snowball is located approximately 4.8 miles south of MWS (Fig. 4; Fig. 19). Many sinkholes are located near the town, and three were chosen for the Snowball-area dye-tracing test. The first sinkhole (35° 55’ 12.72” N, 92°50’25.584” W) chosen was referred to as Roberts sinkhole. This sinkhole was small in diameter but about four feet deep. The next sinkhole was located (35° 55’ 27.732” N, 92° 49’ 53.04” W) in a hay field next to a cemetery and referred to as Cemetery sinkhole during the study. This field had several large sinkholes that were included on the topographic map but a smaller one was chosen because it had less soil and growth and likely better connection to the subsurface. This sinkhole was roughly ten feet in diameter and 5 feet deep. The last sinkhole chosen, the largest sinkhole used, was located at 35° 56’ 19.72” N, 92° 49’ 47.28” W) in a cow pasture and had several small open-throats where air could be felt coming up which were used for the dye injection.

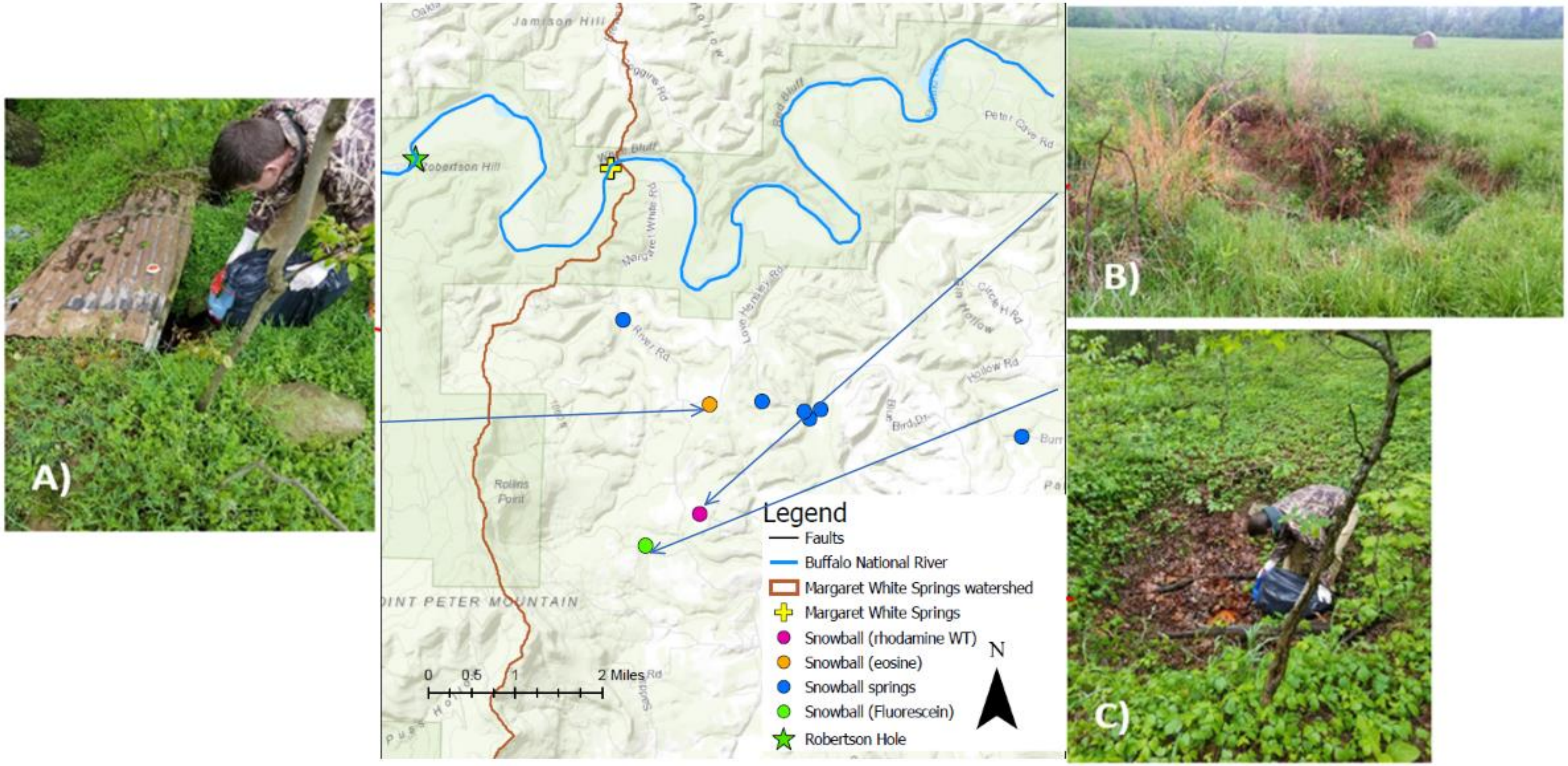

Figure 19: Site map of the Snowball area dye trace indicating locations of springs. Pictures are of A) Alexander sinkhole, B) Cemetery sinkhole and, C) Roberts sinkhole

4.4 Background Fluorescence

Prior to the dye injection, passive dye receptors were placed in each spring, including MWS, to obtain background fluorescent levels. The samplers were placed in the springs and river approximately one to two weeks before each dye injection, and then collected prior to the injection of dye. All background samples were negative for any dye prior to each dye-tracing test. Obtaining background fluorescent levels is important because many fluorescent materials can be found in many natural flow systems, caused by algae, organic substances, certain minerals, manmade pollutants, and laundry detergent brighteners (Wilson et al. 1986).

4.5 Dye Injection

The primary purpose of these dye tracer tests was to determine the recharge area to MWS outside of the BNR surface drainage area and determine if interbasin flow of groundwater is occurring. This was tested by injecting dye into karst features beyond the surface-drainage watershed of MWS. For the first two dye-tracing tests (St. Joe area and Pindall area) (Fig. 4) eight pounds of Fluorescein and Eosine dye were used, and for the last dye-tracing test (Snowball area) twelve pounds of Fluorescein and Eosine were used. Prior to each dye-tracing test the Fluorescein and Eosine dyes which were provided in powder form were mixed with water to facilitate thorough mixing. One gallon of water was added for each pound of dye used. The dye mix was stored in clean high-density polyethylene (HDPE) jugs. The Rhodamine WT dye came pre-mixed as a 20% concentration in a five-gallon bucket; approximately one- third of it was used for each dye-tracing test, about 1.7 gallons. Each dye trace took place during a rainfall even to facilitate flushing the dye into the groundwater system. To avoid contamination of the passive dye receptors and ensure quality control during the test, the dye was transported to the sites in a separate vehicle from the passive charcoal receptors, and dye was injected by an individual that had no contact with dye receptor collection and replacement. The dye injection for each trace is summarized in Table 3.

Table 3: Summary of the dye injection locations for each dye-tracing test

Summary of Dye Injections								
Test Name Town:	***Dye Injection Date:***	***Time:***	***Location Name:***	***Latitude: Ddmmss.sss***	***Longitude: Ddmmss.sss***	***Type of Dye and mass injected:***	***Distance from Margaret White Springs***	***Feature:***
St. Joe	*06/17/2015*	*2:25 p.m.*	*Mill Creek*	*36°2' 13.344" N*	*92°49'15.996" W*	*Fluorescein 8 pounds*	*4.9 miles*	*Stream*
St. Joe	*06/17/2015*	*2:45 p.m.*	*Baker Sinkhole*	*36°0'8.57" N*	*92°48'47.52" W*	*Eosine 8 pounds*	*3.01 miles*	*Sinkhole*
St. Joe	*06/17/2015*	*1:45 p.m*	*Scott Sinkhole*	*36°1'30.5" N*	*92°49'20.93" W*	*Rhodamine WT 1.7 gal *0.2*7.48 lbs*	*4.12 miles*	*Sinkhole*
Pindall	*03/08/2016*	*9:00 a.m.*	*Jones Hollow*	36°8'40.092" N	92°53'48.804" W	*Fluorescein 8 pound*	*12.40 miles*	*Losing stream*
Pindall	*03/08/2016*	*8:30 a.m.*	*Clear Creek tributary*	36°6'32.112" N	92°54'29.772" W	*Eosine 8 pound*	*10.20 miles*	*Losing stream*
Pindall	*03/08/2016*	*7:45 a.m.*	*Stream near Jack Keith*	36°4'33.996" N	92°53'15" W	*Rhodamine WT 1.7 gal *0.2*7.48 lbs*	*7.72 miles*	*Losing stream*
Snowball	*04/21/2017*	*12:00 p.m.*	*Robert's Sinkhole*	*35°55'12.72" N*	*92°50'25.44" W*	*Fluorescien 12 pounds*	*3.47 miles*	*Sinkhole*
Snowball	*04/21/2017*	*12:35 p.m.*	*Alexander Sinkhole*	35°56'19.72" N	92°49'47.28" W	*Eosine 12 pounds*	*2.31 miles*	*Sinkhole*
Snowball	*04/21/2017*	*1:00 p.m.*	*Cemetery Sinkhole*	35°55'27.732" N	92°49'53.04" W	*Rhodamine WT 1.7 gal *0.2*7.48 lbs*	*3.24 miles*	*Sinkhole*

4.6 Dye Receptor Collection Intervals

Collection of the passive dye receptors began two hours after the dye injection for each separate dye-tracing test. Sampling intervals were every 2 to 4 hours for the first day of each test. The second day, samplers were collected and replaced at each location on an approximate six-hour schedule, in the morning, afternoon, and evening. The 3rd day after the dye injection, samplers were collected in the morning and evening. They were then collected daily, bi-weekly, and weekly until enough rain had saturated the local flow system to sufficiently move the dye. By doing a more intensive sampling frequency during the beginning of the dye-tracing test, time of travel and dye concentrations can be considered, allowing for more semi-quantitative conclusions to be made. If a positive dye detection was made, travel time was determined and a determination of a short duration pulse or movement over a longer period of time was made.

4.7 Processing the Dye Receptors in the Lab

The passive dye receptors were taken to the University of Arkansas Geosciences Department after collection. Gloves were worn at all times while handling the samples, whether in the field or in the lab, and replaced at the time of retrieval between each sample to prevent cross contamination. Samples were prepped in a lab and analyzed using the Shimadzu RF-5301PC Series spectrofluorophotometer (Fig. 20). The Ozark Underground Laboratory's Groundwater Tracing Handbook by Tom Aley and the Procedures and Criteria Analysis of Fluorescent Dyes in Water and Charcoal Samplers: Fluorescein, Eosine, Rhodamine WT. and Sulforhodamine B Dyes by Tom Aley and Shiloh L. Kirkland were used as references for determining positive versus negative dye readings.

Figure 20: Image of the Shimadzu RF-5301PC Series spectrofluorophotometer

4.7.1 Elution Process

Charcoal samplers were collected and placed into labeled individual ziplock bags and kept chilled to prevent bacterial growth until analysis could take place. Prior to analysis, charcoal samplers were rinsed in deionized water to remove any debris or organic matter, and then were dried under a vent hood. Organic matter can interfere with analysis by decreasing the amount of light that can pass through the elutant in the spectrofluorophotometer (Aley, 2002), thus the reason for the rinsing. After the samples were dry about one tablespoon of charcoal from each sample was placed into individual two-ounce plastic cups. The charcoal from each sample was then eluted in a solution of 70% isopropyl alcohol and 2-3 potassium hydroxide pellets.

4.7.2 Measuring the Intensity and Wavelength of Dye from in the Eluent

After the elution process, the eluent samples were placed in small square cuvettes for analysis on the Shimadzu RF-5301PC Series spectrofluorophotometer. The spectrofluorophotometer reads a physical phenomenon known as fluorescence which is a form of luminescence and a property of each of the dyes used (Wilson et al, 1986). The spectrofluorophotometer measures the wavelength of the fluorescence of each eluted sample from a specified wavelength of an initial light source. The fluorescence wavelength of each of the dyes used is unique, providing an identifying "fingerprint" of dye occurrence [or no dye occurrence] (Quinlan, 1986). The spectrofluorophotometer determines the wavelength of the fluorescence of any dye or other substance which may be present in the elutant. Based on predetermined parameter settings for each dye, the light passes through the samples, and the photometer reads the amounts of photons that are absorbed and the amount of specific wavelengths that are transmitted. As previously discussed, each dye has a determined emission wavelength range. Standards were analyzed on the machine for each dye to calibrate and determine the correct parameters. To create these standards a small amount of the as sold dye (typically 1 gram) is placed in a pre-weighed container and then diluted with water to create a 1 percent solution by weight. After this standard has set for an hour 1 part of the solution is mixed with 99 parts of water to create a 100 parts per million dye standard (Aley and Shiloh, 2015) The spectrofluorophotometer can detect each dye in the elutant to as little as 0.010 parts per billion (ppb), 0.035 ppb, and 0.275 ppb, for fluorescein, eosine, and rhodamine WT respectively (Aley,2002).

4.8 Specific Conductance

Specific conductance and temperature measurements were made from August 9th to November 10th of 2017 using the YSI Model 30 Handheld Salinity, Conductivity, and Temperature System. Specific conductance is the measure of the capacity of water to conduct electricity (Radtke et al., 2005), and the meter is calibrated with a set of known standards. It is a function of the amount and types of dissolved ions present in the water. Specific conductance is temperature dependent and can vary as much is 3% for every one degree Celsius, and measurements are typically corrected to a reference temperature of 25°C. The Model 30 automatically adjusts the reading which would have been read if the water sample were 25°C. Specific conductance measurements were also downloaded from the National Water Quality Monitoring Council (www.waterqualitydata.us) for Searcy County, and were compared to the measurements taken during this study.

4.8.1 Statistical Analysis

Two statistical tests were completed using Microsoft Excel to assess the percentage of surface water contributed from the BNR at Woolum (mixing sample 1) with an assumed wholly-groundwater source (mixing sample 2, based on data derived from nearby springs occurring outside the MWS watershed) based on the specific conductance measurements of water resurging from MWS (the final mixed water). Insofar as the data 1) do not have a statistically normal distribution, and 2) the sample sizes were small, non-parametric tests were used to assess the likelihood that statistical differences. The range of specific conductance measurements were organized into boxplots and scatterplots to give a visual comparison (Fig. 29).

The Mann-Whitney U Test was used to statistically determine if the specific conductance measurements of water samples came from the same population, specifically, if they were derived (same median). The Mann-Whitney test (also known as the Wilcoxon Mann Whitney rank-sum test) is a nonparametric test that makes no assumptions about the population distribution and works well for sample sizes greater than five and less than twenty. It compares two independent samples by ranking (Helsel and Hirsch, 1992). An alpha value of 0.05 was used to determine the critical value. The ranking is done by combining the two independent samples and ignoring which sample each measurement came from. The null hypothesis is that the distributions of both sample populations are equal; the alternate hypothesis is that the distributions are not equal. The null hypothesis is rejected when the lowest of the U-statistic is less than the critical value. The U-statistic equation is:

$$U_1=R_1-n_1(n_1+1)/2$$

Where n_1 is the sample size for sample one and R_1 is the sum of the ranks for sample one. This equation is repeated for sample two.

The Wilcoxon signed-rank sum test was also used to compare the specific conductance measurements. It is used to determine whether the median difference between paired observations equals zero, and if the samples come from the same population (Helsel & Hirsch, 1992). It assumes that the samples are paired and come from the same population, and that they have a similar shape in distribution; however, the test does not assume that the distribution is normal. The null hypothesis is that the median difference between the pairs of samples equals zero, and the alternate hypothesis is that the median difference between the paired samples does not equal zero. The samples are ranked by the absolute value of the difference between the pairs, and then the sum of the positive ranks and the sum of the negative ranks is used to find the test statistic. The test statistic is equal to the lower value of the two rank sums. An alpha value of 0.05 was used to determine the critical value. The null hypothesis is rejected if the test statistic is less than the critical value.

4.8.2 Mixing Analysis

The discharge at MWS is thought to be equal to the streamflow loss at Robertson Hole plus the contribution of groundwater from contiguous groundwater basins that had not provided baseflow to MWS. To determine the amount of groundwater at MWS, the specific conductance measurements were applied to a binary mixing model. The binary mixing equation is:

$$X_1 = (C_{mix}-C_2) / (C_1-C_2) * 100$$

where X_1 is the proportion of end-member 1 in the mixture (in percent), C_1 is the specific conductance or concentration of end-member 1, C_2 is the specific conductance or concentration of end-member 2, and C_{mix} is the specific conductance concentration of the water mixture (USGS, 2015).

For this study the X_1 is assigned as the proportion of water at MWS that comes from Robertson Hole. C_1 will be the specific conductance at Woolum—representative of the conductance of BNR water, C_2 will be the specific conductance of the springs, which will represent the specific conductance of groundwater, and C_{mix} will be the specific conductance of MWS—representing a mix of river water and groundwater. Although the springs used for this study were outside the local watershed for MWS it should be noted that springs within the watershed would have very similar values therefore this experiment will not reveal if the groundwater contribution is coming from within the watershed or outside. Knowing X1—the proportion of water coming from river water—will allow determination of the fraction contributed by groundwater by difference.

5. Results

5.1 St. Joe area Dye-tracing Test

The first dye-tracing test was conducted in the St. Joe area (Fig.13 and 17) on June 17, 2015 during a large precipitation event of 4.4 inches of rainfall occurring for a period of 3 days. At 1:45 p.m., approximately 1.7 gallons of 20% rhodamine WT was injected into Scott sinkhole (Fig. 16). At 2:25 p.m. eight pounds of fluorescein was injected into Mill Creek, and at 2:45 p.m., eight pounds of eosine was injected into Baker sinkhole (Fig. 17). In May prior to the dye-tracing test the St. Joe area received 11.2 inches of rain (NOAA's NCEI, 2017). Rainfall on the day of the dye injection was measured as 1.28 inches (NOAA's NCEI, 2017). The surface-water gaging station of the USGS (07056000 Buffalo River near St. Joe, Arkansas) approximately 10 miles downstream 10 miles of MWS, reached approximately 14,000 cubic feet per second in the 3 days following the dye-tracing test (Fig. 21). After a total of 14.32 inches of rain and

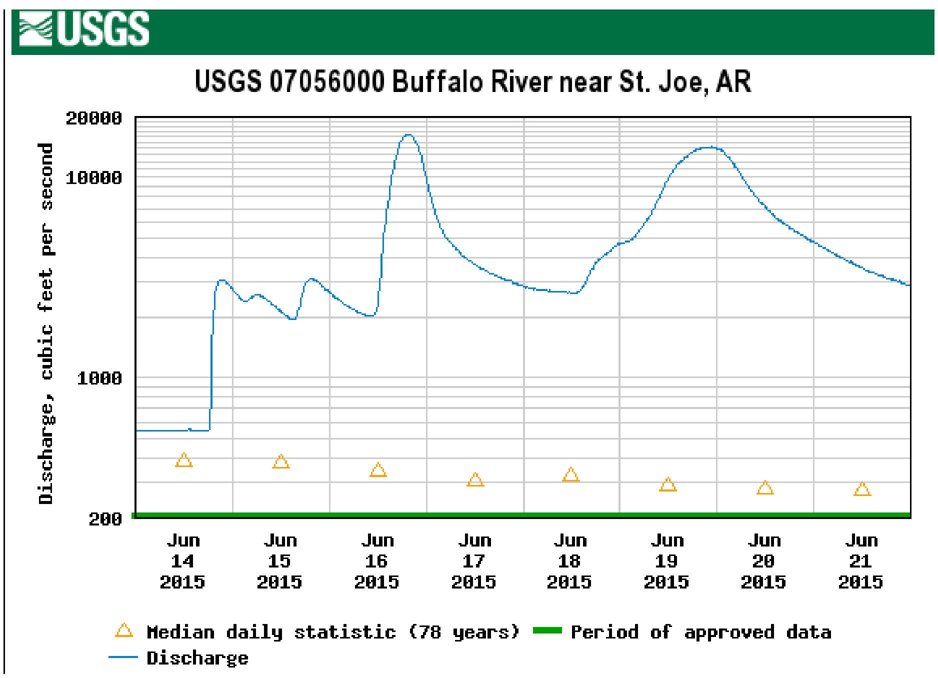

Figure 21: Chart of the discharge of the Buffalo River near St. Joe from 06/14/2015-06/21/2015 (USGS, 2018)

approximately 3 months of sampling no positive dye detections were made at any of the locations sampled, including MWS.

5.2 Pindall area Dye-tracing Test

The second dye-tracing test took place in the Pindall area on March 8, 2016 (Fig. 4). At 7:45 a.m. approximately 1.7 gallons of rhodamine WT was injected into a losing section of a small stream (Fig. 18). At 8:30 a.m. eight pounds of eosine was injected into a small losing section of a tributary to Calf Creek. At 9:00 a.m. eight pounds of fluorescein was injected into

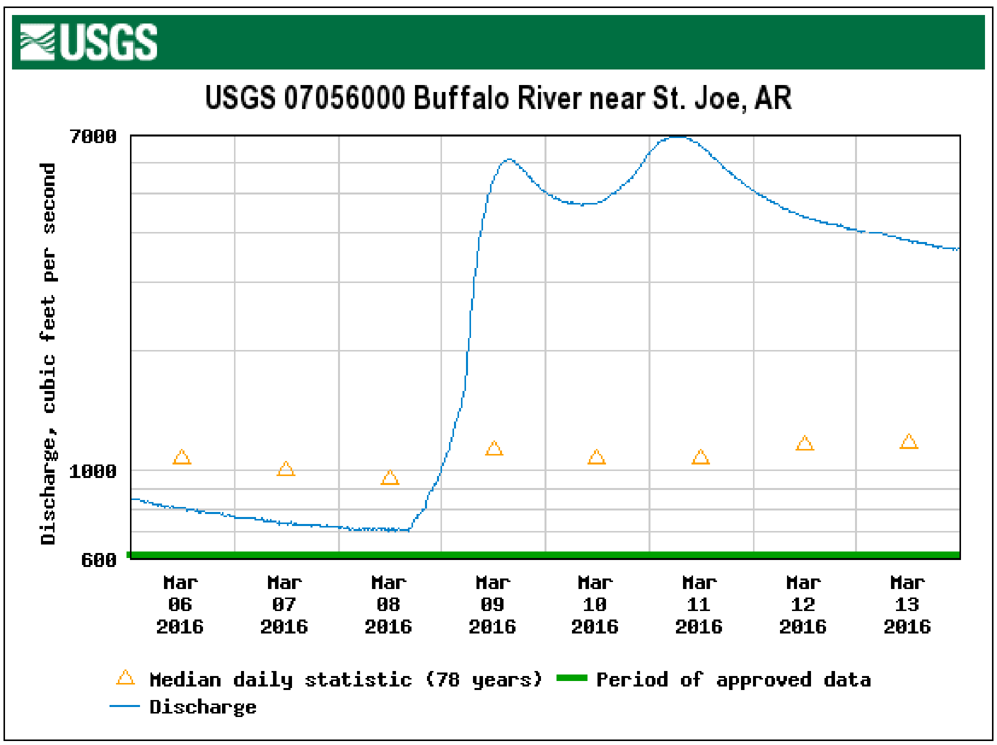

Figure 22: Chart of the discharge of the Buffalo River near St. Joe from 03/06/2016-03/13/2016 (USGS, 2018)

Jones Hollow (Fig. 18). The day of dye injection it rained 0.05 inches and a total of 3.15 inches the following 6 days (NOAA's NCEI, 2017). In the month prior to the dye-tracing test precipitation totals were 2.55 inches (NOAA's NCEI, 2017). Throughout the entire sampling period the rain total was 20.88 inches (NOAA's NCEI, 2017

On March 10th Hatchery spring (36° 7' 10.056" N, 92° 54' 12.024" W) tested positive for eosine, and on March 14th the spring tested positive for rhodamine WT. On April 2nd a small amount of fluroscein was detected at Hatchery spring. Hatchery spring is located 0.8 miles north of the losing section of unnamed stream where eosine was injected and 3.1 miles north of the losing section of stream where rhodamine WT was injected into and (Fig. 22). Rhodamine WT's common emission range is between 561.7 to 568.9 nanometers, with the peak being 565.0 nanometers (Aley, 2002). However, the peak wavelengths can very slightly due to differences in optics and electronics of the instrument; for the machine used during this study rhodamine WT peaked at 559 nanometers (Fig. 24). The common emission range for eosine in elutant is between 533.0 to 539.0 nanometers with a peak fluorescence at 536.0 nanometers (Aley, 2002). The exact peak for eosine during this study was not determined because the peak intensity was higher than the parameters for the Shimadzu RF-5301PC (Fig. 25). Fluorescein peaked on April 2nd at 516 nanometers, with an intensity of 327, which was much lower than the intensity of the other positive results (Fig. 26). Fluorescein typically peaks between 510 to 515 nanometers (Aley, 2002). The intensity of the dyes is reflective of the dye concentration present in the eluting solution and does not indicate the dye concentrations in the spring. The intensity values are useful in determining travel times and whether or not the dye discharged from the spring as a short duration pulse or over a longer duration. Each dye continued to emerge at the spring throughout the sampling period at high intensities indicating each dye discharged from the spring as a long duration event and not a short duration pulse (Fig. 24 ,25, and 26).

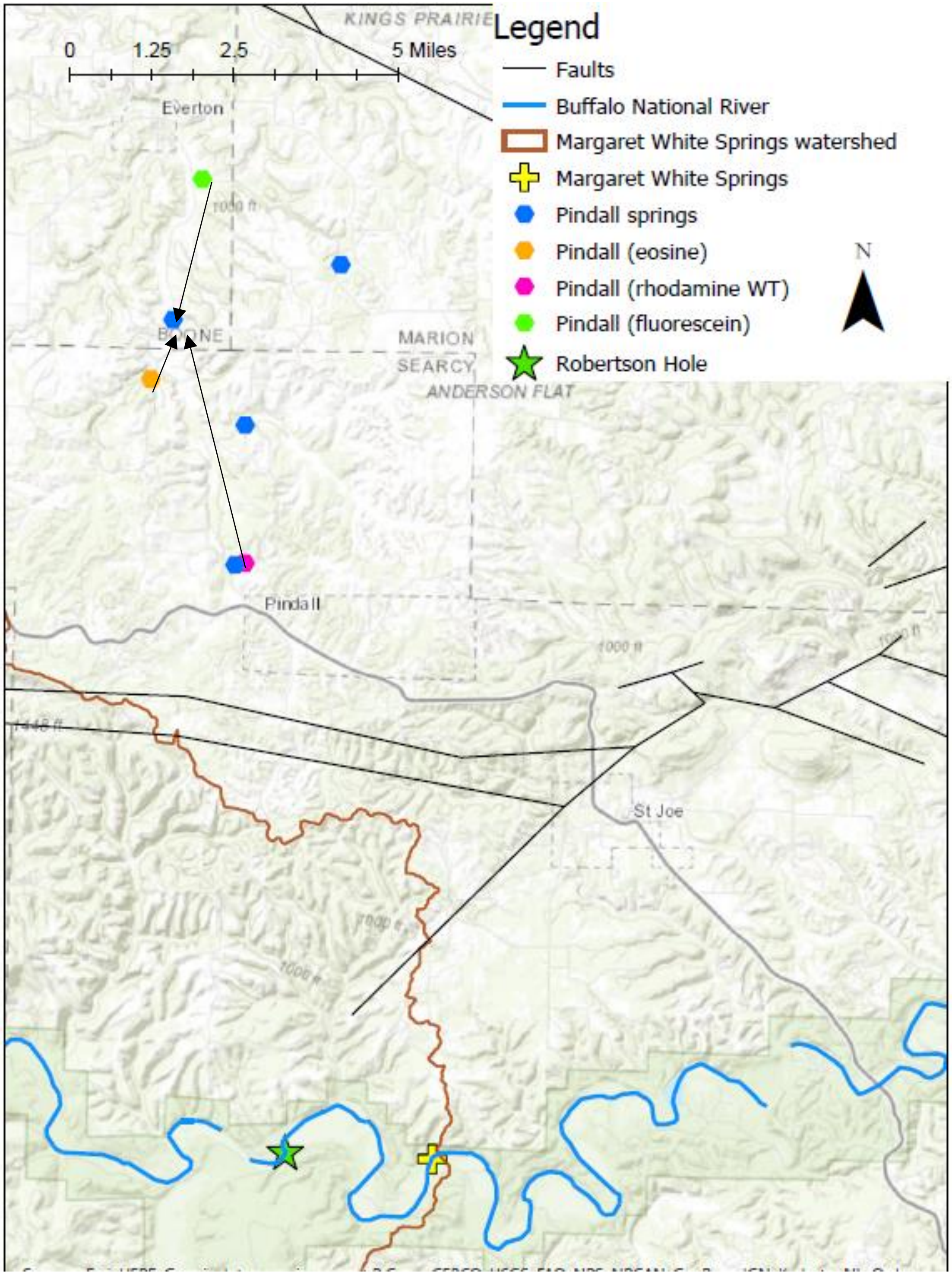

Figure 23: Map of the Pindall area dye trace, pink square indicates location of rhodamine WT injection, orange circle indicates location of eosine injection. The black arrows indicate the general flow direction from input to resurgence. The actual flow paths are much more complicated than the straight lines shown.

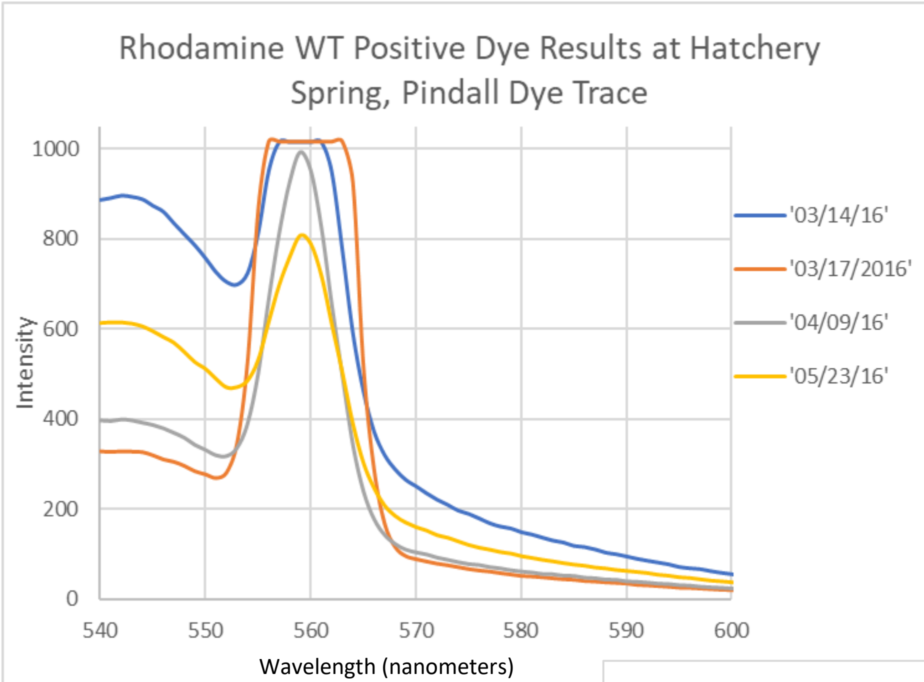

Figure 24: Chart of several of the positive rhodamine WT results at

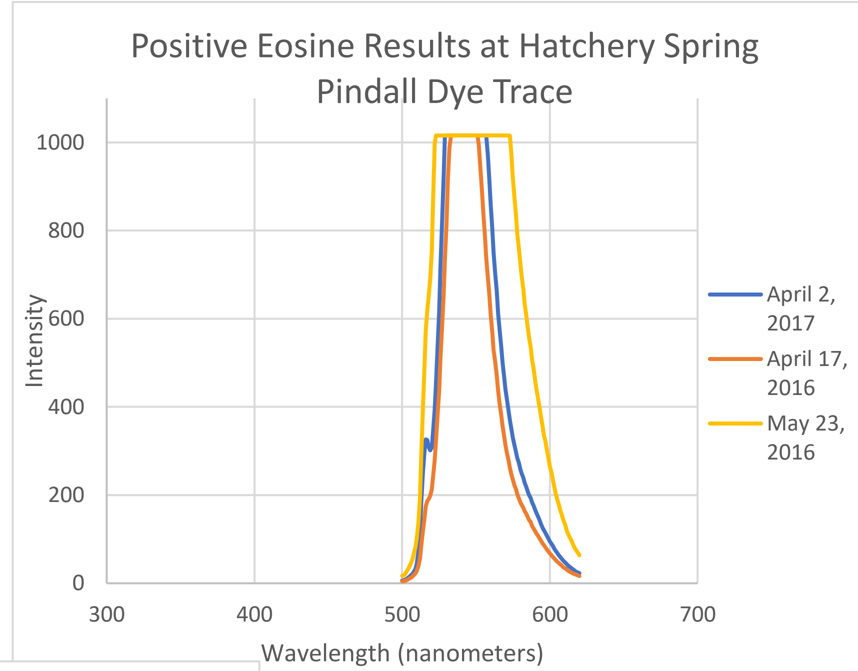

Figure 25: Chart of several of the eosine results at Hatchery Spring

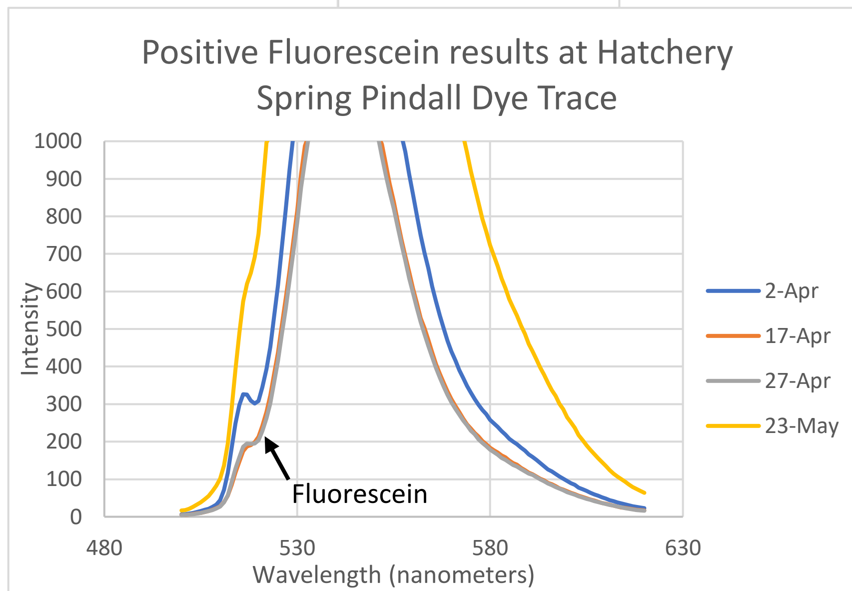

Figure 26: Chart of fluorescein results at Hatchery spring

5.3 Snowball Dye-tracing test

The last dye-tracing test took place on April 21, 2017 in the Snowball area (Fig. 4). At 12:00 p.m. twelve pounds of fluorescein was injected into Roberts sinkhole. At 12:35 p.m. twelve pounds of eosine was injected into Alexander sinkhole and at 1:00 p.m. 1.7 gallons of rhodamine was injected into Cemetery sinkhole (Fig. 19). Snowball received 1.55 inches of rain in April before the 21st and 6.6 inches in March. On the day of the dye-tracing test it rained 0.42 inches and 2.98 inches the following day (NOAA's NCEI, 2017). Figure 27 shows the BNR's discharge reaching just over 30,000 cubic feet per second on the day following the dye injection (USGS, 2018). After several months of sampling and a total of 22.56 inches of rain (NOAA's NCEI, 2017) no positive traces were confirmed.

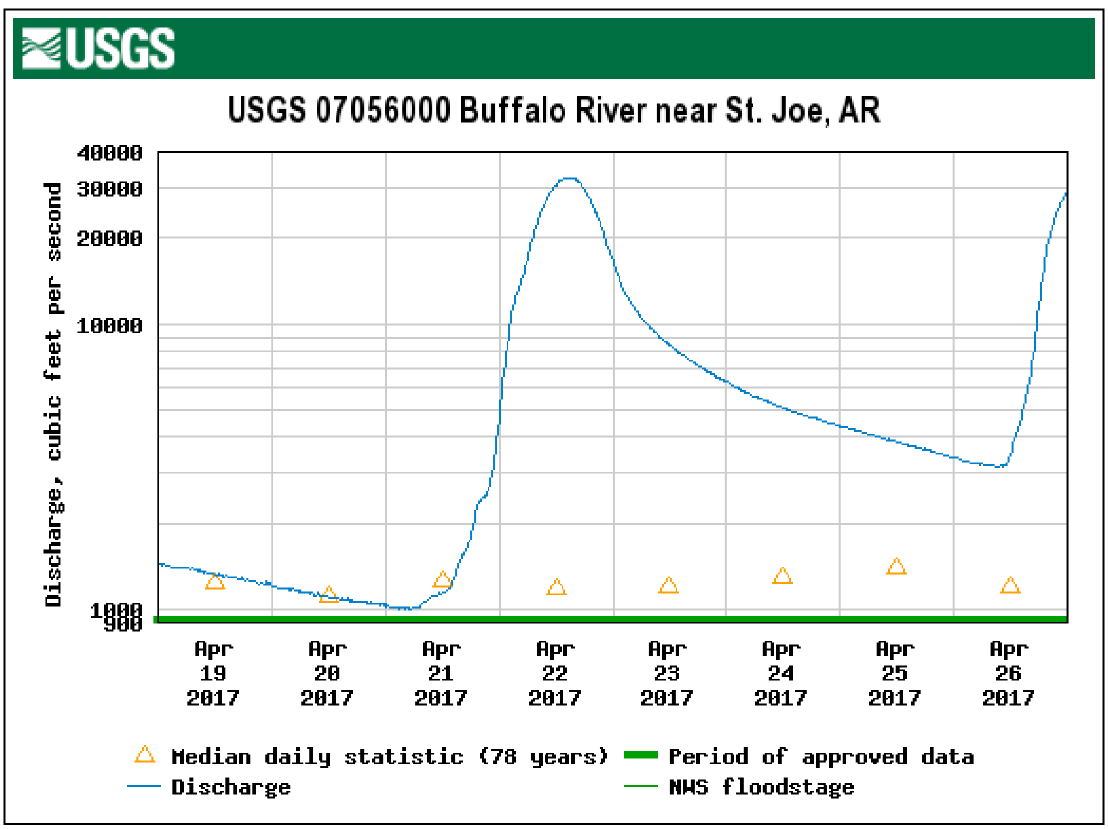

Figure 27: Chart of the discharge of the Buffalo River near St. Joe from 04/19/2017-04/26/2017 (USGS, 2018)

5.4 Specific Conductance

Specific conductance measurements were taken at six springs in the study area, the BNR at Woolum, and MWS (Table 4) Seven days of sampling were conducted between August 29, 2017 and November 9, 2017. The measurements were then applied to the binary mixing equation to determine the groundwater contribution at MWS. The measurements were also compared to specific conductance measurements from the National Water Quality Monitoring Council for Searcy County. Results indicated an 18% groundwater contribution at MWS on August 29th . A 1% groundwater contribution was calculated for October 18th, and a 2% groundwater contribution was calculated for October 26th (Fig. 28); because of error inherent in the estimate of groundwater specific conductance, these lower contribution time estimates are considered questionable. The National Water Quality Monitoring Council measurements spanned several years and when plotted by month show a seasonal trend in the data at Woolum (Fig 29). Specific-conductance values are highest in January, June, and October, and lowest in March and December.

Table 4: Table of specific conductance measurements taken from 08/29/2017-11/09/2017, and the percent groundwater contributions calculated.

Specific Conductance (µS/cm) Measurements for Binary Mixing analysis							
Location:	Date:						
	29-Aug	**9-Sep**	**20-Sep**	**18-Oct**	**26-Oct**	**3-Nov**	**9-Nov**
Cave	378.9	386.2	388.5	388.5	390.1	388.9	386.7
East	379.8	383.2	385.5	385	387.3	386.2	388.3
Church	185	253.5	241.2				
Calf Creek	316.8	443.8	388.1	440.4	370	397.4	426.7
Alexander	297	401	420.6		431.1		
Road	347.6	439.1	445.2	415		439.8	421.2
Daily average specific conductance of groundwater	**317.516667**	**384.467**	**378.183**	**407.225**	**394.625**	**403.08**	**405.725**
Woolum	171.2	225.1	241.2	244.2	251.3	264.4	269.2
				250.3	250.1	264.8	267.5
				249.4			
Daily average of specific conductance at Woolum				**247.9667**	**250.7**	**264.6**	**268.35**
Margaret White Springs (MWS)	201	220.9	231	249.6	263.1	256.2	258.7
	183	219	229	250.1	252.6	255.9	255.9
	200.6	219	231	249.5	254.7	254.9	255.9
	197	220	230	248.7	250.4	256.7	258.5
	201	219	229.5	250.6	247.2	256.1	258.1
	201.6	218.5	229	249.8	252.8		256.6
Daily average specific conductance at MWS	**197.366667**	**219.4**	**229.917**	**249.7167**	**253.4666667**	**255.96**	**257.283**
Percent groundwater contribution at Margaret White Springs	**17.884**	**N/A**	**N/A**	**1.099**	**1.923**	**N/A**	**N/A**

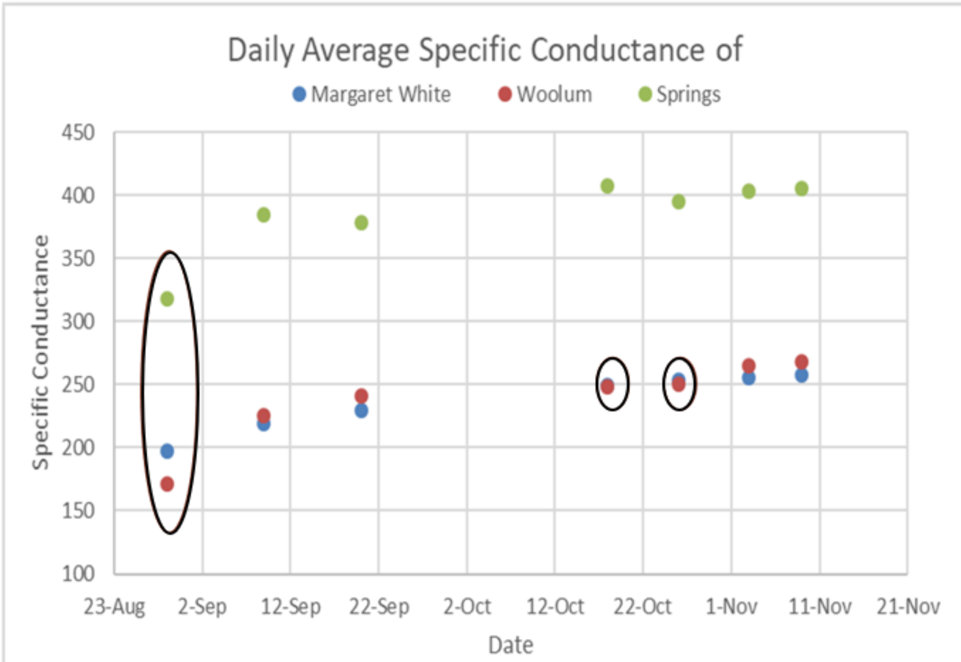

Figure 28: Graph of the daily average specific conductance of Margaret White, Woolum, and the springs. The black circles, indicate the days that a groundwater contribution at Margaret White took place.

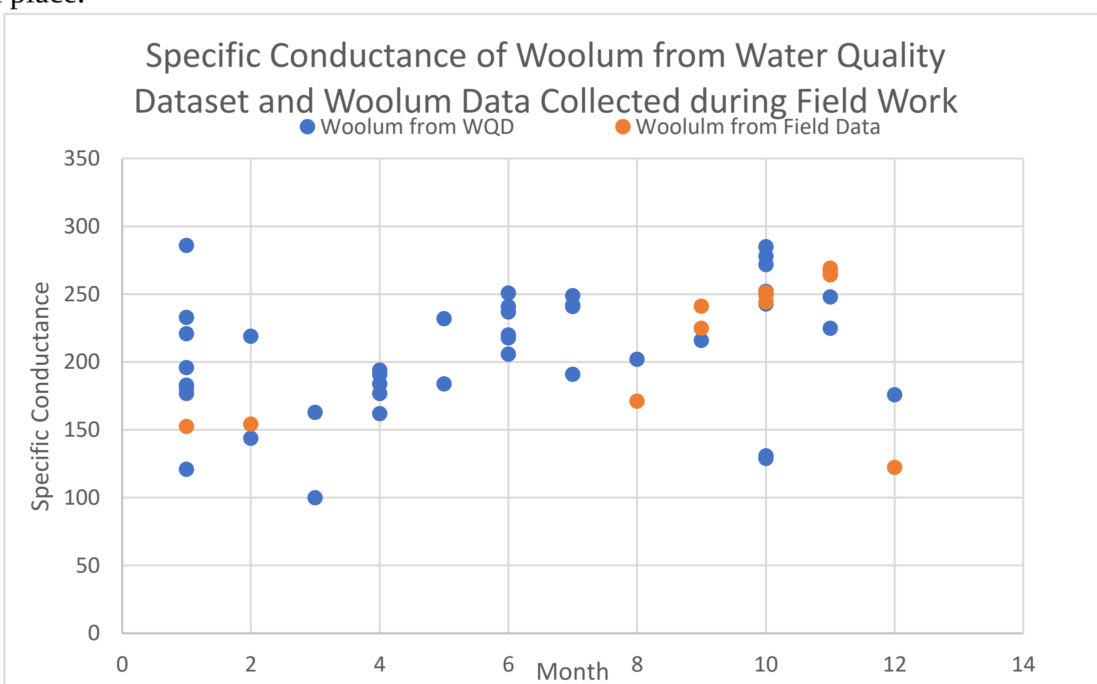

Figure 29: Graph of the specific conductance of the Buffalo River at Woolum from the water quality data set (blue) and the measurements taken during field work (orange). This chart shows the seasonal trend in the measurements.

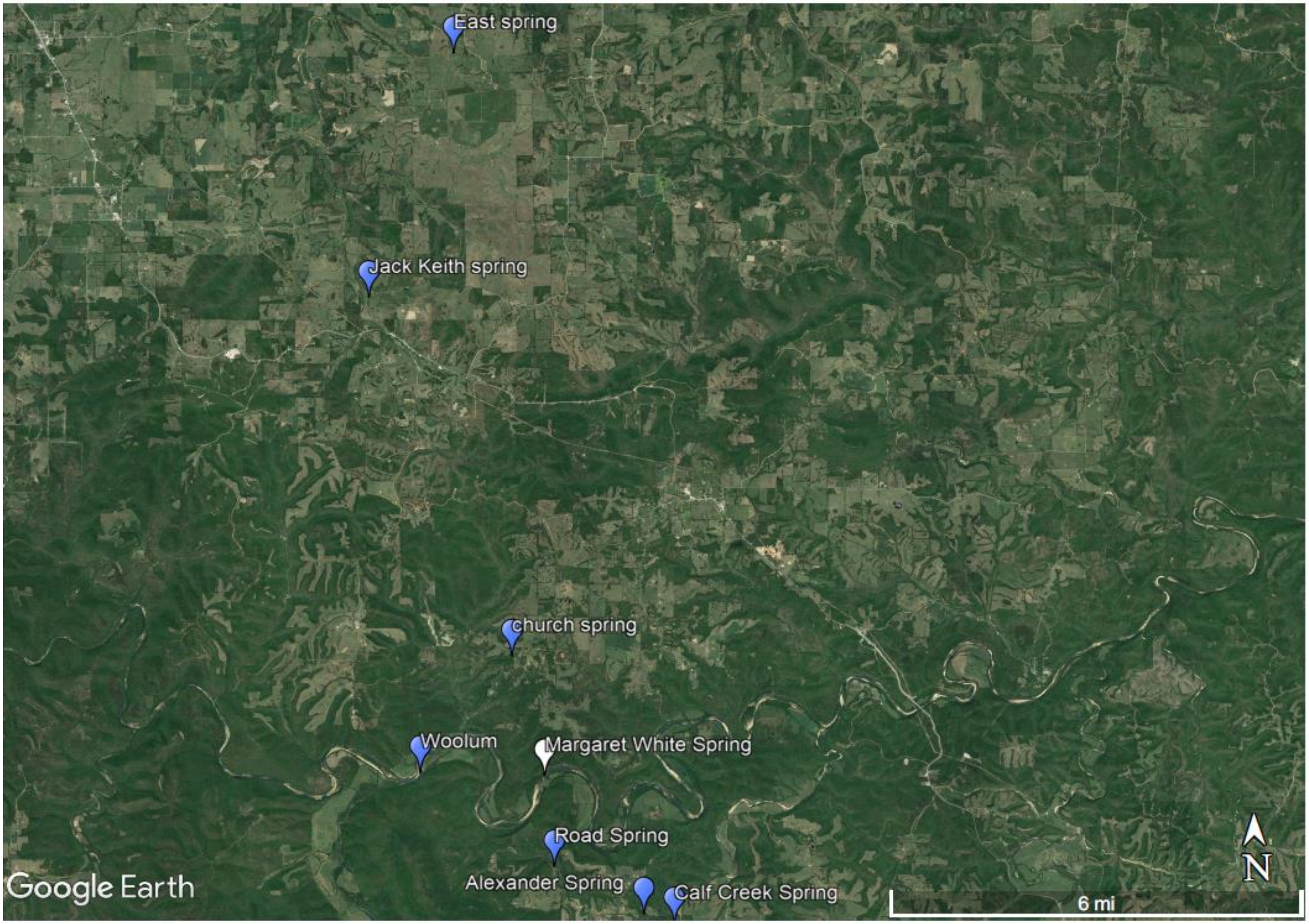

Figure 30: Google Earth map showing locations where specific conductance measurements were taken

6. Discussion and Conclusions

Because no positive dye detections were noted at MWS during the three dye-tracing tests, the three areas where dye was injected cannot be concluded as being recharge zones for MWS for similar groundwater conditions that existed during these tests. These negative results are inconclusive at this point in time, and a number of factors could be responsible for dye not being recovered:

1) The dye moved along groundwater flow paths to locations for which dye receptors were placed, and the locations that were sampled for this study had no connection to the dye injection locations.
2) Previous studies in the area show that the groundwater flow paths change direction depending on recharge and water-level conditions (Aley, 1989; Brahana et al., 2017). All of the dye-tracing tests were done during the months of spring when stream stage was high. Dye-tracing tests done under different hydrologic conditions could possibly show positive results indicating connections.
3) The dyes injected could have been adsorbed to clay minerals, or diluted along the flow pathways to the point that concentrations were below detection limits.
4) Mixing of groundwater and river water at MWS during the high flow conditions after the dye injection, may have resulted in dilution of the dye to limits below detection. Figures 21, 22, and 27 show the rivers quick response after each precipitation event. The discharge increased significantly during

each dye trace which could have resulted in dilution of the dye to limits below detection, and the loss of many charcoal samplers placed in MWS.

5) The dye that was injected into sinkholes was not transported into flowing groundwater, and was temporarily hung up in the vadose zone. Although rain followed all dye injections, it was not evident that if moved the dye into the flow system.

6) The locations of the three dye-tracing areas were near the top of the Boone Formation, and the intervening chert layers of the middle and lower Boone acted as effective confining layers, perching the dye above the karstified zone in the Boone that transmitted groundwater to MWS. This is not unexpected in areas where the chert layers are areally continuous (Brahana et al., 2017; Murdoch et al., 2016)

The first dye-tracing test suggests regional groundwater movement does not flow along the St. Joe fault--- northeast to southwest--during recharge events. Groundwater movement may possibly be controlled by the gentle dip to the southeast from what was previously described as the St. Joe monocline (McKnight, 1935, Fig. 31). This dipping block is now thought to be a

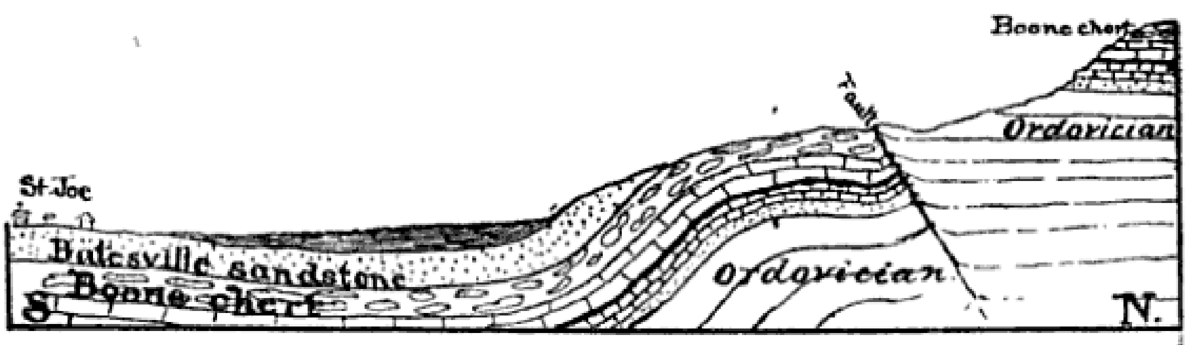

Figure 31: Image of the gentle dip to the southeast in the St Joe area from (McKnight, 1935) The Boone formation in this source was referred to as the Boone chert.

separate structural feature that Hudson et al. (2007) linked to the growth of the Confederate Fault and the dip of the strata to northwest of the fault (Fig. 6).

The second dye-tracing test in Pindall on 03/17/16 resulted in several positive dye hits at Hatchery Spring from eosine, which was injected into a losing section of a tributary to Calf Creek, and rhodamine WT, which was injected into the east losing stream (Fig. 23). This showed that the dye moved to the north during the study (Fig. 23). Previous dye-tracing studies in the Pindall and Mitch Hill Spring area showed complex radial flow of the groundwater (Aley and Aley, 1989, Fig 24). Figure 32 shows the results of this previous dye traces along with the results of the Pindall dye trace. This previous study found that, under high-flow conditions, the Pindall area contributes a great deal of water to Keith Spring which is located just north of the town. Under dry conditions the trace showed the groundwater reversed flow direction and contributed to Mitch Hill Spring (Aley, 1989). This study is consistent with the results found during the Pindall dye-tracing study conducted by Aley, as no dye was recovered in any of the springs south of Margaret White, Both this and Aley's study that recovered dye in the north took place in very wet conditions.

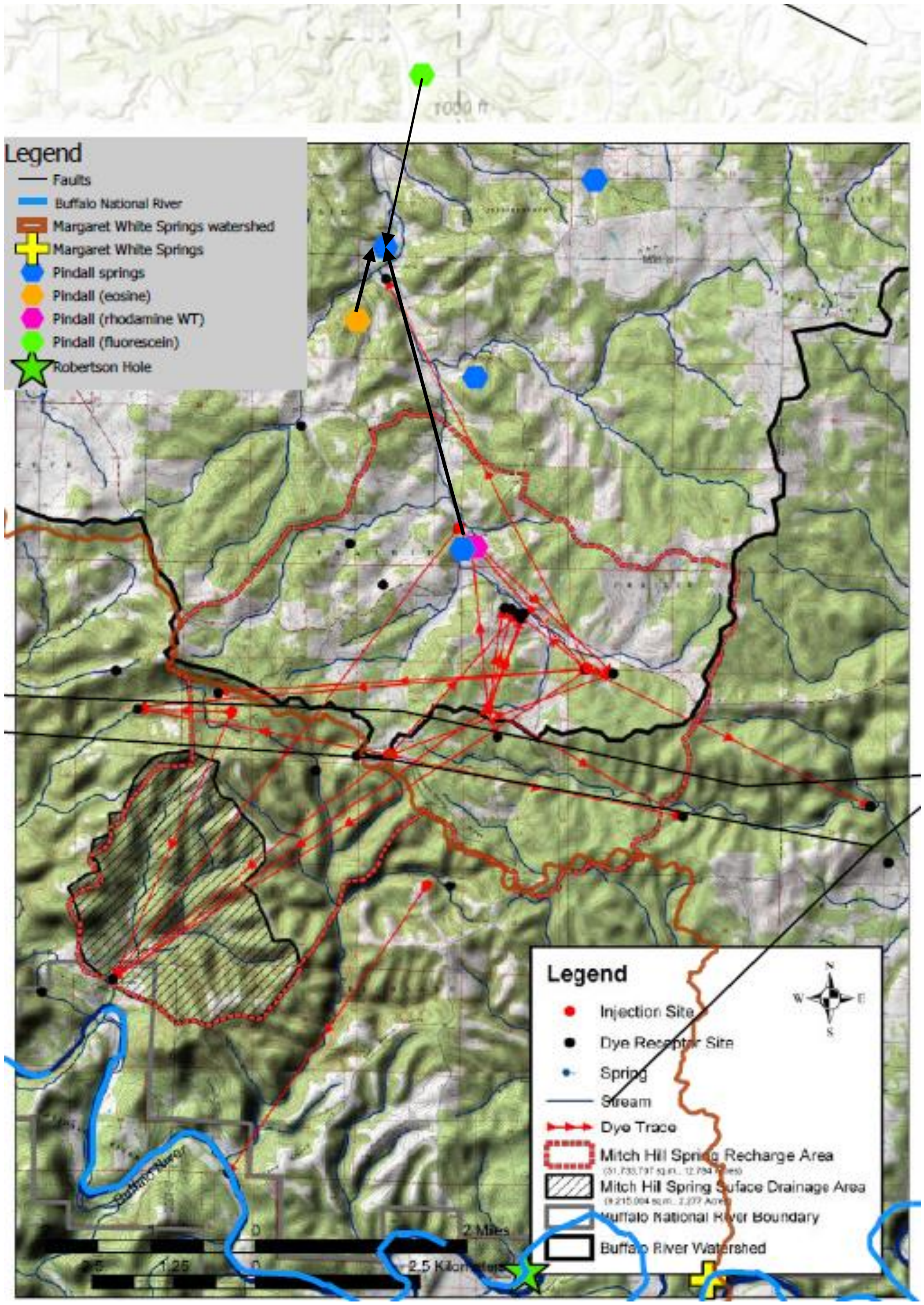

Figure 32: Map of Tom Aley Pindall dye trace from 1989 with data from this studies 2016 dye trace. Top legend is from 2016 dye trace and bottom legend is from 1989 dye trace.

The most northern spring sampled during the study, Hatchery Spring (Fig. 23), was the only spring to have positive results for dye. Conducting dye-tracing studies in the study area during low-flow conditions may result in different groundwater flow directions, and possible connection to MWS. Although hypothetical at this time, such a result would be consistent with the results of other dye tracers conducting studies nearby (Aley and Aley, 1989; Brahana et al., 2017)

Mixing models using specific conductance data show a seasonal change in conductance, and indicate that not all MWS recharge originates at Woolum. This is consistent with previous discharge measurement comparisons. The seasonal trend of the specific-conductance measurements at Woolum shows higher values in the summer and winter and lower values in the spring and fall, likely due to mixing and dilution (Fig. 28 and Fig. 29). Summer and winter are times of low flow when baseflow of the river is primarily contributed by groundwater. During this time a greater proportion of groundwater is represented by matrix and small-pore flow with greater residence times. This leads to greater time for rock-water interaction to increase TDS and specific conductance. The opposite effect occurs during the wetter months of spring and fall; groundwater recharge increases, a greater proportion of groundwater is represented by conduit flow with high travel velocities and short residence times, and groundwater has less time to dissolve rock material; in addition, river discharge comprises a higher proportion of surface runoff and quick flow having lower TDS and specific conductance. During the months of August, September, October, and November, 3.54, .09, 2.36, and .42 inches of rain were recorded, respectively (NOAA's NCEI, 2018). Precipitation would result in greater groundwater recharge and lower specific conductance values at local springs and also result in lower river specific conductance values, this explains the much lower spring values in August as August had the largest amount of precipitation, compared to the later dates. The August specific conductance data showed that MWS specific conductance was markedly different than river specific conductance values at Woolum. MWS specific conductance was intermediate to BNR values at Woolum and groundwater specific-conductance values at local springs, consistent with MWS discharge being a mix of river water and groundwater. The dates that had a groundwater contribution appear to be after a precipitation event (Fig. 33).

Determining the recharge area for MWS is important for protecting the water quality of the BNR. While none of the dye-tracing tests yielded positive results at MWS, the specific conductance data collected show a significant, but variable, groundwater contribution in addition to the captured flow at MWS. This study suggests that under the conditions the dye-tracing tests

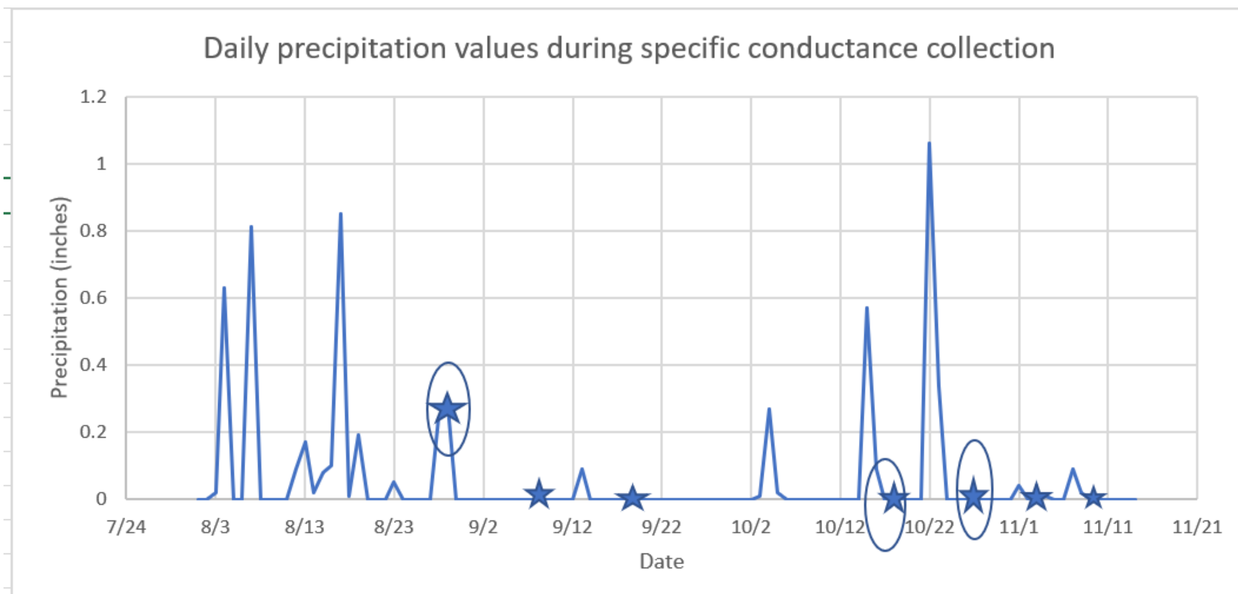

Figure 33 : Daily precipitation values during the collection of specific conductance measurements. Stars indicate days the specific conductance measurements were taken and the circles are days when a groundwater contribution was determined at Margaret White Springs.

took place—wet antecedent conditions, high flow, no connection to the dye injection areas and MWS exists. Under different hydrologic conditions these areas possibly could be contributing water to the spring as a complex radial groundwater flow pattern has been previously described under lower-flow conditions (Aley, 1989). The only dye recovery came from dye injected into losing streams, so it is possible that in the study area losing streams are better connected to the groundwater than sinkholes. A longer period of specific conductance measurements would also help further explain the groundwater contribution, and possibly show a seasonal trend like the water quality data set. Although little dye was recovered during this study, results are consistent with earlier dye-tracing studies showing the complexities of karst aquifers in the area of the BNR. Further investigations, including a focus on low-flow conditions, will be necessary to better characterize the recharge area to MWS.

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