SPRINGSHED DELINEATION AT CAVE WITHOUT A NAME, TX:

DYE TRACING IN THE LOWER GLEN ROSE LIMESTONE

by

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ABSTRACT

Cave Without a Name (CWAN) in Kendall County, TX contains ~5.5 km of active stream conduits formed in the karstic Lower Glen Rose Limestone which forms part of the Trinity Aquifer System. The primarily rural Kendall County lies just northwest of San Antonio in the Texas Hill Country. The Trinity Aquifer is the primary source of freshwater for this and many other Hill Country counties, although its yields are relatively low compared to the adjacent Edwards Aquifer.

Springsheds contribute water via recharge features to a spring and are similar to watersheds, except that their boundaries are not constrained by topography. To delineate a springshed for Cave Without a Name, dye tracing was performed by injecting dyes into recharge features in the land surface. Dye tracing utilizes conservative tracers (dyes) to trace recharging waters from direct recharge sites to a point of discharge (e.g., springs). For this project, multiple traces were performed from direct recharge sites (sinkholes and/or caves). Regional flow near CWAN is to the Southeast while local flow is towards springs and streams. The Guadalupe River, Spring Creek, and Sabinas Creek are assumed to act as local discharge boundaries, along which a number of known springs occur. This work supports prior work by Veni (1994 that suggested there may be several adjacent springsheds in the area, which is near a large oxbow in the Guadalupe River, just upstream from the confluence with Spring Creek.

Results showed groundwater flow velocities in the area ranging from ~0.36 km/day through preferential flowpaths to diffuse flow through the epikarst of ~0.02 km/day. Type of recharge feature, injection method, and hydrologic conditions were found to play significant roles in the behavior of each dye trace. Results may help with future efforts to manage water quality in the area.

I. INTRODUCTION

Groundwater

Freshwater is a valuable resource for human consumption, irrigation, ecosystem health, and a host of other uses. Though water on earth is plentiful, freshwater (and especially attainable freshwater) is a small percentage of total water, accounting for only 2.5% of all water. That 2.5% breaks down further into 1.2% surface water, 30.1% groundwater, and 68.7% trapped in glaciers and ice caps (Gleick 1996). Groundwater is the primary, usable source for freshwater, though slightly more than half of groundwater's 30.1% (0.75% of all water) is saline.

Groundwater is stored in aquifers, defined by the USGS as "a water-bearing rock [that] readily transmits water to wells and springs" (Walter 1982). All aquifers contain groundwater resources, but the movement and geochemistry of groundwaters are dependent on the type of aquifer they are hosted in. Sand and gravel, sandstone, igneous and metamorphic, and carbonate / karst are types of aquifers found in the US. Karst aquifers occur in carbonate bedrocks in which porosity and permeability along fractures, bedding planes, and other heterogeneities become enhanced by dissolution, forming open conduits and pathways for rapid flow. In contrast, sand and gravel aquifers are characterized by intergranular porosity and permeability (KSG 2012).

Groundwater Protection

Springs are natural features where water from an aquifer discharges at the surface. As mentioned earlier, a springshed is a “groundwater contributing area defined by a potentiometric surface or groundwater flow model” (FL DoEP 2013). A comparable term is “watershed”, which refers to surface topography drainage divides. Watersheds are easily delineated using a Digital Elevation Model, but springsheds can be difficult to delineate due to variable factors such as regional geologic structure, fractures, pumped wells, and shifting hydraulic gradient due to changing hydrologic conditions causing uncertainty. Hydraulic gradient is the difference in hydraulic head between two or more points. Hydraulic head (also known as piezometric head) is the sum of pressure head and gravitational head (Bear 1988). In a karst aquifer system, groundwater often crosses surface watersheds. Delineating watersheds is a good place to start in determining groundwater flow, but should not be relied on.

Groundwater is typically cleaner than surface water due to natural filtration of pollutants when passing through rock and soil, though this is not to say that groundwater isn’t subject to contamination. The federal government passed the Safe Drinking Water Act in 1974 and in 1986 amended the act to include the Wellhead Protection Program, protecting groundwater resources used for public water supplies (EPA 1991). This amendment required more contaminants to be regulated, well head protection, and the disinfection of certain groundwater systems. The EPA, specifically the office of Ground Water and Drinking Water, oversees the implementation of the act. Many states have passed their own acts such as the Illinois Groundwater Protection Act, or have formed dedicated organizations like the Texas Groundwater Protection Committee. With a rising population placing increasing and often unsustainable demands on aquifers, groundwater protection increasingly becomes important.

Springhead and wellhead protection are essentially the same thing. The goal is to protect the source or contributing area for a spring or well, which is referred to as a “springshed” or “wellhead protection area”. The EPA specifically defines a wellhead or springhead protection area as “the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants may potentially pass and eventually reach the water well or well field” (US Environmental Protection Agency 1987). Cleaning polluted water or finding new replacement water sources is costly and inefficient, and protecting an existing water supply is easier (Schindel 1996).

Karst

Karst aquifers are defined by Dr. Steve Worthington as “A body of soluble rock that conducts water principally via enhanced (conduit or tertiary) porosity formed by the dissolution of the rock. The aquifers are commonly structured as a branching network of tributary conduits, which connect together to drain a groundwater basin and discharge to a perennial spring” (Worthington 2012). Limestone is the most common rock type in which karst aquifers are formed, but karst can occur in other soluble rock types such as dolomite, gypsum, and marble (Miller 1999). Bedding planes, fractures, and joints are solutionally enlarged to form conduits and caves. Karst topography is characterized by sinkholes, losing streams, blind valleys, and other recharge features.

Pinnacles, towers, and cones are commonly found in tropical karst environments, and surface streams are often intermittent or non-existent due to surface water quickly moving through the dissolution features and into the aquifer.

Hydraulic properties in karst aquifers are highly variable and exceptionally heterogeneous and include some of the largest springs and most productive aquifers in the world. This high variability is often dependent on the type of environment the rock layer was formed in. For example, Tertiary and younger carbonate rocks commonly exhibit both intergranular porosity and solutionally enlarged conduits. Older rocks typically contain lower intergranular porosity as a result of diagenetic processes such as cementation, and flow is primarily through conduits. Compaction and cementation are diagenetic processes which act on carbonate rock and change porosity and permeability (Miller 1999). As mentioned, dissolution is the primary post-depositional process.

About a quarter of the world's population depends on karst aquifers for drinking water (Ford and William 2007). Rapid recharge rates and movement of water in karst aquifers makes them vulnerable to groundwater contamination (Quinlan et al., 1988). Rapid recharge through large openings on the land surfaces above karst systems means that contaminants are not well filtered or attenuated by natural processes and can be rapidly transported through the aquifer. Because it is easier to protect water from contamination than it is to remove contamination, delineation of springsheds in karst landscapes is especially important. However, with unpredictable conduit flow, springsheds in karst aquifers are difficult to delineate and require different methods for delineation than in a granular system, which frequently utilize numerical modeling methods in combination with field-collected hydraulic head measurements.

Many different methods of springshed delineation exist, with no single method being the best for all situations (Schindel 1996). Background information, such as type of aquifer and the local stratigraphy and structural geology are essential knowledge for determining which methods to use. Other important considerations are time and money. In karst aquifers, methods such as flow boundaries, hydrologic mass-balance, and tracer testing are applicable (Schindel 1996). In this project, I used tracer testing and flow boundaries in an attempt to delineate groundwater basins. Tracer testing measures flow direction and velocity while the flow boundaries boundaries method uses surface and groundwater divides.

Study Area

Caves in this area are typically low gradient, slow moving, and muddy (Veni 1994). Cave Without a Name (CWAN) is located in Kendall County northeast of Boerne in the Texas Hill Country (Jasinski 2010). This area is the southeastern margin of the Edwards Plateau and is characterized by stream erosion and a steep gradient towards the Balcones Escarpment. A characteristic stair-step topography can be found in Kendall County due to the Glen Rose Limestone containing alternating beds of softer dolomites and hard limestones, giving the area a karst landscape.

CWAN is a Natural National Landmark and commercial show cave that is known for its impressive formations and is a popular destination for tourists. The cave likely began forming in the Lower Glen Rose Limestone around 880 ka B.P (Veni 1994). CWAN consists of a dendritic network of gravity drained vadose passages with hydraulic gradient dominating passage development. A few passages, including the show-cave tour route, show evidence of early phreatic development prior to the incision of nearby Spring Branch. The cave is formed in a calcarenite unit that above a dolomite (Veni 1994).

An active stream flows through the cave from the southwest in a southeasterly direction and eventually discharges at the Deadman's Cave spring entrance. Discharge from Deadman's Cave has been reported from 2-29 L/s and is in the Spring Creek valley; flow from Deadman's Cave joins Spring Creek (Veni 1994). Overall, the cave exhibits a joint-controlled dendritic pattern, with numerous active tributaries adding flow to the main stream conduit. At the upstream end of current exploration, the passage continues to the southwest as a phreatic conduit that has been partly explored. Along the main stream conduit, passage dimensions consistently increase in a downstream direction, and frequently enlarge below the tributaries. With 5.7km of surveyed passageways, CWAN is the 7th longest cave in Texas (Texas Speleological Society 2016).

Other major caves in the area include Alzafar Water Cave and Spring Creek Cave. Alzafar Water Cave has much less flow than CWAN and is also much smaller at 2,100 feet (640 meters) of surveyed passage (Hardin 1982). The entrance to Alzafar Water Cave is 2.4km west from CWAN. Flow in the mapped portion of Alzafar Water Cave is towards the southwest, though a previous dye trace found evidence of flow to the north and west (Harden 1982). This cave is described as a "phreatic tube with vadose modifications" (Veni 1994, 118).

Spring Creek Cave is the 11th longest cave in Texas with a surveyed length of 2.8km (Veni 1994). This cave has two entrances in Spring Creek valley. Discharge from Spring Creek Cave flows about 15m before joining Spring Creek. Spring Creek Cave is on eastern side of Spring Creek while CWAN is on the western side. The entrance to Spring Creek Cave is 326m southeast from Deadman's Cave. Baseflow from Spring Creek Cave's lower entrance is 2.2 L/s. Spring Creek Cave's main passage extends southeast, though significant tributary passages split and extend south. The study area is locally known as Kreutzberg, German for "Cross Mountain". This area is hydrologically bounded by three surface drainages that are assumed to be approximate hydrogeologic boundaries: spring-fed Sabinas Creek to the northwest, the large Guadalupe River to the north and east, and the spring-fed, gaining/losing Spring Creek to the south. To the west of CWAN towards Highway 474, elevation rises. See Figure 1 for a location of the study area, as well as locations of caves and stream within the study area.

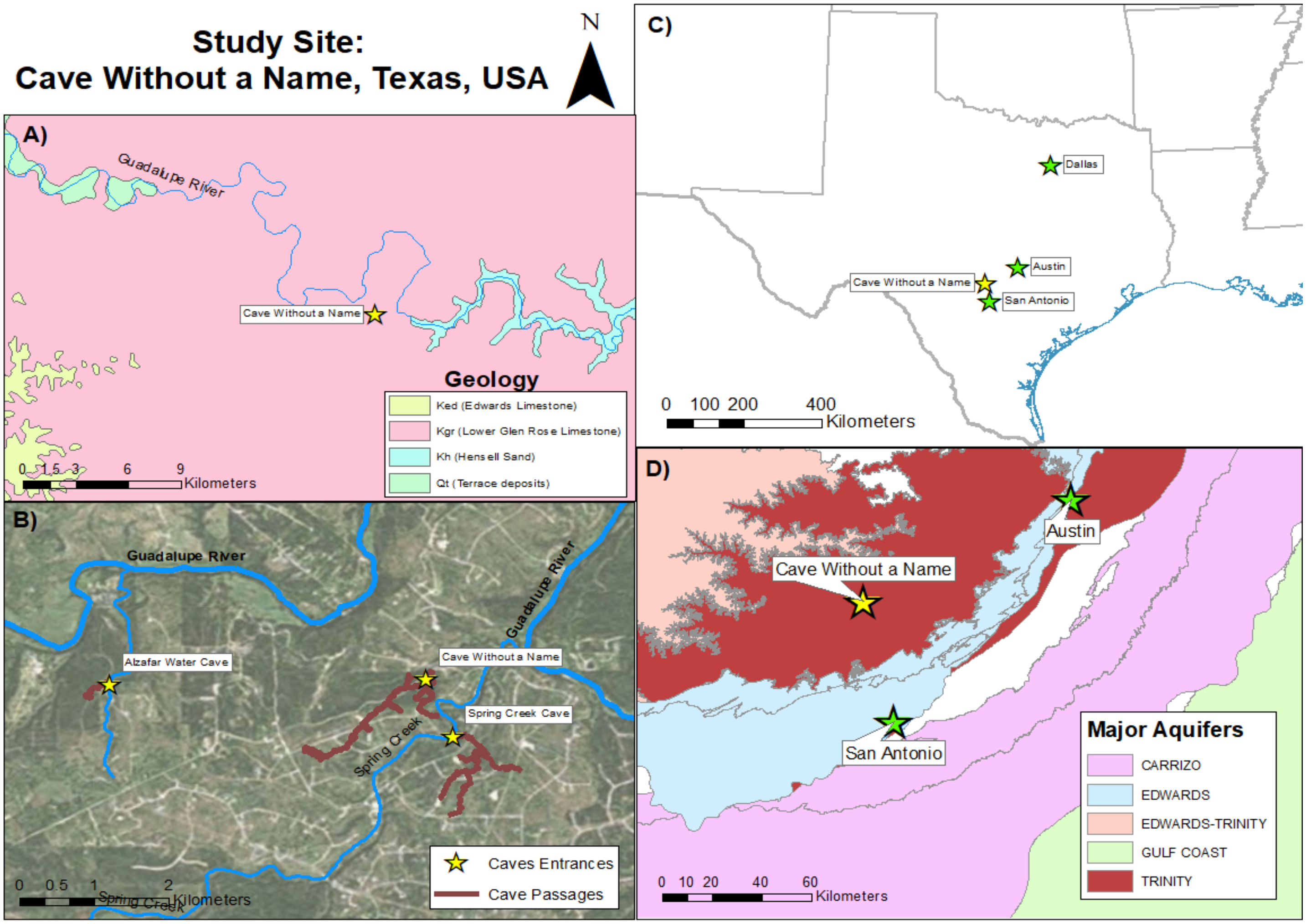

Figure 1: A) The Lower Glen Rose Limestone outcrops in the study area. B) Major caves in the study area: Cave Without a Name, Spring Creek Cave, and Alzafar Water Cave. Major streams: Guadalupe River, Spring Creek, and Sabinas Creek. C) The study area is north of San Antonio and west of Austin. D) The Lower Glen Rose Limestone is part of the Middle Trinity aquifer.

Trinity Aquifer

The Trinity Aquifer is a major aquifer that is the primary source of freshwater to Kendall and many other Hill Country counties in central Texas. Yields in the Trinity are small compared to that of the neighboring Edwards Aquifer, which yields generally better quality water at an average of 250 times more water due to its cavernous nature (Mace et al. 2000) (Jones et al. 2009). Low yields in the Trinity are concerning in times of drought due to an increase in pumping and a population growth rate that is third highest in the state by percentage increase (Kendall Co. EDC 2014). Studies by Ashworth (1983) and others agree on the vulnerability of the Trinity Aquifer in the Hill Country; increased withdrawals will not only have a negative effect on aquifer levels, but also on water quality due to intrusion of poorer quality water.

Water levels in the Trinity generally mimic surface topography in a subdued way, meaning that higher topography generally could also be expected to have relatively higher water levels. Water level maps produced show that water in the aquifer generally flows towards rivers locally and towards the southeast regionally in this area (Hunt and Smith 2010). On a local scale, the exact direction of flow becomes unclear due to preferential flowpaths through conduits and fractures, and flowpaths can be opposite regional gradients, cross over or under one-another, and may not be consistent across time and variable aquifer conditions.

Lower Glen Rose Limestone

Based on hydraulic characteristics, the Trinity Aquifer is divided into the Lower, Middle, and Upper Trinity Aquifers (Figure 2). CWAN, as well as the entire study area, lies in the lower member of the Glen Rose Limestone (LGR), which is part of the Middle Trinity Aquifer. The LGR is a Cretaceous age (145-66.5 mya), karstified limestone and is one of the most cavernous units in Texas. Stream caves in the LGR are typically long and dendritic, exhibiting rapid storm responses and drainage. The Lower Glen Rose Limestone is exposed at CWAN due to erosion by the Guadalupe River and Spring Creek and permeability is high where it is exposed. At CWAN, the LGR is either thinly or massively bedded (Veni 1991).

In the LGR, local flow is often towards rivers and springs; this movement occurs through secondary porosity, which refers to the fractures, conduits, etc. that are solutionally enlarged as chemically aggressive groundwater moves through them. Flow in these features is often high velocity and turbulent, as opposed to the lower velocities and laminar flows observed in most porous media aquifers.

Recharge to the LGR occurs primarily via rainfall directly onto the outcrop (autogenic recharge) where a portion of the water seeps into the ground through sinkholes or diffuse infiltration. Gerard (2012) used CWAN as a study site to describe recharge characteristics in the Trinity Aquifer. Using a chloride mass balance method, he calculated an average recharge rate of ~8%, which is consistent with rates reported in other studies that range from 1.5% to 11% (mean of 6%) (Gerard 2012). Using this recharge rate and measured annual discharge in CWAN's stream (~1.2 million cubic meters) from 2010 to 2012, an estimated watershed area of ~27km^2 was obtained. Recharge in this area only occurs during significant rainfall events due to high potential evapotranspiration exceeding precipitation in most cases, and environmental conditions such as moisture content, vegetation cover, and evapotranspiration all have strong influence on both the timing and amount of recharge that occurs during a storm event.

In the study area, the Cow Creek Limestone is the formation in which the majority of private wells draw water from (TWDB 2017). The Cow Creek is deeper than the LGR and the limestone units are separated by the Hensell Sand (Figure 2). The Cow Creek is capable of yielding small to moderate quantities of generally good quality water (Ashworth et el. 2001). The LGR, though capable of producing moderate quantities of water, is generally of poor quality due to higher concentrations of TDS, sodium, chloride, and sulfate.

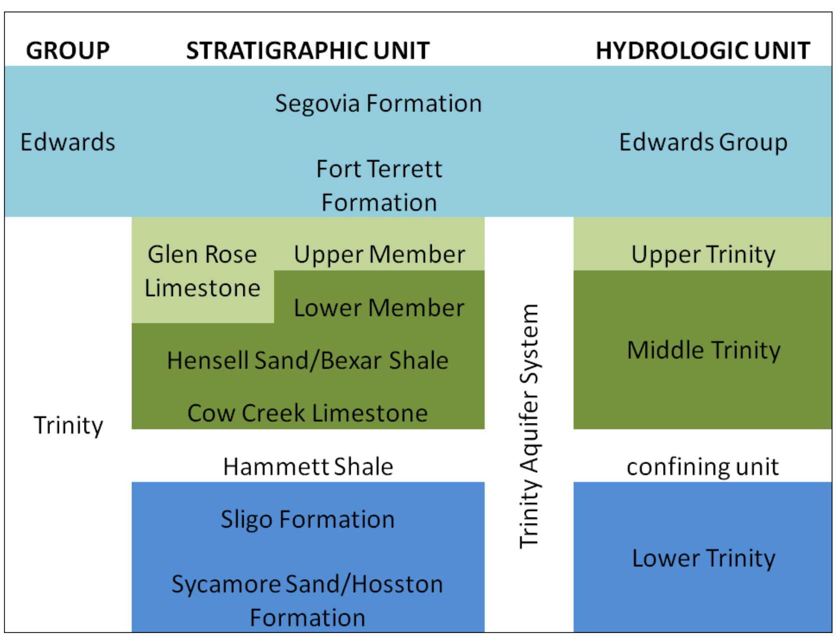

Figure 2: Jones et al. (2009) The Lower Glen Rose Limestone is in the Middle Trinity Aquifer.

Dye Tracing Background

Many methods of springshed delineation exist, and any one method may not always be better than another method (Schindel 1996). Background information, such as type of aquifer, hydrologic conditions, hydrogeologic properties, etc., are essential information for decisions about selecting which methods to use. Other important considerations are time and resources (funds, equipment, etc.). In karst systems, three methods of delineation are often used: flow boundary, balancing of discharge, and tracer testing. For this project, the flow boundary and tracer testing methods are used.

The Flow Boundaries method uses known hydrogeological features to delineate springsheds. Hydrogeological boundaries include watershed delineation, groundwater divides, fractures, faults, lithologic changes, and other natural boundaries. Anthropogenic boundaries also exist; examples are man-made lakes, or a pumping well creating a large cone of depression redirecting water flow towards it. Previous research, detailed geologic maps, and potentiometric surface maps are used to determine flow boundaries. Potentiometric maps can be misleading wells intersect deeper aquifers that are not connected with the near surface groundwater flow system (Schindel 1996). Often, hydrologic boundary mapping will overestimate the actual contributing area to a spring. This method can be used in karst aquifers that are unconfined or only locally partially confined.

The balancing of discharge method is used to determine the size of a springshed (Schindel 1996). However, it does not attempt to determine the boundaries, location, or shape of the springshed. This method compares the normal discharge of a spring in the same aquifer or geological setting to the well or spring of interest. Balancing of discharge requires detailed background information of the reference springshed base flow, and the area needs to have the same stratigraphy and structure. If the study area's geology is variable, this method is not as useful.

Tracer testing is the most reliable method of springshed delineation in in karst aquifers (Schindel 1996). Though tracing can be done using any distinctive substance such as isotopes or ions, it is most commonly done with a fluorescent dye. Simply put, tracing is performed by introducing a tracer into the aquifer at a specified location, often a recharge feature, and monitoring for the tracer at discharge locations or wells (Mull 1993). Groundwater flow boundaries, and thus springsheds, can be identified based on the direction(s) tracer travels. Tracer testing can determine general flow direction and minimum flow velocity, producing a qualitative yes/no answer to whether a recharge feature is connected to a discharge feature. Flow direction is not the exact flow path or route the tracer took to reach its destination. The velocity is determined by dividing distance by time, where distance is the straight line distance from injection site to recovery site and time is the time between injection and recovery.

In this project I use fluorescent dye as the tracer. For dye tracing to be successful, complete background information about a study area is essential. Existing groundwater models or potentiometric surface maps can help determine where to inject tracers (higher potentiometric surface) and where to place detectors (lower potentiometric surface). Predictions can be made on where water is likely going, and a hypothesis can then be tested with dye traces. Understanding structural, lithological, and hydrogeological properties of the geologic setting is also important, and provides researchers with an idea of what to expect. An example would be having a general idea of how quickly water moves through a particular formation; in karst with quick flow, the dye may only take a short amount of time (days) to be detected, while in a less permeable formation, the dye may take years to be detected. Another important piece of background information is knowing if any dye is currently in the study area's hydrology and if previous dye tracing has been performed.

Many different types of conservative, non-toxic, organic dye exist. Eosine, Sulforhodamine B, and Uranine are used in this study. These dye fluoresce at specific wavelengths so they are able to be differentiated. Activated charcoal packets are used to continually adsorb dyes from the water over extended periods of time (a time-integrated sample). These charcoal packets consist of about a tablespoon of charcoal in a mesh bag. The dyes are then released from the charcoal in the lab and quantitatively measured or detected using a scanning spectrometer (Hunt 2005). The charcoal packets allow for detection of dye over a longer period of time, as opposed to in a single sample of water, and can confirm whether dye passed through a monitoring site, even at extremely low concentrations (Johnson 2012). Collecting and replacing charcoal packets at short time intervals can quantify more precisely how fast the water moved through the system, but this requires more extensive fieldwork. An ISCO automatic sampler can be used to collect water samples at various intervals, durations, and frequencies, but is not as effective as charcoal packets at detecting dye because low concentrations in water are harder to detect. Water samples may not be as useful for detecting dye as charcoal packets because charcoal packs accumulate dye over extended periods of time when it is in extremely low concentrations in the water. However, when dye concentrations are high enough to detect directly in a water sample, they are useful for determining exact timing of dye arrival, peak concentration, and complete flushing of the dye from the system.

A ‘positive’ result is one where either a charcoal packet or water sample, after being analyzed with a spectrometer, shows an intensity peak at the same wavelength as the dye standard (Illustration 1). A positive result will give a yes/no answer as to whether the dye passed through the discharge monitoring site and a period of time during which that dye may have passed through. A charcoal packet is not ideal for determining the exact amount of dye that passed through, but can deliver qualitative results such as “very positive” or “slightly positive”. Parameters that dye tracing can determine accurately in karst systems are hydrologic connections between points in an aquifer, and the time of travel between those points.

A negative result is one where a charcoal packet or water sample shows no intensity peak at dye standard wavelengths. It is important to not draw too many conclusions based on a negative trace, especially if the dye one is testing for has not been found at any site. A negative result at all monitoring sites can indicate a few possibilities: 1) the dye is moving slowly and has not been discharged at any location, 2) the dye was diluted and unable to be detected, or 3) the dye discharged at an unknown location not being monitored. Even when tracing is performed in quick-flow conduits, a large percentage of dye is not recovered due to dilution and absorption into the rock material.

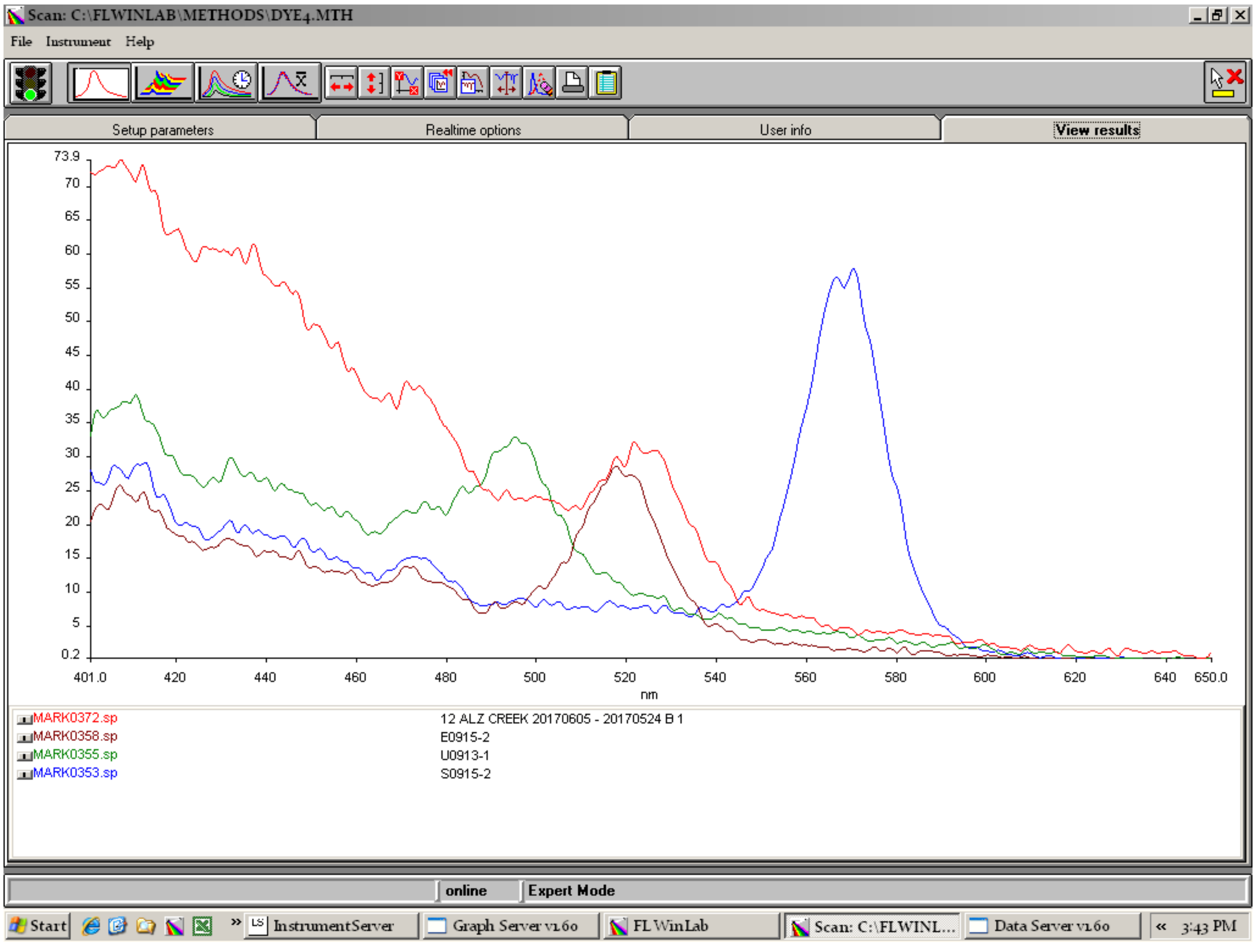

Illustration 1: Example of a positive trace shown in a spectrograph. The green, maroon, and blue lines represent dye standards. The red line represents a sample elutant. The red and maroon lines have peak at a similar wavelength, indicating a positive result.

II. RESEARCH QUESTIONS

- Where is the water in Cave Without a Name coming from and what is its springshed?
- What are the flowpaths and rate of flow in this conduit system?

III. LITERATURE REVIEW

Dye tracing in the study area has been limited to one dye trace in 1982 by Scott J. Harden in Alzafar Water Cave (Figure 2). Alzafar Water Cave is a large (though smaller than CWAN), hydrologically active cave. Alzafar Springs form a small creak that flows north into the Guadalupe River. The Harden (1982) trace was performed with 4.8 ounces of the common dye Uranine. Charcoal packets were placed at Alzafar Springs and CWAN, but at no other locations. These detectors were replaced every two weeks.

Results of that trace found that water in Alzafar Water Cave flows east to CWAN (approximately 3.8km) in 5 weeks (.12 km/day), and north to Alzafar Springs (approximately 1.7km) in one to two weeks (0.24 km/day) (Harden 1982). The multi-directional flow suggests a bifurcation in the underground stream; a groundwater divide. Harden (1982) describes the results as “somewhat surprising but understandable” (Harden 1982, 2). Karst conduits typically behave similar to surface streams in that tributary conduits join together and form larger flowpaths as they head to a spring or lower hydraulic head. This is similar to surface streams that begin as small streams in higher elevation but join together downstream forming a branch-like network.

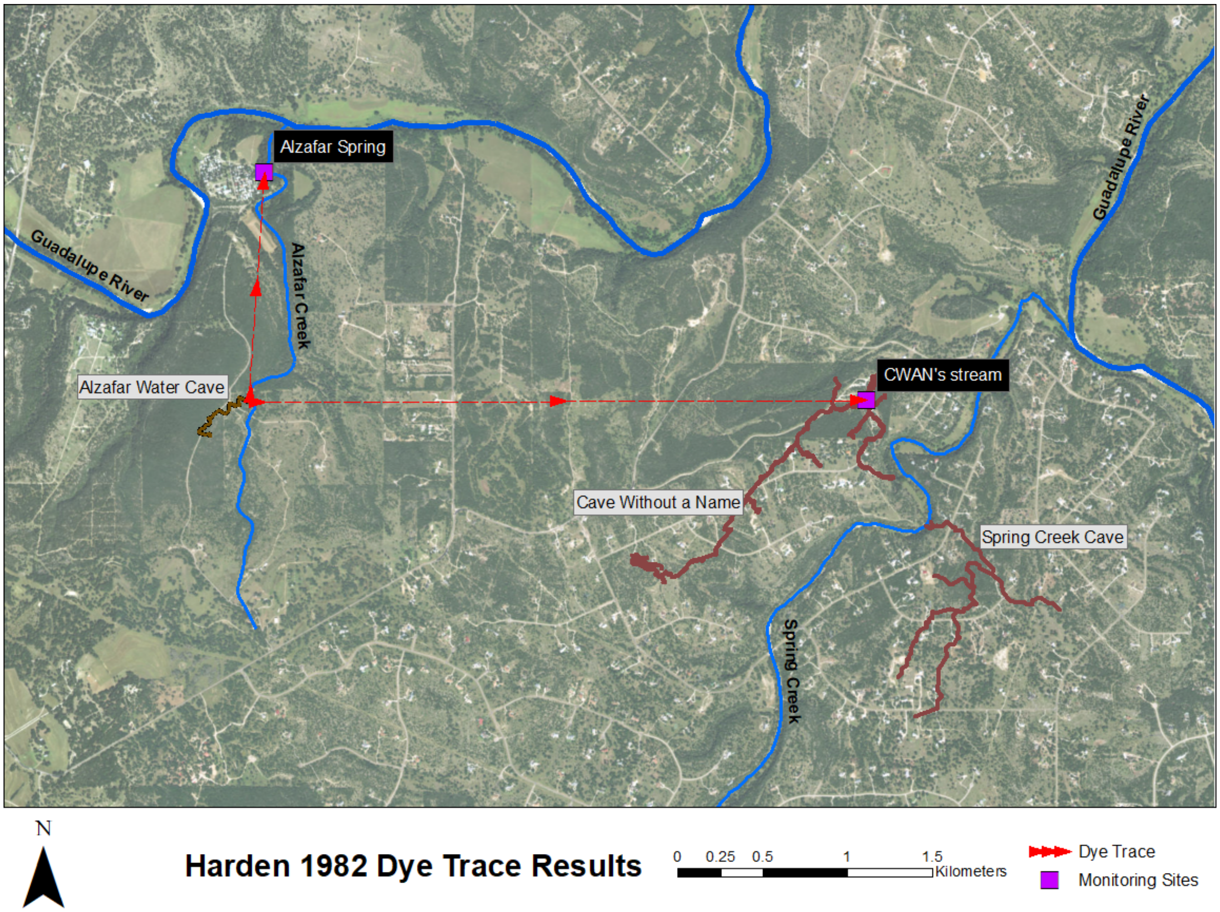

Figure 3: Harden (1982) trace showed a bifurcation (a split into two) in flow with a dye detection at both Alzafar Springs and CWAN.

Gerard (2012) also studied CWAN, and the goal of his study was to "estimate annual recharge rates and quantify how cumulative environment effects, and their timing, influence epikarst infiltration and recharge in the karstic Trinity Aquifer" (Gerard 2012, xii). He used stable isotope and hydrologic data from within the cave to create models capable of predicting if a recharge response will occur and the magnitude of that response. Chloride mass balance calculations was used and produced a recharge rate of around 8%. This information was combined with measured discharge in CWAN's stream to estimate a springshed of ~27km^2.

CWAN's main stream was found to respond to rain events when precipitation was at least 14.3mm, though rain events up to 24.1mm did not cause a response. Meaning that, after rainfall events between 14.3mm and 24.1mm, CWAN's main stream may respond, and any event larger than 24.1mm, CWAN's main stream will respond. These responses are highly dependent on antecedent environmental conditions. If soil moisture content is high, a small rain event will cause a response in the cave whereas during dry/low moisture content conditions, a rain event of the same size may not cause a response. The water discharging in CWAN's main stream after a rain event is not necessarily from the rain event, but could be residual water already stored in the aquifer being pushed through by the newly infiltrating rain water. Though the research conducted in this paper's dye tracing study does not deal with drip rates and discharge amounts, precipitation likely plays a role in the velocity of dye movement through the groundwater system.

Markowski (2016), like Gerard (2012), was also a graduate student at Texas State whose thesis was focused on CWAN. His research is similar to mine in that we both focused on conduit-dominated flow in a karst system. Particularly, the main stream in CWAN was a point of focus as cave streams provide an ideal location for sampling waters transported through a karst system. The cave stream integrates basin-wide sources ranging from fast flow in conduits to slow flow through the bedrock matrix" (Markowski 2016, x). This integration is relevant to dye tracing because the dye, if moving in the direction of the cave, is highly likely to end up in the cave stream. Markowski (2016) used a large dataset of high frequency sampling across storm hydrographs to determine how the cave stream responds to storm events. Five storms within a single year were used to assess this relationship. Just like Gerard (2012), environmental conditions pre-storm event heavily influenced the response of the cave stream. Evapotranspiration, soil moisture, and cave stream discharge were the primary factors affecting stream response. Relatively wetter conditions (high soil moisture, for example) correlated with the cave stream responded to storm events. Along with discharge, dissolved and particulate loads varied across storm events. For my dye tracing study, this would imply that dye traces conducted during wet conditions or during/just before storm events will result in relatively high flow velocities. Karst is heterogeneous in nature due to preferential flowpaths, so it is not surprising that cave stream discharge is affected by environmental conditions. Markowski (2016) highlights this connection between hydrology and environmental conditions in karst research by stating that “a single storm event cannot be used to accurately describe how a karstic groundwater system responds to storm events under a wide range of hydrologic conditions” (Markowski 2016, xi). In the same line of thought, a single dye trace should not be used to represent to entire system.

Childre (2013) performed a study involving dye tracing near Magic Spring about 16.5km east of CWAN. This study’s geologic setting is quite similar to the CWAN setting in that it is also in the Lower Glen Rose Limestone and near the Guadalupe River. The major cave, CM Cave, is dendritic and connected to Magic Spring. CM Cave is recharged by sinkholes and other caves overlying CM Cave. These are, once again, similar to CWAN and method of recharge. All four Childre (2013) dye injections were performed in caves and all four dye traces were detected at Magic Spring. Behavior at Magic Spring indicates two flowpaths upstream from CM Cave. Meaning that “recharge enters the groundwater system at multiple focused locations” (Childre 2013, 4). The specific conductance response curve indicated multiple recharge locations as well. During storm events, Cool Creek Cave can overflow and partial flow will continue as surface water. During this study, groundwater piracy occurred across surface water drainage areas during two of the dye traces.

Smith et al. (2005) compared groundwater modeling with dye tracing in the Edwards Aquifer. The Edwards is a well-studied karst aquifer with similarities to the Trinity as it is also a limestone and dolomite aquifer of the Cretaceous age. Tracer tests were done in the Barton Springs (22 injections) and San Antonio (14 injections near San Marcos) segments of the Edwards Aquifer and its recharge zone. Dyes were injected into caves, sinkholes, and other recharge features and monitored for at springs, creeks, and wells. Results showed preferential flow in conduits and flow directions generally agreed with potentiometric surface maps. In this study, they recognized that dye tracing is inherently biased towards conduit flow and models are biased to matrix flow.

Zara Environmental described the interconnection between the Trinity and Edwards aquifers near San Antonio with dye tracing (Gary et al 2011). The injections were done at Camp Bullis, about 30km south of CWAN, and results showed rapid flow velocities in the south to southeasterly direction directly from the Trinity into the Edwards. Complications arose during low flow with dye recovery being lower

The Edwards Aquifer Authority has done dye trace studies in several areas. One of these was done in northern Bexar County, directly south of Kendall County where CWAN is located (Johnson et al. 2010). Uranine, Eosin, and Phloxine B dyes were used. These results also showed rapid groundwater velocities and “excellent communication” between the Edwards and Upper Trinity, CWAN is in the Middle Trinity (Johnson et al. 2010, iii). The tests showed a vulnerability to contamination not limited to obvious karst features (like caves, sinkholes, fractures), as one of their injection sites was a square meter area, thinly covered in soil and without any observable karst features. During different or changing aquifer conditions, flowpaths shifted both vertically and laterally.

IV. METHODOLOGY

Background Methods & Sampling

During this study, protocols from the Ozark Underground Laboratory, Crawford Hydrology Lab, and verbal instruction from EAA and Texas State staff were followed, with adjustments made for the study area, as appropriate. Dye was monitored for at twenty discharge sites: 8 spring orifices, 6 streams (including spring-fed creeks and the Guadalupe River), 5 private wells, and the CWAN main stream. These discharge sites were monitored using charcoal packets before the first dye trace occurred to determine whether a substance with the same wavelength as a dye was already in the water. No such interference was found.

Each site was continuously monitored for dye with about a tablespoon of activated charcoal placed in mesh packets, which were placed in the water and securely attached to rock, gates, roots, etc. using steel wire or strong plastic string. Each packet was tagged with site ID number, site name, and deployment date. These packets were replaced at 1-4 week intervals, depending on time since dye trace, ease of access, and site importance. At each site visit, the charcoal packet and tag were placed in individual plastic bags labeled with site and retrieval date, and were either taken directly to the Edwards Aquifer Authority's lab for analysis on the same day, or were dried and stored in a cool, dark cabinet space for 1-2 weeks until being taken to the lab.

A 24-bottle ISCO automatic water sampler was placed in CWAN to collect samples from the cave stream at either 8- or 12-hour intervals.

Lab Analysis

At the EAA's lab, charcoal packets were opened and the charcoal was placed into individual, labeled small plastic cups. An eluent that releases the dye (95mL isopropyl alcohol and 5g potassium hydroxide) was poured into each cup, enough to completely cover the charcoal, and allowed to sit for 1+ hours. After extraction, the eluent and dye mixture is called an elutant. The elutant is transferred with a plastic, single-use dropper into a labeled vial where it is ready for analysis (Illustration 2).

Illustration 2: Sydney Treviño transfers the elutant into a vial where it is ready for analysis.

Before the sample elutants are analyzed, dye standards and deionized water were analyzed for comparison. All samples and standards were analyzed at the EAA's Camden lab using a synchronous scanning spectrometer. Using this machine provides "low detection limits and reliable dye analysis" (CHL 2016, 10). The spectrometer produces a spectrograph in which dye standards will have intensity peak at specific wavelengths and deionized water has no peaks. Spectrographs from elutant samples can be compared to standard spectrographs and if an elutant peak occurs at the same wavelength as a dye standard, then a positive result is recorded. If the elutant sample spectrograph does not exhibit a peak where the dye standard peak occurs, and instead matches the deionized water spectrograph, then a negative result is recorded. Post analysis, the elutants are stored together in a cool, dark, cabinet.

Dye Injection

Dye traces were performed using methods appropriate for the recharge feature injected into. Liquid dye solution was stored in sealed plastic bottles at room temperature and away from sunlight. Before dye injection, the sites were "primed" with water to decrease the chance of dye absorption into rock and soil; post-dye injection, the dye was flushed into the recharge feature with water. While handling dye, latex gloves were worn by the handler and post-injection the plastic bottle and gloves are placed in a plastic bag and disposed of. Care was taken to not get dye on skin or clothing. The amount and type of dye was site specific, as sites farther from CWAN required more dye due to dilution. The amount of dye for the first two traces were based on recommendation from EAA and Texas State staff. Subsequent traces were based on the results from the first traces. If there were concerns about discoloring private wells, a small amount of dye was initially used, with the amount increasing if the dye was not detected. If multiple traces were performed simultaneously, different dyes were used. The same dye can be re-used at a later time after the dye is found to undetectable at all monitoring locations. If a dye was used and not recovered, then that dye was not used again.

All recharge and discharge features' GPS locations were recorded and stored in a GIS (Figure 4). These recharge and discharge features were found primarily by talking with local landowners as the majority of land in the study are is private property. Speaking with CWAN staff and conducting field surveys by foot and kayak were are responsible for the discovery of karst features. After recharge features' locations and characteristics were compiled, injection sites were determined by proximity to wells/water hoses, roads, and type of feature. Recharge features varied in characteristics and included such karst features as caves, large sinkholes by passing the epikarst, small holes/cracks in the epikarst, slumps, and losing streams.

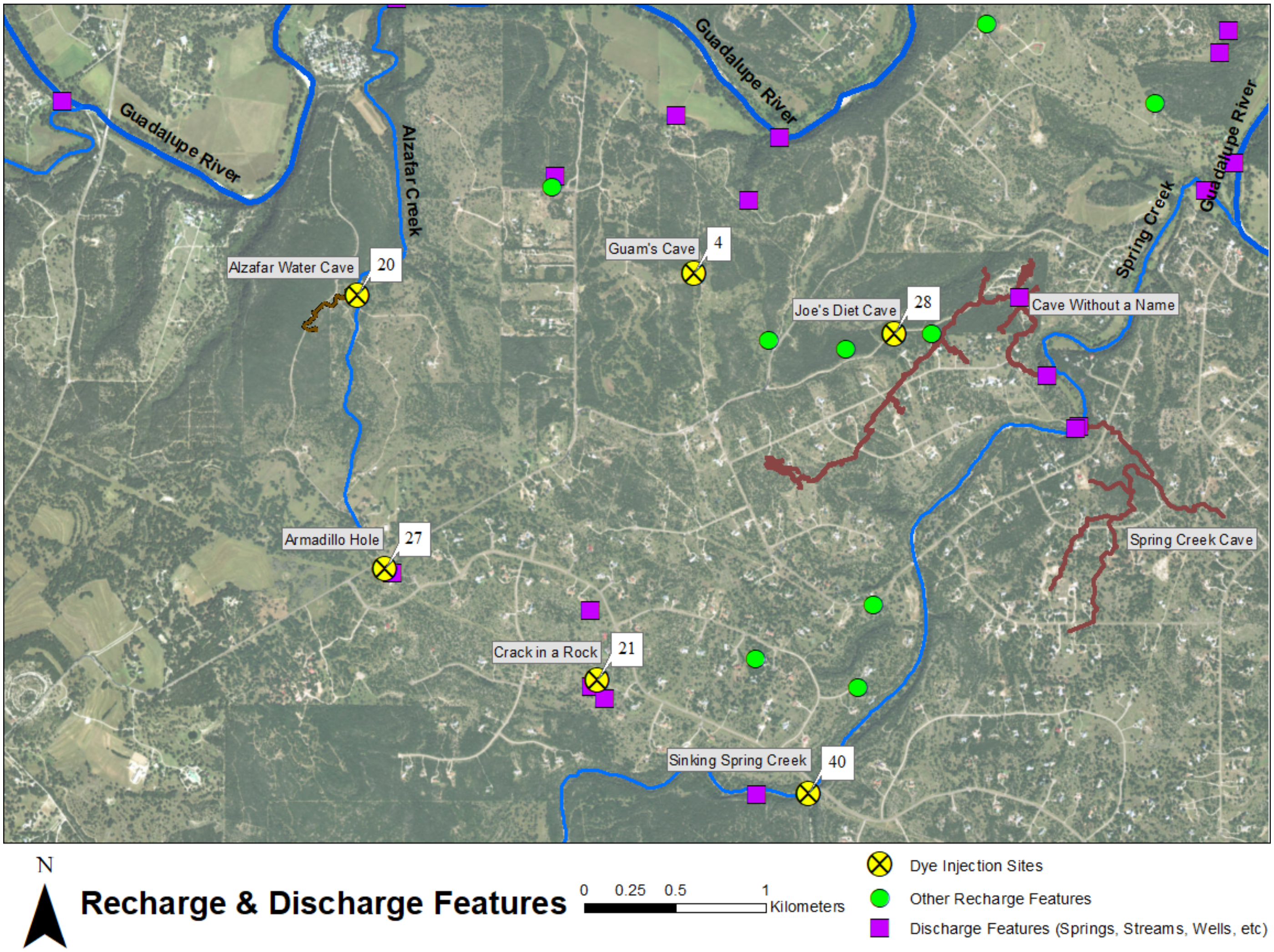

Figure 4: Locations of recharge (green circles), injection sites (yellow circles with black X), and discharge features (springs and wells) in the study area.

Site 28 "Joe's Diet Cave"

On November 22nd, a trace was performed by injecting dye into a small cave (Illustration 3). Site 28 "Joe's Diet Cave", is a known direct recharge feature in a roadside ditch. This site was selected as it was expected to contribute to CWAN and would be a good first trace to confirm injection and monitoring methods. This was estimated to be about 6m in depth and 1m in diameter, though a visual inspection could not occur due to a large boulder on top of the feature. Site 28 is 0.8km southeast from the CWAN (Figure 4) monitoring site and was primed with approximately 500 gallons of water pre-injection, and flushed post-injection with 1,500 gallons, using the Bergheim VFD's water truck. 150g of Sulforhodamine B was used.

Illustration 3: Sulforhodamine B is injected into Site 28 "Joe's Diet Cave" with help from the Bergheim VFD.

Site 4 “Guam’s Cave”

On November 22nd, another trace was performed by injected dye into a small cave or large sinkhole (Illustration 4). Site 4, “Guam’s Cave” (unofficial name), is a large recharge feature similar to size 28, approximately 6m deep and 2m in diameter, and 1.8km east from the CWAN monitoring site (Figure 4). This site was found by communication with the landowner. It was selected due it being an obvious karst feature (an open cave entrance), its proximity to a road, and relationship to CWAN. A fracture in the recharge feature was visible and oriented in a direction trending toward CWAN. A water truck operated by the Bergheim VFD was used to prime this feature with approximately 2,000 gallons of water prior to injection and flushed with another 2,000 gallons. All water was pumped directly from the Guadalupe River. 180g of Eosin was used.

Illustration 4: Eosin is injected into Site 4 "Guam's Cave" with help from the Bergheim VFD.

Site 27 "Armadillo Hole"

On January 22nd, a dye trace was performed at a small recharge feature called "Armadillo Hole" (Illustrations 5 & 6), this site was farther from CWAN than the previous traces. This site was found after communication with the landowner. It was selected because it was a small feature, unlike the features for the first two injections, had easy access to a private well, and was about twice the distance from CWAN compared to the first two injections. Due to proximity to residential housing and concerns about well discoloration, a small amount of dye was initially injected before a larger amount of dye was injected 14 & 19 days later. Nearby wells were monitored for any sign of dye before proceeding with the larger amounts.

Site 27 is a very small recharge feature in epikarst, which is the "uppermost part of the bedrock" (Schindel 1994), and is approximately 0.5m deep and 0.5m in diameter. This site is 3.9km southeast from CWAN (Figure 4). Due to its proximity to a house, a garden hose was used to prime the feature by adding water for approximately 2 hours pre-injection and then flushed for another 2 hours post-injection. 30g of Uranine was used. On February 5th this site was re-traced with 165g of Uranine and again re-traced on April 22nd with 3,740g of Uranine. During each re-trace, the dye was flushed with a garden hose for 3-6 hours.

Illustration 5: Site 27 "Armadillo Hole" was injected with Uranine and flushed with a garden hose.

Illustration 6: Uranine sits in Site 27, slowly infiltrating into the surface.

Site 21 “Crack in a Rock”

On January 22nd, another trace was performed at a small recharge feature called “Crack in a Rock” (Illustration 7), this site near site 27 (Figure 4). This site was found and selected for the same reasons as Site 28. Due to proximity to residential housing concerns about well discoloration, a small amount of dye was initially injected before a larger amount of dye was injected 14 & 90 days later. Nearby wells were monitoring for any sign of dye before proceeding with the larger amounts.

Site 21 is a recharge feature which appears as a crack in rock and is approximately 1.5m long, 0.2m wide, and 1.0m in depth. This site is 3.2km southeast from CWAN and 1.3km southwest from site 27. Also located near houses, a small amount of dye was initially used. During the first trace, 19g of of Sulforhodamine B was used, primed with a garden hose at full strength for 2 hours and flushed for 2 hours. This site was re-traced at February 5th with 72g of Sulforhodamine B and again on April 21st with 729g of Sulforhodamine B; the dye was flushed for 3-6 hours.

Illustration 5: Site 21 "Crack in a Rock" was injected with Sulforhodamine B and flushed with a garden hose.

Site 40 “Losing Spring Creek”

On March 24th, at “Losing Spring Creek”, one trace was performed at site 40 in Spring Creek, a gaining and losing stream. This site was found during a karst inventory survey. It was selected as Spring Creek is a major hydrologic feature and the hypothesis that it contributes to CWAN needed to be tested. This creek sinks in a gravel bed 3.1km from the CWAN monitoring point (Figure 4). At the end of the losing section of the creek, a small hole was dug and a channel was formed to direct flow into the hole. 200g of Eosin was dumped directly into this hole and slowly was flushed into the hole and under the creek bed (Illustration 8). Spring Creek is considered a local hydrologic boundary and its watershed is approximately half of the study area.

Illustration 6: Site 40 "Losing Spring Creek" was injected with Eosin and flushed by stream flow.

Site 20 “Alzafar Water Cave”

On May 10th, a trace was performed at site 20, “Alzafar Water Cave” (Illustrations 9 & 10). This cave is similar to CWAN in that it contains an active stream. Alzafar Water Cave is 3.7km due east from CWAN (Figure 4). This cave was known and selected as it is a major hydrologic feature in the study area. This cave was entered and the cave passage was followed for approximately 100m. At this point and during hydrologic conditions at the time, the cave passage continues but the stream stops. Water was discovered to be slowly losing into the cave floor through mud and gravel. A container of 306g of Eosin with a rope attached was carefully placed on a ledge above the losing section of the cave stream. From approximately 15m upstream, the rope was lightly pulled in a way to tip the bottle over, spilling the Eosin into the losing section of the cave stream.

Concerns about whether enough dye was used was discussed, and after not finding the dye in Alzafar Creek after two weeks, a second trace consisting of 3,309g of Eosin was injected into Alzafar Water Cave on May 28th (Figure 5). This injection was done further back into the cave about 200m from the entrance. At this specific site, water was again pooled but in a smaller passage. During/after a rain event, it is likely this passage will fill with flowing water.

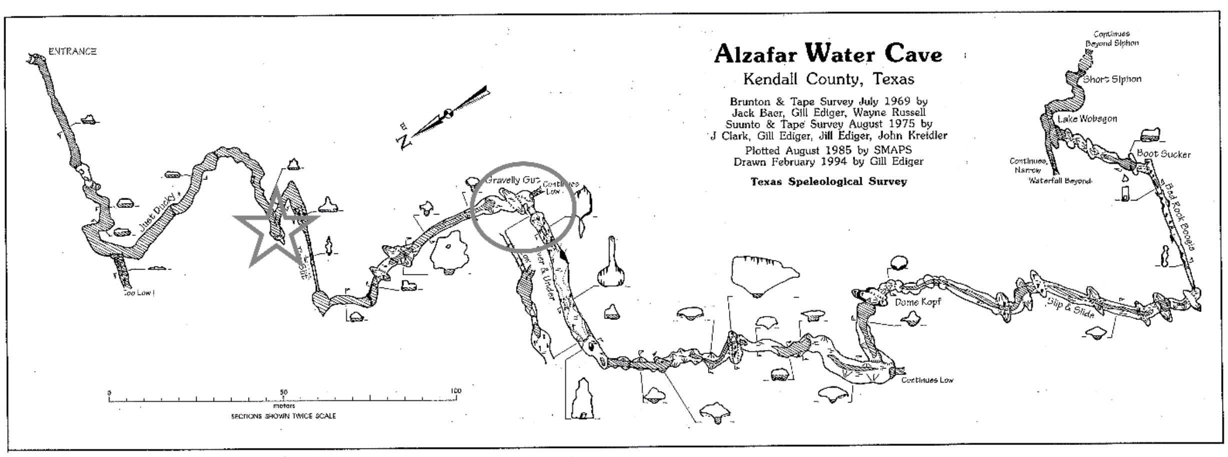

Figure 5: Map of Alzafar Water Cave showing initial dye injection site indicated by a star and second injections site indicated by a circle. Cave map is courtesy of Texas Speleological Society.

Illustration 7: A tributary contributing flow into Alzafar Water Cave's main conduit.

Illustration 8: Alzafar Water Cave was injected with Eosin.

V. RESULTS & DISCUSSION

Site 28 “Joe’s Diet Cave”

The first detection of Sulforhodamine B dye (injected at Site 28 November 22nd, 2016) dye occurred on November 26th at 11:30 and was visually seen in the cave stream by Cave Without a Name tour staff (Figure 6). This dye traveled at an approximate minimum velocity of 0.20km/day. A water sample at 14:00 the same day confirmed this sighting and was also the time of peak dye concentration passing through the cave. Sulforhodamine b was also detected at the mouth of Deadman’s Cave by water sample on December 1st and confirmed by charcoal packet; this result is unsurprising as Deadman’s Cave is the spring discharge for the CWAN main stream. Deadman’s Cave flows into Spring Creek and a charcoal packet at the mouth of Spring Creek just before it joins the Guadalupe River detected Sulforhodamine B between December 1st-8th.

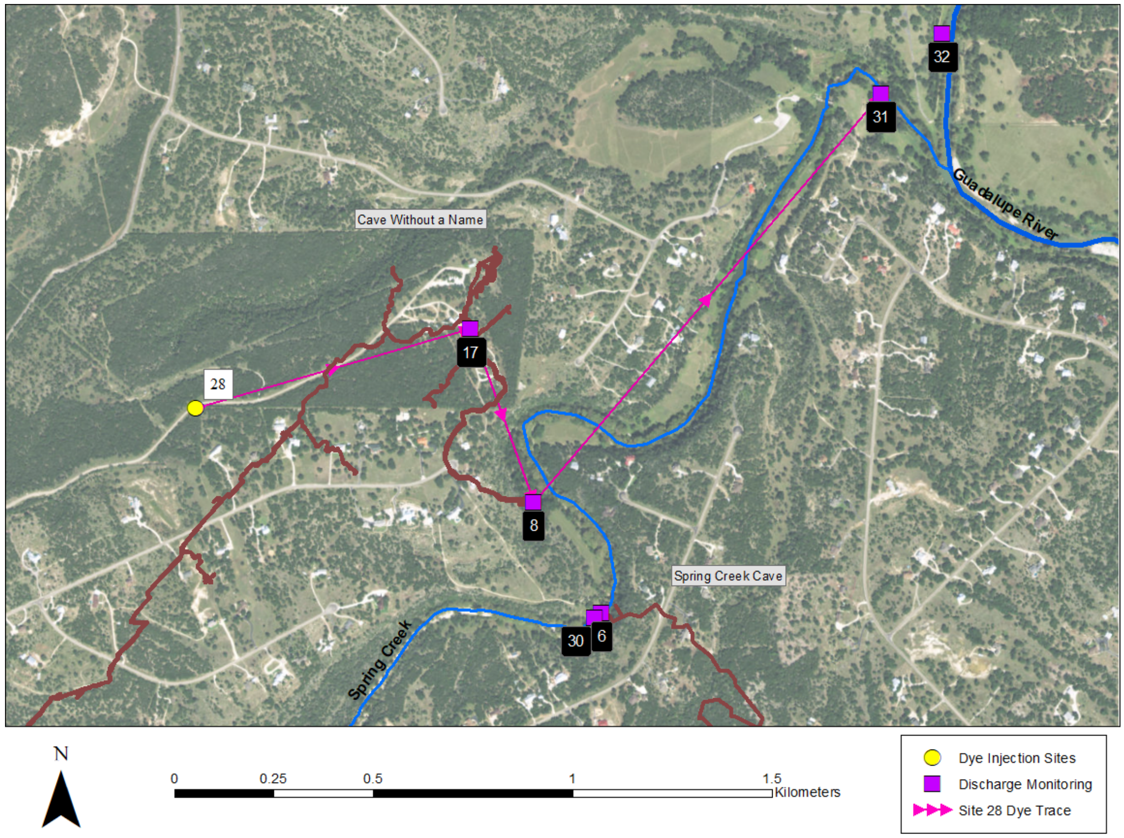

Figure 6: Dye from Site 28 was detected in CWAN (Site 17), Deadman's Cave (Site 8), and in Spring Creek (Site 31).

Site 4 "Guam's Cave"

Site 4 was injected with Eosin on November 22nd, 2016. Though at a location 1.8km from CWAN, the results for this trace mirrored what occurred at the trace done at site 28 the same day. Eosin was found in CWAN and first detected by water sample on December 4th at 16:00, peaked on the 5th at 08:00 (Figure 7). These results were confirmed by charcoal packet, as well as by visual inspection by cave tour staff. The Eosin moved through the ground at an approximate minimum velocity of 0.15km/day. Eosin was also detected at Deadman's Cave between December 1st-8th and at the mouth of Spring Creek also between December 1st-8th. As shown in Figure 7, flow from the inject site crosses a watershed boundary east while surface water would flow north from the same location.

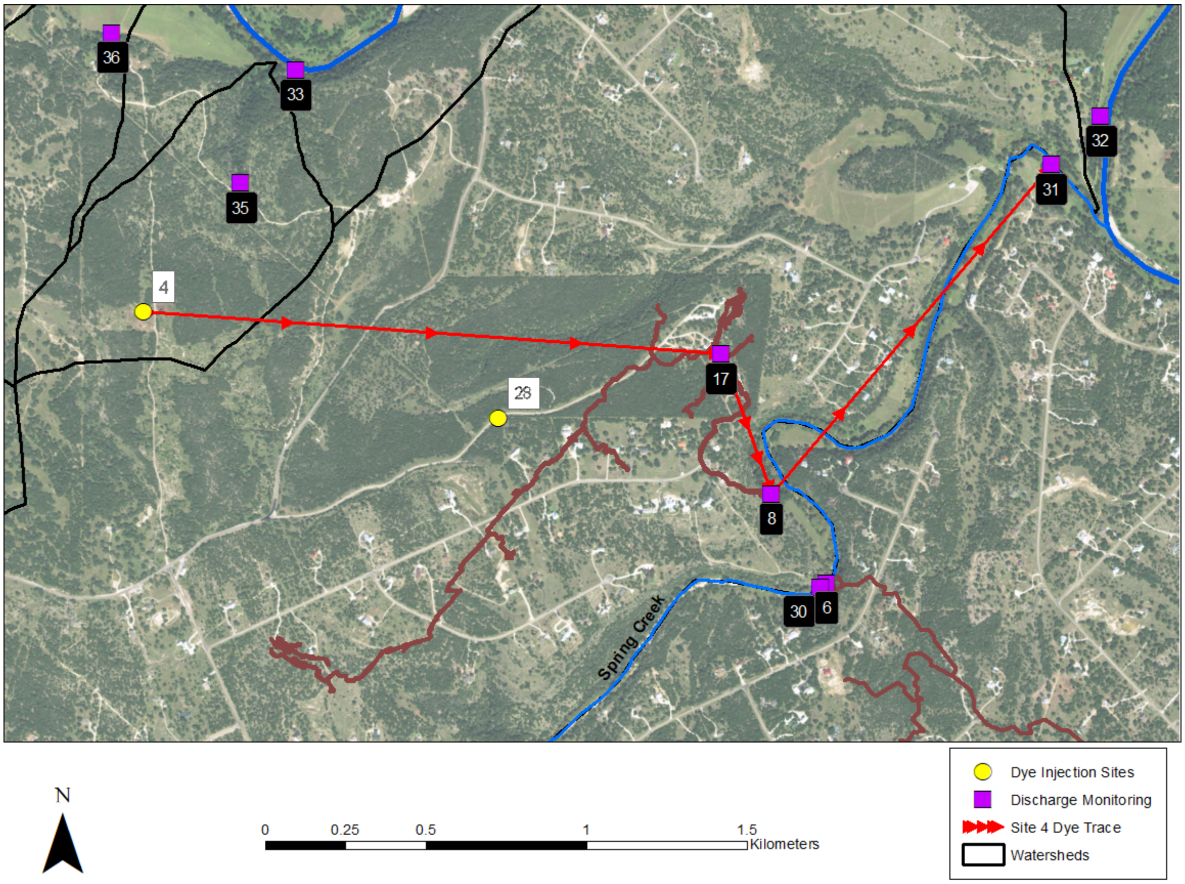

Figure 7: Dye from Site 4 was detected in CWAN (Site 17), Deadman's Cave (Site 8), and in Spring Creek (Site 31).

Conduit Flow – Sites 28 & 4

Results from injection sites 4 and 28 suggests preferential flow through conduits. The dye from either trace appeared only in CWAN, Deadman's Cave, and the mouth of Spring Creek. There is no evidence for bifurcated or diffuse flow as the dye arrived in CWAN as one body with a single peak in the traces from both sites. As mentioned, both sites are deep open conduits and dye injection likely bypassed the topsoil and epikarst flowed directly into major conduits. Dye velocity for both traces was also similar. These results are unsurprising considering the karstic Lower Glen Rose Limestone outcrops in the study area and is characterized by high permeability and conduit flow due to dissolution. Local groundwater flow is to the east/southeast, similar to regional flow. Of note, the flowpath from site 4 crosses surface watersheds, illustrating that surface water and groundwater in the same geographic location often flow in different directions. Groundwater flow is determined by hydraulic head (pressure gradient) or dye tracing methods, while surface water flow is determined by gravity and topography.

Site 27 “Armadillo Hole”

Uranine was injected at Site 27 on January 22nd and again on February 5th and April 21st. The dye was found by charcoal packet at a small seep 1.4km southeast of the injection site, at a gaining section of Spring Creek 2.4km southeast of the injection site, and at another Spring Creek site 2.7km downstream from the previous Spring Creek site just before the entrance to Spring Creek Cave (Figure 8). These three sites’ charcoal packets were deployed from April 12th-21st. The dye found at these sites came from either the January 22nd trace or the February 5th trace and traveled at a velocity between 0.02km/day and 0.03km/day to either site. Between April 10th-21st this area received 53.1mm of precipitation (Figure 8), enough that the typical gaining/losing spring-fed Spring Creek had continuous flow in typically dry reaches. Flow velocities are difficult to calculate from this trace due to multiple injections and length of time before a positive result. Finding the dye in Spring Creek was not unexpected as surface water flow in the same direction and Spring Creek is a major hydrologic feature in the study area. The length of time it took to arrive in Spring Creek suggests the recharge feature (site 27) does not connect to a major conduit or preferential flowpath like the previous two traces at sites 4 and 28. This recharge feature, unlike the features at sites 4 and 28, was small and not obviously connected to any fractures or significant geologic features.

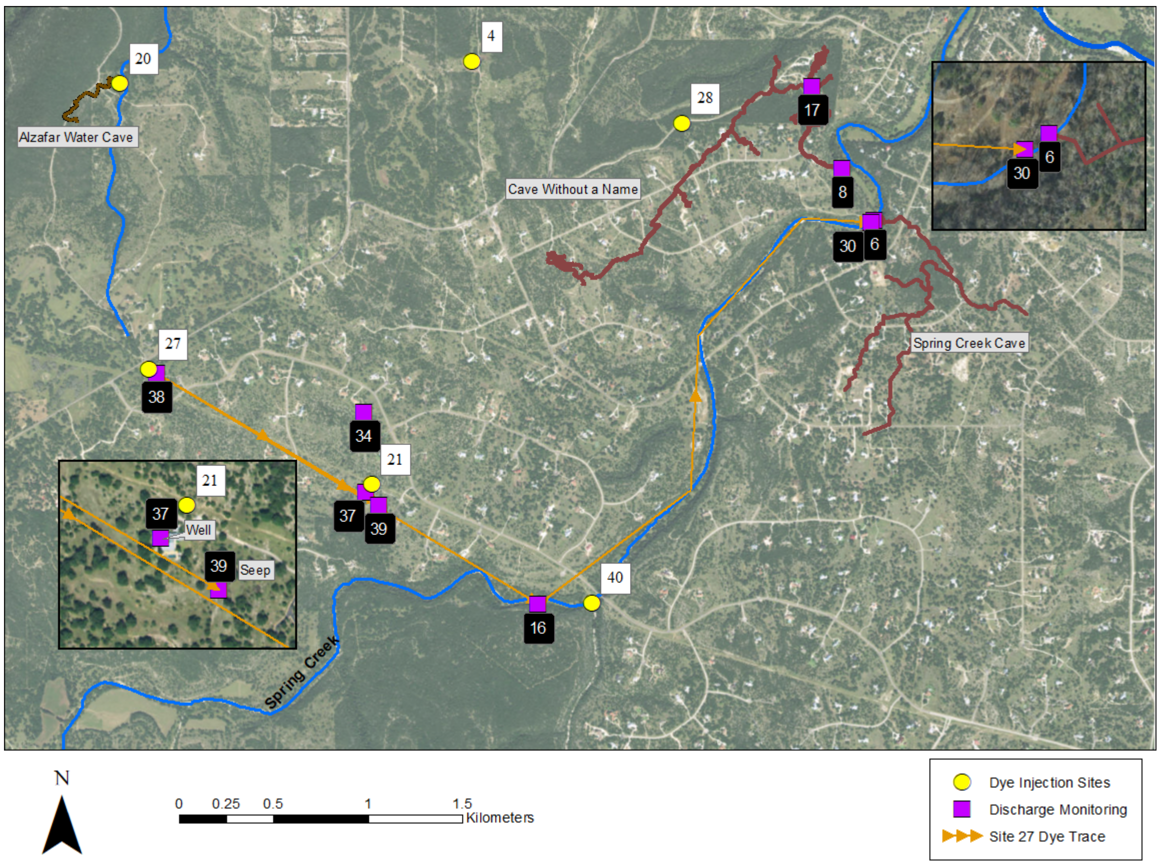

Figure 8: Dye from Site 27 was detected at a small seep (Site 39) and in two locations in Spring Creek (Sites 16 & 30).

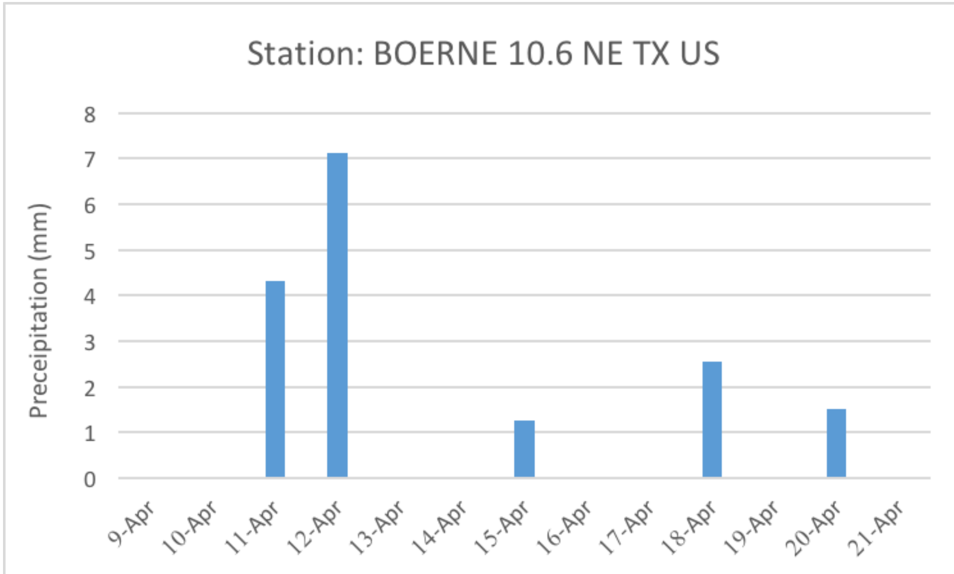

Figure 9: A weather station within the study area recorded a large storm event during the sampling period in with dye from site 27 was detected. Smaller events occurred during the sampling period. Data provided by NOAA (2017b).

As mentioned, a positive result was found in a very small (and at times dry) seep 1.4km from the injection site and in the direction of Spring Creek. The lengthy travel time and appearance at a seep unconnected to any major conduit could indicate the dye injected into site 27 remained near the surface in a perched aquifer at the base of the epikarst. The epikarst zone is difficult to precisely identify, but is described as the "uppermost weathered zone of carbonate rocks with substantially enhanced and more homogeneously distributed porosity and permeability, as compared to the bulk rock mass below" (Klimchouk 2004). This homogeneous and perhaps diffuse flow could account for the dye arriving at the small near-surface seep. The perched aquifer contains pooled water that slowly moves downwards through fissures and smaller distributional features, so the epikarst can potentially store water for quite some time (Gerard 2012). This slow movement explains the 2+ month period post dye injection when there was no sign of the dye. A large precipitation event just before charcoal packet collection likely increased the velocity of epikarst flow, pushing the shallow groundwater towards small seeps and to Spring Creek and explaining why all three sites the dye was found at showed a positive result during the same week long period.

Site 21 "Crack in a Rock"

Site 21 was injected with Sulforhodamine B on January 22nd and again on February 5th and April 21st. To date, this dye has not been recovered. Site 21 is similar to site 28 in that the recharge feature is small and in the epikarst. The dye may still be in the epikarst, slowly moving towards Spring Creek or vertically down in the Lower Glen Rose Limestone. Other possible explanations are that the dye was diluted and was undetectable, discharged in areas not being monitored, or discharged at a pooled surface water feature and was quickly decayed by sunlight. Due to the variable properties of karst systems (Miller 1999), it is not uncommon for sites within a study area to behave dramatically different from each other, as evidenced in the relatively quick flow from sites 4, 28, and 40 and the slow from from site 27. One of the positive results from the dye trace from site 27 is only 115m from site 21 (see Figure 8) and continued in the same southeasterly direction into Spring Creek. From this information, the dye from site 21 is *likely* also traveling in the same direction.

Site 40 "Losing Spring Creek"

Site 40 is a losing section of Spring Creek where flow enters the creek bed through gravel. Losing streams are a common feature in karst landscapes where the water table is below the bottom of the stream channel. This site was injected with Eosin and found at the entrance to Spring Creek Cave (Illustration 11) 2.5km to the northeast (Figure 10). The Eosin traveled quickly through the ground at a minimum velocity of 0.36km/day. Dye was not found just upstream of Spring Creek Cave, meaning the dye left the creek bed, entered Spring Creek Cave, and later came out of Spring Creek Cave and entered Spring Creek. As shown in Figure 10, Spring Creek Cave has two tributaries extending towards the injection sites and one of them is the likely path the dye took.

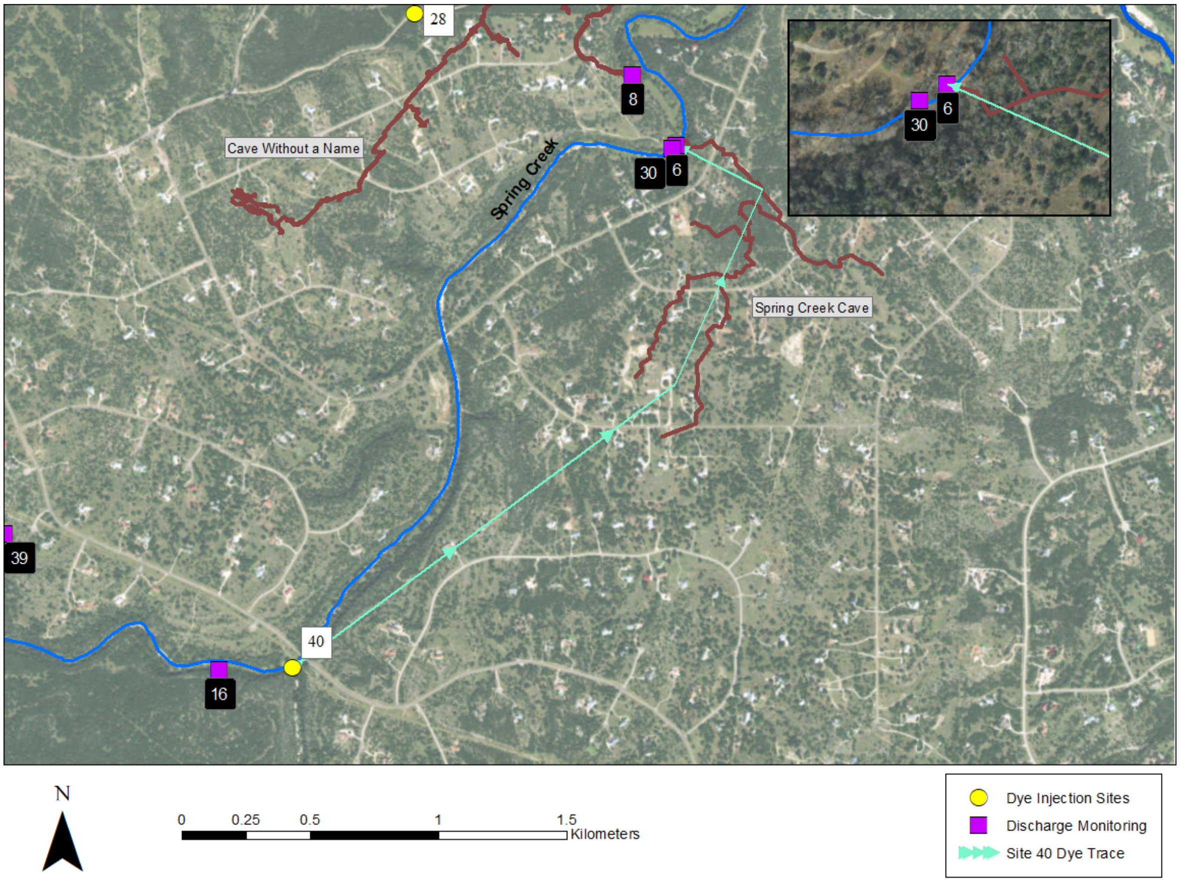

Figure 10: Dye from Site 40 was found at the entrance to Spring Creek Cave.

Illustration 9: Entrance to Spring Creek Cave.

Site 20 “Alzafar Water Cave”

Site 20, Alzafar Water Cave, was injected with Eosin on May 10th and again on May 28th with an increased amount of dye. This dye was detected 1.63km north in Alzafar Creek at its confluence with the Guadalupe distance (Figure 11). Though the detection came after the injection of the second dye, the detection likely came from the first trace as the detection of this dye was mid to low in strength. If from the firs trace, the dye traveled between 15-26 days at a velocity between 0.06km/day & 0.11km/day. If the dye is from the second trace, it would have had to arrive in less than 8 days at a minimum velocity of 0.20km/day. The previous 1982 trace found that dye injected into the cave appeared at Alzafar Springs (300m upstream from Alzafar Creek & the Guadalupe River) in 7-14 days at a velocity between 0.19km/day & 0.10km/day.

In the Harden (1982) trace, approximately 350% more precipitation occurred just before (10 days) and during sampling (6 weeks) compared to my study (NOAA 2017a). As seen from the results at site 27 “Armadillo Hole”, and through research by Gerard (2012) and Markowski (2016), precipitation events play a significant role in groundwater movement in the CWAN study area. Guadalupe River discharge, an indicator of antecedent conditions, was approximately the same during the course of both traces (USGS 2017).

Other sites, such as Sabinas Creek (site 19) to the west and the Guadalupe just upstream from Alzafar Creek (site 41), did not detect dye. The dye likely traveled through preferential flowpaths (like Alzafar Water Cave) discharging at Alzafar Springs, entering Alzafar Creek and continuing to flow north to site 12.

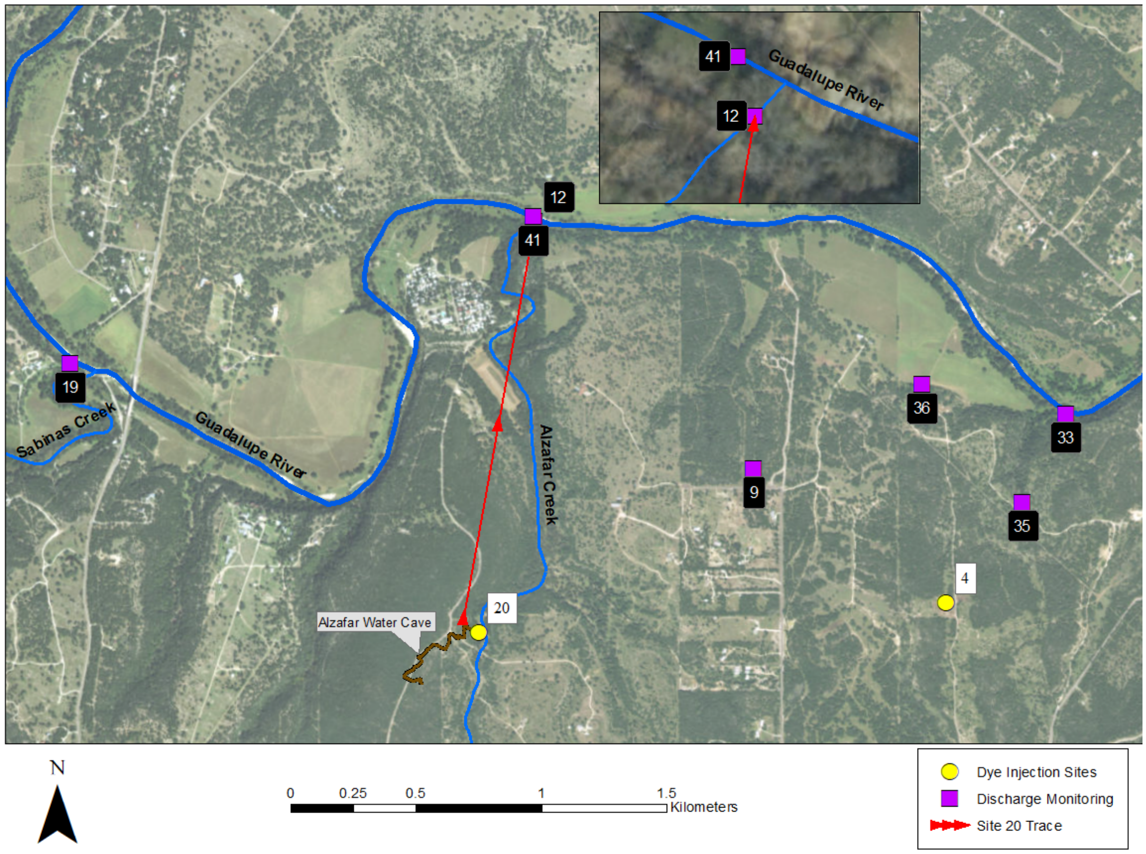

Figure 11: Dye from Site 20 was detected in Alzafar Creek (Site 12).

General Discussion

As described in the methodology section, many types of karst recharge features were included in this tracer study, ranging from large open fractures or small vertical shafts to small sinkholes in the epikarst, as well as an active water cave and a losing stream. Monitoring sites were spread throughout the study area in an attempt to detect the dye and accurately determine flow direction and velocity; these sites included a major river, spring-fed creek, springs, wells, and an active cave.

This dye trace study can be compared with other studies done at CWAN and the neighboring Edwards Aquifer. Childre (2013) was a dye trace conducted in the Lower Glen Rose Limestone and is first described in the literature review section of this paper. Flow was found to cross watershed boundaries (also known as piracy). During my study, groundwater crossed a surface drainage boundary as well. This is not uncommon in karst landscapes in general, but is a phenomenon that may be overlooked by researchers who are unfamiliar with karst hydrology. As discussed previously, groundwater direction is determined by geology (fractures, caves, etc.) and hydraulic gradient (Veni 1994).

Site 40 “Losing Spring Creek” is a section of Spring Creek where water infiltrates into the ground through a gravel bed. The dye from this trace left the creek bed, entering Spring Creek Cave and discharged at its entrance. Comparing the trace at site 40 to site 27 “Armadillo Hole” is interesting; site 40’s dye left Spring Creek and entered Spring Creek Cave, whereas site 27’s dye entered Spring Creek and continued flowing in Spring Creek and was detected in Spring Creek before its confluence with Spring Creek Cave. Site 27’s dye either did not recharge into the losing section of Spring Creek, or was diluted to an undetectable amount. The site 20 “Alzafar Water Cave” trace, when compared to a trace done in 1982 at the same cave, further proves a relationship between groundwater flow and precipitation. While Harden (1982) found a bifurcation with flow traveling both north and east, my trace only found flow traveling north. During Harden (1982), 350% more precipitation occurred. A bifurcation suggests a groundwater divide near the point of injection. However, groundwater divides are not static like watershed divides, but can move dependent on hydrologic conditions. In the Edwards Aquifer, groundwater divides have been found to move during time of drought (HDR Engineering 2010). These traces highlight the variability of karst landscapes and the influence of storm events on ground and surface water.

Markowski (2016), a study done on Cave Without a Name, found a significant relationship between storm events, antecedent conditions, and CWAN's main stream's discharge. Gerard (2012) also found a quick response in CWAN's main stream to local storm events, making the assumption that many recharge features have a direct connection to CWAN's main stream. This assumption was confirmed during two dye traces, at site 4 "Guam's Cave" and site 28 "Joe's Diet Cave", which found a direct, preferential flow to CWAN's main stream.

In the chloride mass-balance study by Gerard (2012), a $27km^2$ contributing area to CWAN's main stream was calculated. This may be accurate, but is not supported by dye tracing conducted in my study. If sites 20 and 27, which did not flow to CWAN, are assumed to represent a groundwater divide, the contributing area to CWAN's main stream would be closer to $8km^2$. However, flow from site 27 "Armadillo Hole" was likely in a perched, homogeneous epikarst aquifer disconnected from the primary Lower Glen Rose Limestone aquifer and suggested a stacked system. Flow through conduits could be traveling underneath the epikarst in this area, traveling east towards CWAN while epikarst flow south towards Spring Creek. Both traces done in surface recharge features bypassing the epikarst and injected directly into conduits flowed to CWAN. Both Gerard

(2012) and Markowski (2016) studies are further explained in the previous studies section of this paper.

The majority of dye traces in the CWAN study area had primarily slow to medium velocities (0.02km/day – 0.20km/day), with one trace exhibiting quick flow (>0.36km/day). These velocities, when compared to some other dye traces and studies done in the Lower Glen Rose Limestone and the neighboring Edwards Aquifer, ranged from much slower to similar. Childre (2013) found quick, conduit flow in the Lower Glen Rose Limestone in the Magic Spring/CM Cave area with apparent velocities from 1.44km/day to 1.12km/day. Hunt (2005) found in the Edwards Aquifer in the Onion Creek area with velocities between 2.7km/day and 1.7km/day. These two studies were in systems where flow traveled more than four times quicker than in the CWAN area. Johnson (2012) is another dye trace conducted in the Edwards Aquifer in the San Marcos Springs area. Results from this study found a wide range of velocities from 0.011km/day to 1.9km/day, on average still quicker than flow found in the CWAN region but much more comparable compared to Childre (2013) and Hunt (2005). Veni (1994) used previous work conducted throughout the Lower Glen Rose Limestone and estimations based on observations to get an average of 0.85km/day the LGR. Though water volume is the primary determinant of velocity in karst systems, caves in this area and the associated conduits are typically low gradient, so slower velocities are not surprising (Veni 1994).

See Figure 12 for a complete map of all dye trace results.

VI. CONCLUSION

This dye trace study reaffirmed the variability of groundwater movement and direction in karst systems. From primarily preferred conduits to occasional diffuse epikarst flow, and from predictable flow to major cave streams to discharge at minor seeps. This study helps to quantitatively and qualitatively describe the characteristics of Cave Without a Name’s main stream, as well as other caves and hydrologic feature in the area.

Precipitation and surface flow (and potentially contaminants) enter karst features and directly recharge the Lower Glen Rose Limestone’s aquifer. Probable direction and speed of groundwater flow was determined by a series of dye traces. The dye tracing method of groundwater delineation showed connections between recharge features and discharge features that other karst delineation methods (flow boundary and balancing of discharge) may not be able to confirm without doubt. However, additional traces at more recharge sites at differing antecedent conditions, as well as the incorporation of additional wellhead delineation methods, is recommended to fully understand the groundwater divides in karst landscapes.

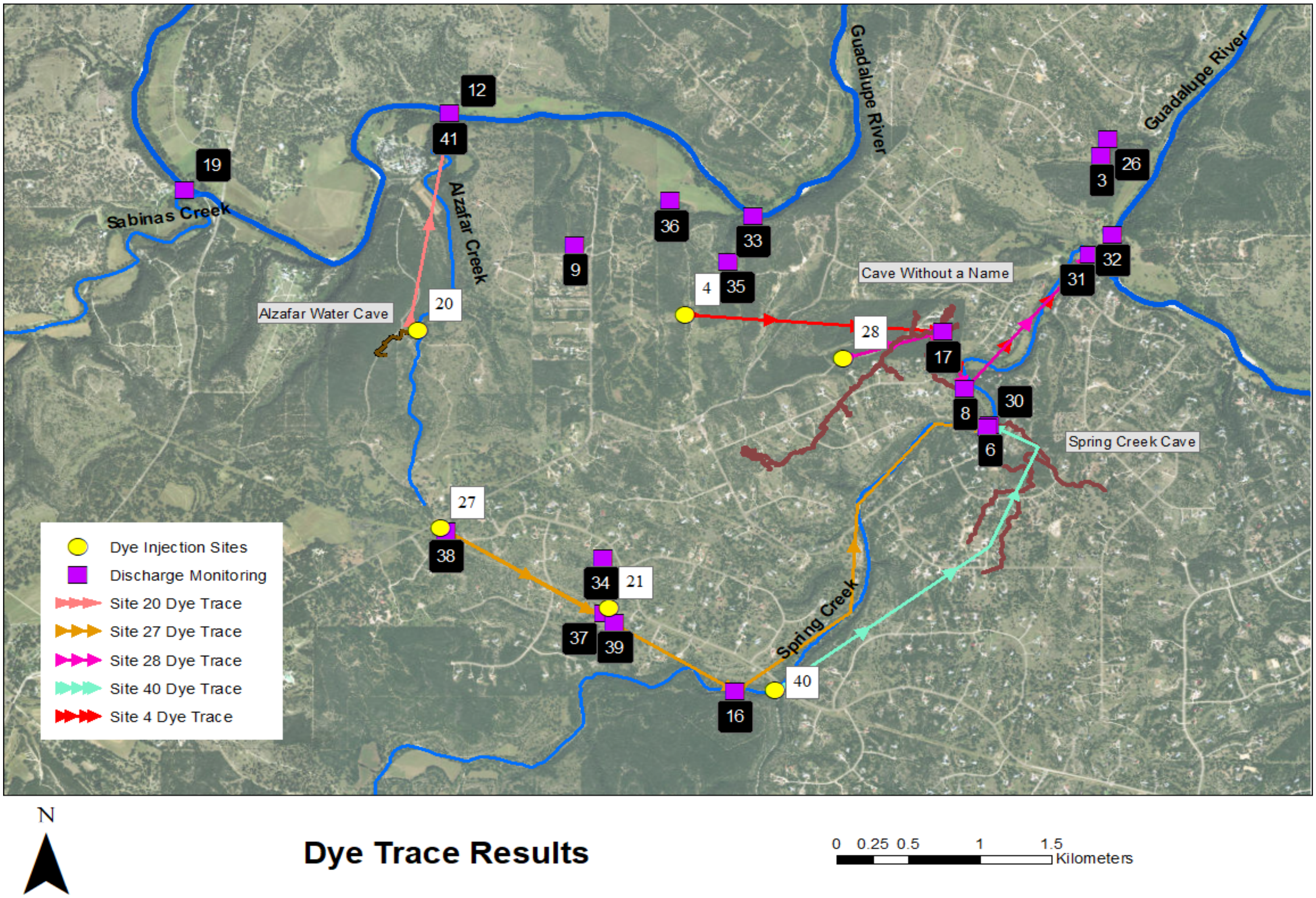

Figure 12: Dye Trace Results

APPENDIX SECTION

RECHARGE FEATURES

ID	Name	Description	Coordinates
1		Sinkhole. Going to Spring Creek. No catchment ditch. Walking distance from dirt road but not close.	29.894488,-98.609725
2		Covered by rocks but looks like a recharge feature. May be going into nearby drainage that goes to Spring Creek.	29.898469,-98.619380
4	Guam's Cave	Deep sinkhole/cave. Next to dirt driveway. No catchment ditch.	29.886094,-98.636195
5		Deep sinkhole/cave. Not as close to dirt road. Across the fence is a dirt road. No catchment ditch.	29.882777,-98.631932
7	Suzette's Unknown Cave	Sinkhole/cave on CWAN property. No catchment ditch. Near road but not directly next to	29.882275,-98.627520
15		Deep sinkhole/cave. Cavers explored it but it eventually narrowed too much.	29.883057,-98.622585
20	Alzafar Water Cave	There's a tributary further down the cave passed the first squeeze. Water in the cave.	29.88507,-98.65548
21		Small crack. 4ft deep. No ditch.	29.865894,-98.641759
22		Slump. Slow recharge.	29.866907,-98.632725
23		Large sinkhole by road. 10ft deep. Moist.	29.865451,-98.626880
24		Rock pile and dirt under. May be filled and difficult to excavate. Near road.	29.869578,-98.625942
25		Deep sinkhole near fence line and road.	29.890427,-98.644313
27	Armadillo Hole	Small hole but does not fill with water, indicating recharge.	29.871426,-98.653921
28	Joe's Diet Cave	Deep sinkhole/cave.	29.883086,-98.624725
40	Losing Spring Creek	Losing section of Spring Creek.	29.860204,-98.629731

MONITORING SITES

ID	Name	Description	Coordinates
3	Grotto Spring	Low to non-existent discharge.	29.897004,-98.606022
6	Spring Creek Cave	High discharge.	29.878427,-98.614175
8	Deadman's Cave	Outlet for CWAN's main stream	29.880928,-98.615946
9	KCNA Spring	Large seep with tree and water in drainage.	29.890944,-98.644117
12	Alzafar Creek	Fed by Alzafar Springs.	29.899729,-98.652935
16	Spring Creek	Spring fed pool in Spring Creek.	29.860139,-98.632667
17	CWAN main stream	High discharge.	29.885890,-98.617444
19	Sabinas Creek	Spring fed creek.	29.894782,-98.672299
26	Beech Spring	Low discharge.	29.898095,-98.605531
29		Well supplied by CWAN's main stream.	
30	Spring Creek	Just upstream of Spring Creek Cave.	29.878321,-98.614352
31	Spring Creek		29.890152,-98.606864
32	Guadalupe River		29.891504,-98.605254
33	Guadalupe River		29.892873,-98.631243
34		Well	29.869349,-98.642146
35	Devloo Spring	Small spring fed pool.	29.889708,-98.633028
36		Well	29.893942,-98.637173
37		Well	29.865525,-98.642101
38		Well	29.871237,-98.653513
39		Small seep in typically dry drainage.	29.865525,-98.642101
41	Guadalupe River		29.899809,-98.653130

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