2017 Groundwater Tracing in the Barton Springs Edwards Aquifer: Onion Creek and Little Bear Creek
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Abstract

A groundwater trace performed in the fall of 2017 verified the connection to Barton Springs from three sites: Crooked Oak Cave on Onion Creek, Fenceline Sink on Little Bear Creek, and Stoneledge Quarry adjacent to Little Bear Creek. Groundwater tracer arrived at Main Barton Spring in 5.4 days from Crooked Oak Cave, in 6.0 days from Fenceline Sink, and in 5.0 days from Stoneledge Quarry. Arrival of groundwater containing the tracers was faster during the high aquifer conditions in 2017 than during traces performed under drought conditions in 1999 and 2000. Results from this study will be applied to aquifer protection and management strategies that include estimating locations of conduits carrying water through the aquifer to Barton Springs.

Introduction

The City of Austin, in cooperation with other partners - principally the Barton Springs Edwards Aquifer Conservation District (BSEACD), has been tracing the flow of groundwater in the Barton Springs Edwards Aquifer for over 20 years (Hauwert et al 2004, Hunt et al 2005, Smith et al 2006, Smith et al 2012, Hauwert 2012, Hunt et al 2013, Smith et al 2017). A major goal of these traces has been preparation for spills of hazardous materials which could impact the aquifer, the springs, and downstream resources. Barton Springs contributes roughly 20% of the flow downstream in Lady Bird Lake and the Colorado River, so the water quality and quantity at the springs has a major impact on downstream flows. As part of the effort to protect the endangered Barton Springs Salamander (*Eurycea sosorum*) and comply with the city's 10(a)(1)(B) incidental take permit (PRT-839031) with the US Fish and Wildlife Service, which allows the City to operate Barton Springs Pool as a recreational facility, it is critical to know the sources of the spring water in order to protect the springs from pollution. The Barton Springs segment of the Edwards Aquifer is the portion of the aquifer located beneath southwest Austin with Barton Springs as the primary outlet (Figure 1). The Edwards Aquifer is a karst aquifer, meaning that it is formed in limestone and has direct, often large, pathways for moving and storing water such as caves, fractures, and sinkholes. Tracing of groundwater flow using non-toxic fluorescent dye is the best available tool to physically study the complicated natural drainage system of water flow through karst aquifers. The most recent study was conducted in the fall of 2017 and tested the connectivity to Barton Springs from three locations: Crooked Oak Cave on Onion Creek, Fenceline Sink (sinkhole) on Little Bear Creek, and Stoneledge Quarry (abandoned) adjacent to Little Bear Creek (Figure 2). These features represent inlets to the natural karst drainage system of caves, interconnected conduits, and fractured rock which tie these features to both natural and manmade outlets such as springs and wells.

These three locations were chosen for a variety of reasons. Crooked Oak Cave was traced once in 2000 (Hauwert et al 2004) during much lower aquifer conditions, and the cave has since undergone a restoration project removing over 30 ft of clay-rich fill and exposing conduits leading deeper into the aquifer. Stoneledge Quarry is the target of a Capital Improvement Project to enhance recharge (increase the volume of water entering the aquifer) into the aquifer from the Little Bear Creek Watershed. The connectivity of Stoneledge Quarry with the aquifer was inferred based on the relationship of the water level in the pond at the bottom of the quarry with water levels in the adjacent wells and a 1999 trace in the vicinity which connected Dahlstrom Cave with Barton Springs (Hauwert et al 2004). The 2017 trace described herein was the first attempt to directly trace the connection from Stoneledge Quarry to Barton Springs. After Dahlstrom Cave, Fenceline Sink was the second traced natural recharge feature in a major tributary to Little Bear Creek. Little Bear Creek is of interest not only due to the proximity to Stoneledge Quarry but also because of interest in the fate of runoff from contributing Water Quality Protection Lands. Water and tracer input at each of these three locations was expected to reach Main Barton Spring, Eliza Spring, and Old Mill Spring (collectively part of the Barton Springs complex), and the tracers were expected to arrive more quickly than those from studies performed during lower aquifer levels (i.e. low spring discharge conditions and low water elevation in the aquifer, which are drought indicators described by BSEACD).

Demonstrating the connection and delineating the recharge zone is important for water resource planning and protection of a sensitive aquifer and a major spring. Water budgets cannot be adequately assessed without thoroughly understanding where the water travels (Hauwert 2016). The conditions within the aquifer are naturally dynamic and vary based on influences from precipitation, drought, well pumping, and land management. Previous studies have demonstrated that the pathways of groundwater flow change depending on the water level in the aquifer (Smith et al 2012). Robust models of the aquifer rely on groundwater traces that are repeatable and thoroughly characterize the flow-paths at various aquifer conditions. Groundwater tracing is fundamental to understanding flow systems within karst limestone aquifers, and the data resulting from this study will help planners, managers, and scientists assess locations for proposed recharge enhancement, determine potential stormwater runoff impacts, predict the effects of hazardous spills and pollution, and evaluate other future projects.

This project ties into specific goals of the Watershed Protection Department's Water Quality mission. Delineating aquifer flow-paths is essential to protect Austin's aquifers for citizen use and the support of aquatic life, such as the swimmers and salamanders at Barton Springs Pool. By protecting and, when possible, improving the water quality in the aquifer, the springs are improved and the downstream creeks and river that rely on spring flow are also improved. During a time of intense development in central Texas, just protecting the current water quality requires vigilant attention. Illuminating the connection from nonurban creeks to urban springs, including Barton Springs, provides justification to preserve the existing baseflow quantity and quality in the creeks which in turn rely on springs for baseflow. Maintaining or enhancing the existing rate of recharge to the Edwards Aquifer is only possible when the recharge areas are fully understood. Results from these traces could influence the Watershed Protection Department policy regarding acquisition of open space as a water quality and quantity benefit. When stream systems are protected and stabilized, property loss from erosion is decreased and the beneficial uses of waterways are increased. The overarching goal of this project is to provide knowledge and context to maintain and/or enhance Barton Springs, a high quality environmental feature with endangered species habitat, recreational value, and immense downstream quantity and quality value, to the maximum extent possible.

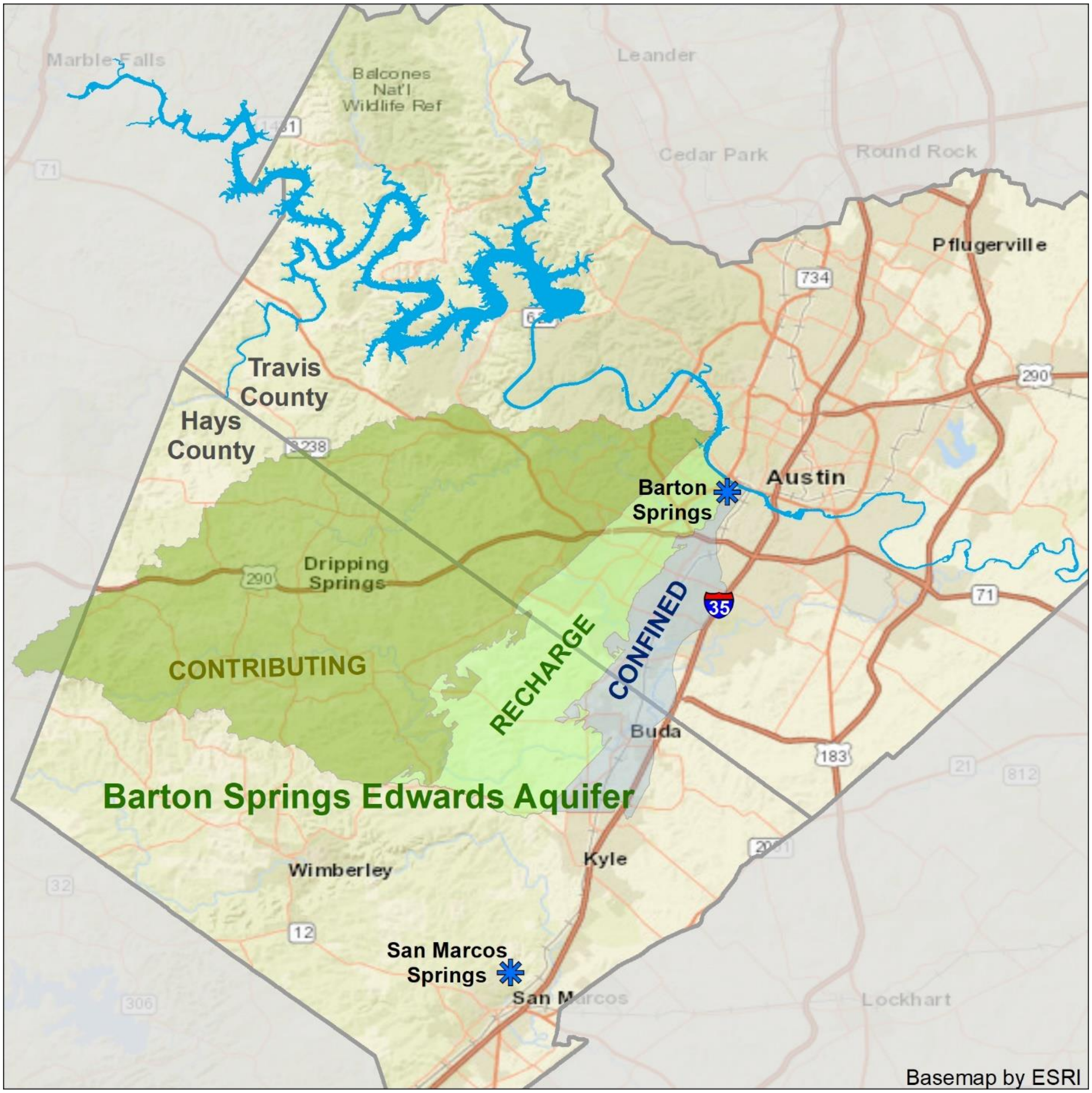

Figure 1. Location of the Barton Springs Edwards Aquifer, Barton Springs, and San Marcos Springs relative to Austin, Texas. The southern boundary of the aquifer shifts between Onion Creek and the Blanco River depending on aquifer levels.

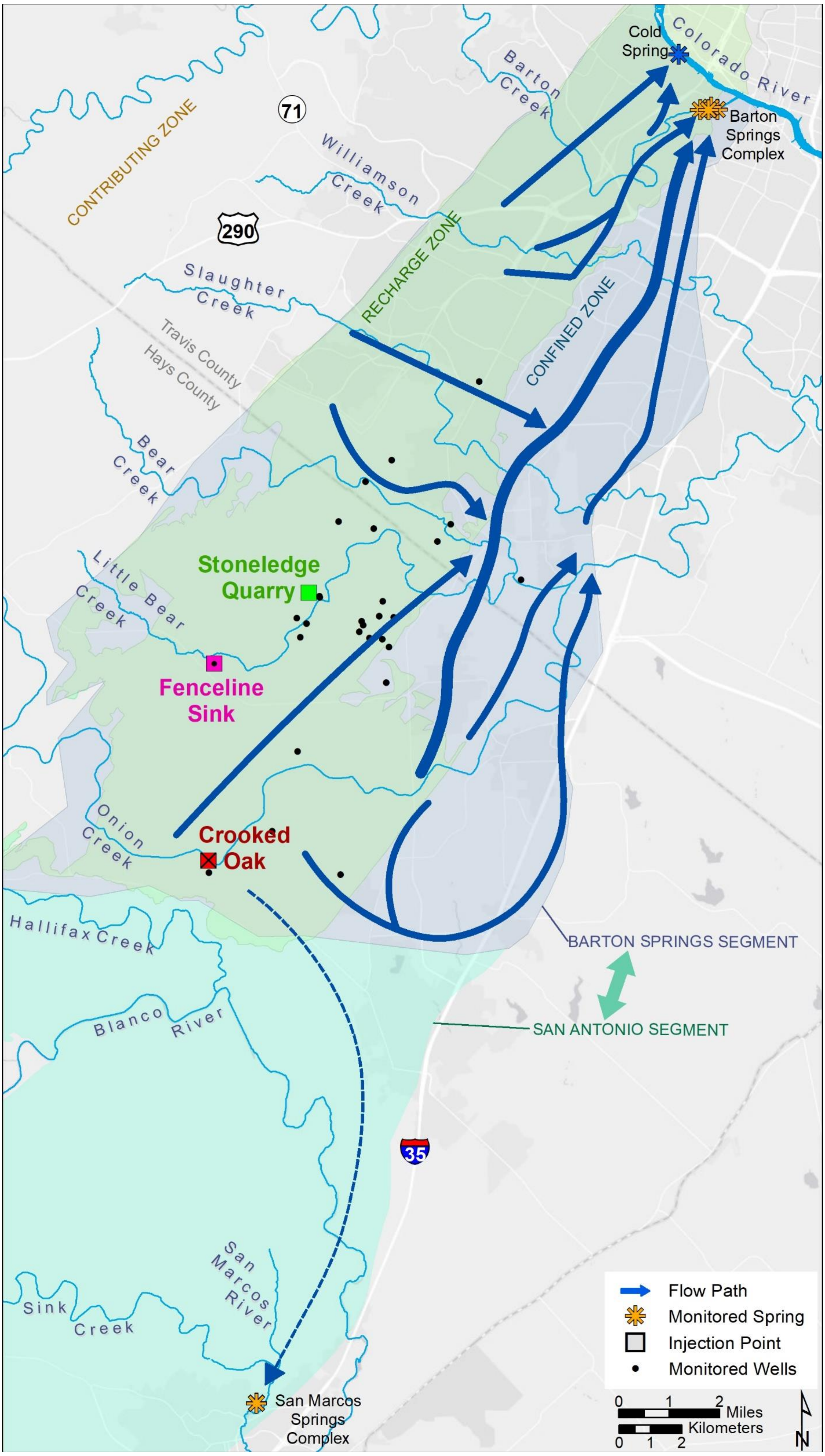

Figure 2. Map of study area showing injection locations and monitoring locations along with general flow paths based on previous groundwater tracing studies (Hauwert et al 2004, Smith et al 2006). The boundary between the Barton Springs and San Antonio Segments of the Edwards Aquifer shifts depending on the aquifer levels. Grayscale background map by ESRI and partners.

Methods

Groundwater tracing is a common technique for documenting groundwater movement in karst systems and shallow groundwater systems (Hauwert et al 2004, Quinlan 1990, Aley 2002). During a groundwater tracing test, a substance (generally a non-toxic fluorescent dye) is introduced (injected) at a recharge feature, and monitoring is undertaken to detect the substance at locations of interest such as springs and wells down gradient from the injection point. The injection involves applying the dye at the site and adding flush water if water is not already flowing at the site. During monitoring, water samples are collected at regular time intervals and then sent to a lab for analysis. Sampling methods include both direct samples of the water and indirect samples collected using charcoal receptors. Charcoal receptors adsorb dye from the water flowing past and are a reliable method of continuous water sampling. Three different dyes were used for the recent study so that the three injection locations could be evaluated simultaneously and independently.

The three non-toxic fluorescent dyes used for this trace were Eosine, Fluorescein, and Rhodamine WT. For a safety comparison, these dyes are also used in the drug and cosmetic industry (Aley 2002). The dyes were purchased from Ozark Underground Laboratory (OUL), the same lab used for the water analyses. OUL reports the dye concentrations based on the "as sold" weight of the dye mixture (Table 1). For consistency with the lab and with other tracing literature, the analyses in this report are based on the "as sold" dye concentration. Since dye manufacturers use a variety of names to describe dyes, the color index name and number are also provided in Table 1. Rhodamine WT was purchased in a liquid form, so it was ready to be applied. Both Eosine and Fluorescein were purchased as powders. To prevent clumping of the powders and aid in pouring the dyes into the features, they were mixed with well water in separate 50 gallon drums prior to injection.

Table 1. Dye details.

Dye	Color Index Name	Color Index Number	Percent Dye in "As Sold" Mixture
Eosine	Acid Red 87	45380	75%
Fluorescein	Acid Yellow 73	45350	75%
Rhodamine WT	Acid Red 388	Not Assigned	20%

The dyes were injected in late September and early October 2017 at the three sites as described in Table 2. Dye volumes were chosen based on the results of previous tracing studies in the region. The dye volumes chosen are high relative to other similar studies, and this is due to the distances involved, the sorption previously observed within the system, and the goal of detectable concentrations at Barton Springs. The ephemeral creeks were dry, so the dyes injected into Crooked Oak and Fenceline Sink were flushed with water to help the tracers reach the water table. Potable water was trucked in by a delivery service at Crooked Oak Cave. For the Fenceline Sink injection, well water was pumped from the aquifer and stored temporarily in firefighting bladders in preparation for the injection. The northern pond at the bottom of Stoneledge Quarry is perennial where the dye was injected, so no flush water was necessary.

Table 2. Dye injection information. *Combined springflow as reported by USGS gage 08155500.

Site	**Watershed**	**Date**	**Time**	**Dye**	**Dye Volume (lbs)**	**Water Volume (gal)**	**Barton Springs* Flow (cfs)**
Crooked Oak Cave	Onion Creek	27 Sep 2017	10:30	Eosine	30	10,000 (flush)	86
Fenceline Sink	Little Bear Creek	27 Sep 2017	12:25	Rhodamine WT	30	10,000 (flush)	86
Stoneledge Quarry	Little Bear Creek	02 Oct 2017	09:50	Fluorescein	50	approx. 4,500,000 (pond)	86

Monitoring for dye detection occurred via water samples at Barton Springs, San Marcos Springs, and 29 wells (Figure 1, Figure 2). Direct water samples were collected via periodic grab samples at most sites and supplemented by an automated sampler at Main Barton Spring. Water samples provide tracer concentration data at a specific point in time for each site. Indirect water sampling via charcoal receptors was used at all sites. Charcoal receptors document the presence of dyes and relative concentrations over a continuous period of time from when the receptor is placed in the water to when it is removed. Since charcoal receptors adsorb the dye over a period of time, dyes can be detected when the concentrations are below detection limits for water samples. Note: Charcoal receptor concentrations can be compared only to other charcoal receptor concentrations and water samples can only be compared to other water samples. Background samples were collected where possible to detect any dye present in the system before the start of the current study.

Special precautions were followed to prevent contamination of samples and cross contamination between sites. For example, gloves were worn to collect samples and only black sharpie pens were used to note field data and write on sample storage containers. Quality control included periodic duplicate samples and a control sample during most visits. The control sample was handled by all field personnel and jostled among the field equipment to detect any cross-contamination that might have been present.

Injection and monitoring was a multi-agency effort:

Staff from City of Austin Watershed Protection Department (COA WPD), City of Austin Wildlands Conservation Division (COA WCD), and the Barton Springs Edwards Aquifer Conservation District (BSEACD), and students from St. Edwards University (SEU) collaborated on choosing the injection and monitoring locations. COA WCD staff arranged access to the injection sites and coordinated flush water for the dry creek sites. COA WPD staff mixed and poured the dye tracers.

COA WPD staff was responsible for deploying and collecting charcoal receptors and water samples from the Barton Springs complex: Main Barton Spring, Eliza Spring, Old Mill Spring, and Upper Barton Spring. Samples were collected more frequently for the first two weeks of the study to target detection of the initial arrival of dye at the springs and the peak and duration of the breakthrough curve. An ISCO automated sampler was used to collect hourly water samples for the first week at Main Barton Springs. Throughout the first two weeks, water samples and charcoal receptors were collected on a daily basis. Collection of samples continued on a weekly basis for 17 weeks to evaluate the duration of the presence of dye in the spring water.

Divers at the Meadows Center for Water and the Environment were hired to collect water and charcoal samples at San Marcos Springs. Samples were collected once a month at San Marcos Springs: Crater Bottom Spring, Diversion Spring, Weissmueller Spring, and the spillway from Spring Lake. Detection was not expected at San Marcos due to the groundwater divide between Onion Creek and San Marcos Springs, but the divide is known to shift and samples were targeted to provide boundary conditions.

Collaborators at the BSEACD and SEU coordinated with private landowners to sample 24 wells. Wells were selected based on location relative to previous dye trace results and access permission. Samples were collected approximately once a week at the private wells.

COA WPD staff also deployed charcoal receptors at five monitoring wells utilized for salamander studies. Direct water samples were not possible at these wells since they lacked pumps and electricity supply. The monitoring wells were sampled approximately every two weeks.

All water and charcoal sample analyses were performed by the Ozark Underground Laboratory for the groundwater tracing project in accordance with standard tracing methodology as described in the OUL Procedures and Criteria Manual (Aley and Beeman 2015).

In addition to the standard groundwater tracer detection methods described above, a submersible Fluorescein sensor (Turner Designs Cyclops Fluorescein sensor mounted on a Eureka Manta sonde with data logger) was placed at the Main Barton Spring and operated by BSEACD staff. The Fluorescein sensor measured and collected data every 15 minutes from 26 September to 5 November 2017. For the purposes of this study and analysis, the Fluorescein sensor data was only a point of comparison. The water samples sent to the laboratory go through a more rigorous analytical procedure with strict quality control, and are comparable to previous studies which used the same laboratory methods.

In addition to the perennial northern pond at the bottom of Stoneledge Quarry, there is an ephemeral southern pond. On 27 October 2017, 25 days after the Fluorescein dye injection at Stoneledge Quarry, COA WCD staff pumped water from the southern pond into the northern injection pond, raising the water level by 7.8 inches. This was done in an effort to increase the hydraulic head in the injection pond, in case that would force additional water and dye into the aquifer while monitoring continued at all of the sites listed above.

Results

The tracers from each of the three locations were detected at Main Barton Spring, Eliza Spring, and Old Mill Spring. Crooked Oak Cave Eosine and Stoneledge Quarry Fluorescein were detected with confidence at one well: 58-50-7DF. A summary of the detections is in Table 3. Figure 3 is a map of the tracer detections.

Questionable detections were found in samples from the Hays County Well, the Walter Tract Well, and Well 58-49-925. The levels of dye found at the Hays County Well were low, dye concentrations did not reflect any trends, background samples were not available, and background dye from a previous trace (injected in 2007, Hauwert 2012) in this area is possible. The dye concentrations detected at the Walter Tract Well rose by an order of magnitude from the first sample to the second sample, but again background samples were not available. After the second sample, the Walter Tract Well went dry, so the detection and the trend could not be confirmed. The charcoal receptor at Well 58-49-925 was left out for over two months, much longer than the maximum recommended time for charcoal deployment, and the Fluorescein detection was both low in concentration and flagged by the lab as "*A fluorescence peak is present that does not meet all the criteria for a positive dye result. However, it has been calculated as though it was the tracer dye*."

Background levels of the tracer dyes were detected at San Marcos Springs (Crater Bottom, Diversion, Weissmueller, and the Spillway), Well 58-57-3DO, and Well 58-57-512. These tracers were present in charcoal receptors deployed and collected before our study injected dye into the ground, and the tracer concentrations did not increase or reflect any other trends during the sampling period. Background tracer dye was also detected at Upper Barton Spring and details are described at the end of this section.

Table 3. Summary of tracer detections. Eos = Eosine, Fl = Fluorescein, RWT = Rhodamine WT. Charcoal peak recovery time and time for concentration to decline one-two orders of magnitude calculated using retrieval date. As mentioned above, please note that water samples cannot be compared to charcoal samples, and dye is readily detected on charcoal below water detection limits. *The initial arrival detection was delayed due to equipment tampering, so the initial recovery and velocity of arrival may have been faster than stated.

Trace From	Detection Site	Medium	Straight Distance (mi)	Initial Recovery Time (days)	Duration (days)	Velocity of Initial Arrival (mi/day)/ (ft/day)	Peak Recovery Time (days after arrival)	Initial Concentration (ppb)	Peak Concentration (ppb)	Time for Concentration to Decline One Order of Magnitude (days after peak)	Time for Concentration to Decline Two Orders of Magnitude (days after peak)
Crooked Oak Cave (Eos)	Main Barton Spring	water	17.90	5.42	36	3.3/ 17,400	1	0.055	11.5	5	15
Crooked Oak Cave (Eos)	Eliza Spring	water	17.98	6.05	63	3.0/ 15,700	0	10.7	10.7	5	22
Crooked Oak Cave (Eos)	Old Mill Spring	water	18.01	4.19	31	4.3/ 22,700	3	0.039	5.12	6	28
Crooked Oak Cave (Eos)	58-50-7DF Well	water	8.96	15	36	0.6/ 3,150	21	0.03	0.14	--	--
Fenceline Sink (RWT)	Main Barton Spring	water	14.74	6.04*	6	2.4/ 12,900*	1	1.35	4.16	3	7
Fenceline Sink (RWT)	Eliza Spring	water	14.81	5.97	5	2.5/ 13,100	1	0.689	1.81	3	5
Fenceline Sink (RWT)	Old Mill Spring	water	14.86	5.99	5	2.5/ 13,100	1	0.055	1.21	3	5
Stoneledge Quarry (Fl)	Main Barton Spring	water	12.45	5.02	5	2.5/ 13,100	0	0.053	0.053	5	5
Stoneledge Quarry (Fl)	Eliza Spring	water	12.52	5.00	5	2.5/ 13,200	0	0.050	0.050	6	6
Stoneledge Quarry (Fl)	Old Mill Spring	water	12.57	4.99	5	2.5/ 13,300	0	0.024	0.024	6	6
Crooked Oak Cave (Eos)	Main Barton Spring	charcoal	17.90	6	>120	3.0/ 15,800	1	575	906	8	>113
Crooked Oak Cave (Eos)	Eliza Spring	charcoal	17.98	6	>120	3.0/ 15,800	1	224	914	3	>113
Crooked Oak Cave (Eos)	Old Mill Spring	charcoal	18.01	6	>120	3.0/ 15,800	1	155	1260	6	70

Trace From	**Detection Site**	**Medium**	**Straight Distance (mi)**	**Initial Recovery Time (days)**	**Duration (days)**	**Velocity of Initial Arrival (mi/day)/ (ft/day)**	**Peak Recovery Time (days after arrival)**	**Initial Concentration (ppb)**	**Peak Concentration (ppb)**	**Time for Concentration to Decline One Order of Magnitude (days after peak)**	**Time for Concentration to Decline Two Orders of Magnitude (days after peak)**
Crooked Oak Cave (Eos)	Walter Tract Well	charcoal	7.79	0-1	2-15	7.8/ 41,100	?	0.21	6.45	--	--
Crooked Oak Cave (Eos)	58-50-7DF Well	charcoal	8.96	8-15	>102	0.6/ 1	49	1.20	33.10	33	>53
Fenceline Sink (RWT)	Main Barton Spring	charcoal	14.74	6	15-22	2.5/ 13,000	1	58.7	460	5	27
Fenceline Sink (RWT)	Eliza Spring	charcoal	14.81	7	14-21	2.1/ 11,200	0	409	581	3	28
Fenceline Sink (RWT)	Old Mill Spring	charcoal	14.86	7	14-21	2.1/ 11,200	0	431	431	5	28
Fenceline Sink (RWT)	Hays County Well	charcoal	3.74	0-1	2-15	3.7/ 19,800	?	1.27	2.61	--	--
Fenceline Sink (RWT)	Walter Tract Well	charcoal	5.05	0-1	2-15	5.1/ 26,700	?	4.62	116.00	--	--
Stoneledge Quarry (Fl)	Main Barton Spring	charcoal	12.45	5	11-18	2.5/ 13,100	2	12.3	21.9	22	22
Stoneledge Quarry (Fl)	Eliza Spring	charcoal	12.52	5	11-18	2.5/ 13,200	2	2.97	8.31	23	23
Stoneledge Quarry (Fl)	Old Mill Spring	charcoal	12.57	6	10-17	2.1/ 11,100	1	12.6	19.3	23	23
Stoneledge Quarry (Fl)	58-50-7DF Well	charcoal	4.08	17-24	22-43	0.2/ 979	22	1.36	4.92	26	26
Stoneledge Quarry (Fl)	58-49-925 Well	charcoal	0.18	<25-93	?	0.0/ 38	?	0.32	0.32	--	--

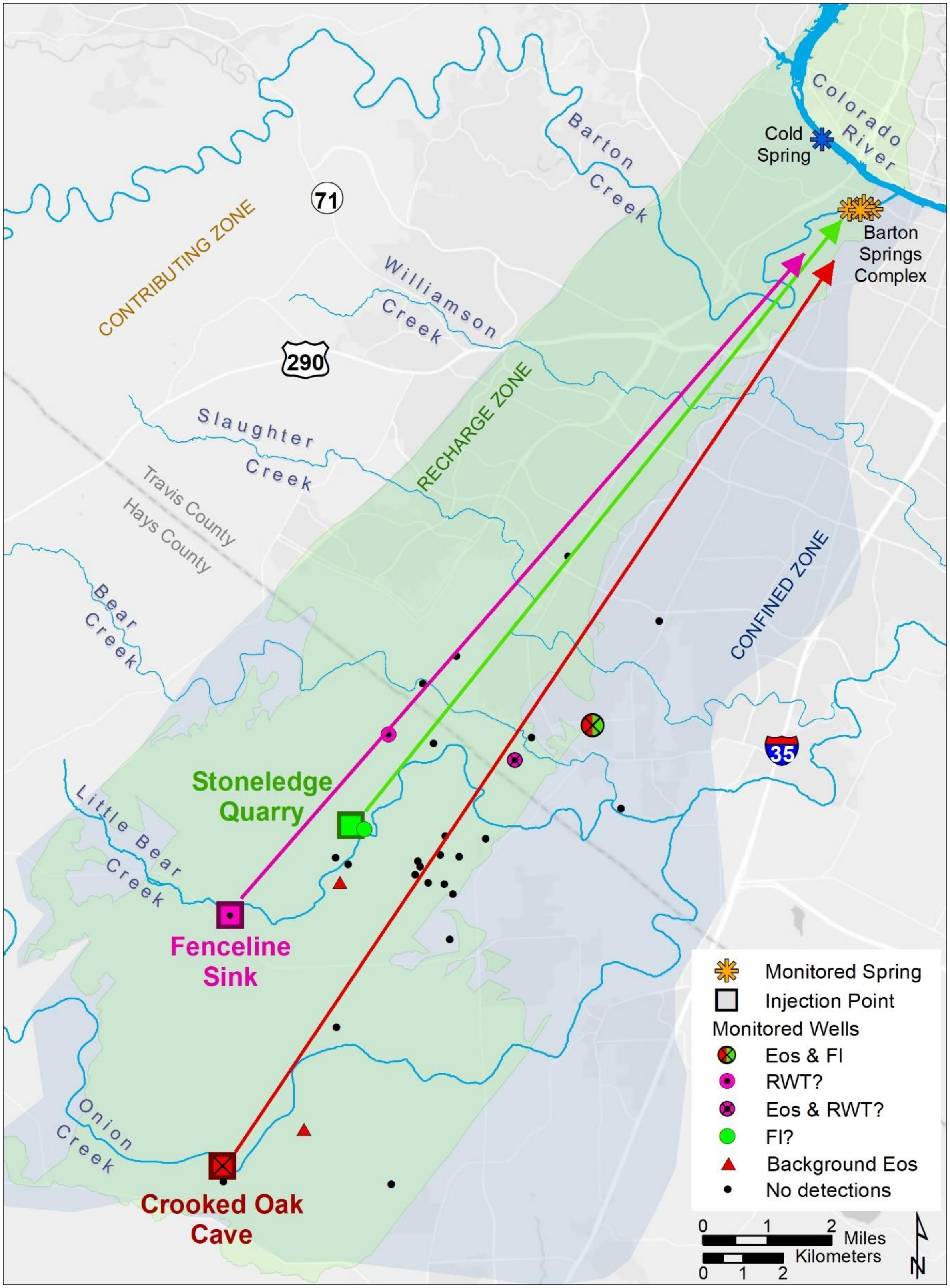

Figure 3. Map of dye detections. Eos = Eosine injected at Crooked Oak Cave, Fl = Fluorescein injected at Stoneledge Quarry, RWT = Rhodamine WT injected at Fenceline Sink. Not shown to the south, San Marcos Springs had only background levels of RWT. Arrows assume a straight line path and are for illustration only. Grayscale background map by ESRI and partners.

The percent recovery of each tracer dye was derived from water samples collected at the springs. The amount of dye that arrives at the springs depends on the properties of each dye, the amount of adsorption and diffusion within the aquifer, and the nature of the connection between the recharge point and the springs. Eosine and Fluorescein are both relatively strong dyes which are known to demonstrate relatively little sorption within karst aquifer systems (Aley 2002). Rhodamine WT is another effective tracer dye, but tends to sorb more within the aquifer system than the other dyes.

Table 4. Percent of injected tracer dye that was recovered at Barton Springs.

Site Name	**Crooked Oak Cave**	**Fenceline Sink**	**Stoneledge Quarry**
	% Eosine Recovered	**% RWT Recovered**	**% Fluorescein Recovered**
Main Barton Spring	36.80%	6.96%	0.15%
Eliza Spring	3.19%	0.32%	0.01%
Old Mill Spring	4.70%	0.40%	0.01%
Total % Recovered:	44.69%	7.68%	0.17%

Breakthrough curves reflect the changes in the concentration of the tracer in the water over time and represent the first arrival, peak concentration, and duration of the tracer presence (or pulse) in the spring discharge. A portion of the breakthrough curve for Eosine was lost due to tampering with monitoring equipment – the automatic sample collection tubing was removed from the water, but the beginning of the arrival was captured along with the peak or near-peak (Figure 4). The Eosine peak, or at least very close to the peak, seems to have been captured based on comparison with the Fluorescein sensor data, as discussed below. A smaller portion of the beginning of the breakthrough curve for Rhodamine WT was lost due to the same incident (Figure 5). The breakthrough curve for Fluorescein is less distinct because the water sampling resolution was coarser scale (Figure 6).

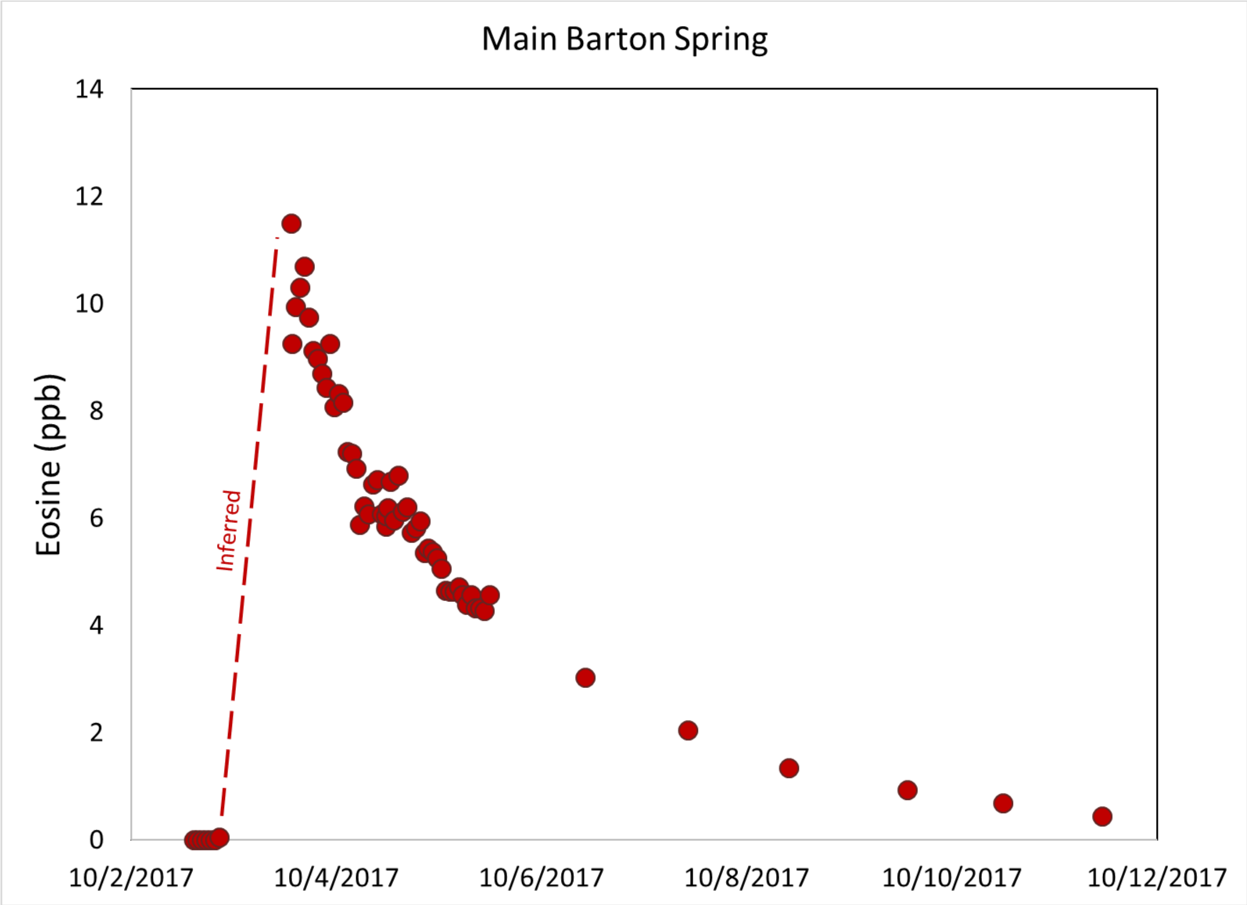

Figure 4. Breakthrough curve of Crooked Oak Cave Eosine concentration in water at Main Barton Spring. Dashed "inferred" line represents portion of curve lost due to equipment tampering.

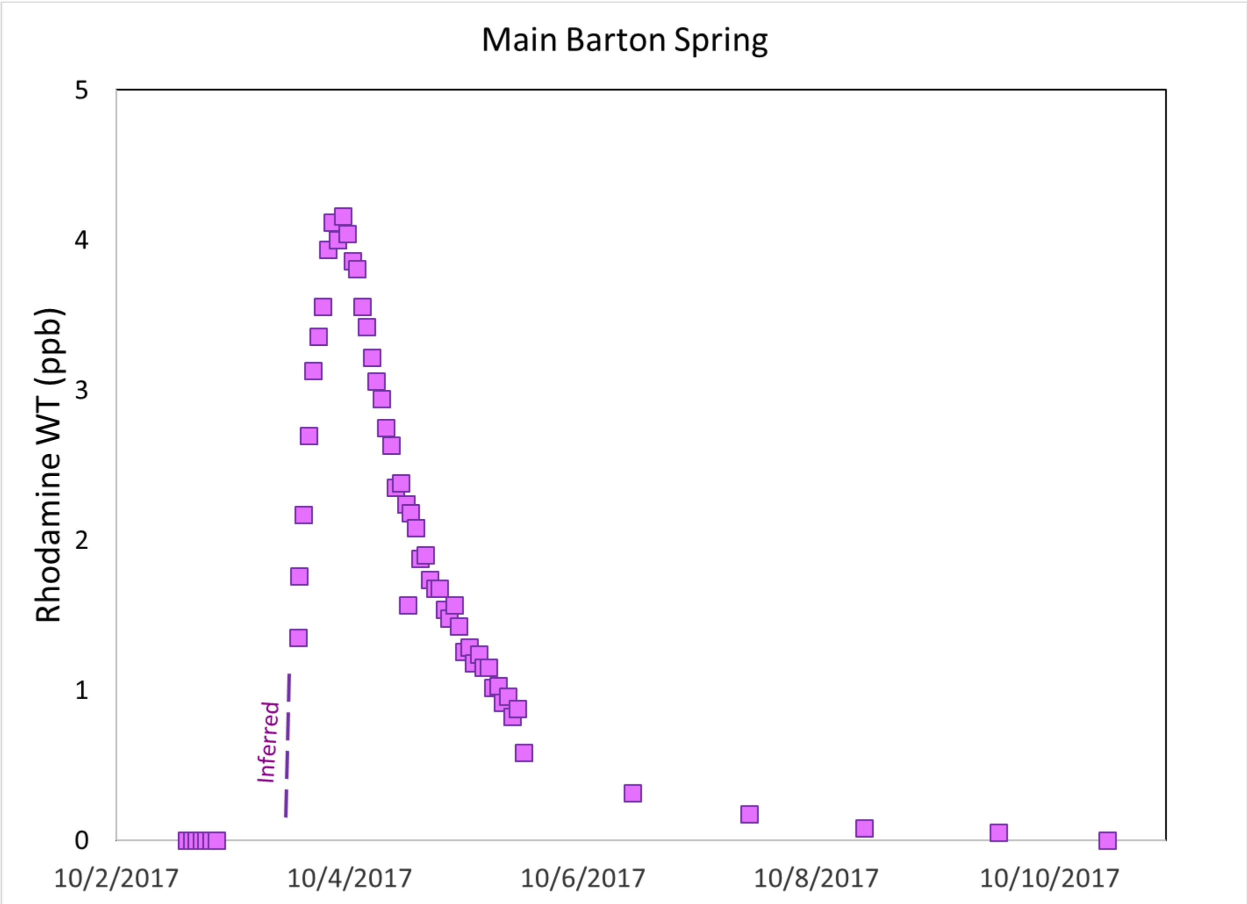

Figure 5. Breakthrough curve of Fenceline Sink Rhodamine WT concentration in water at Main Barton Spring. Dashed “inferred” line represents portion of curve lost due to equipment tampering.

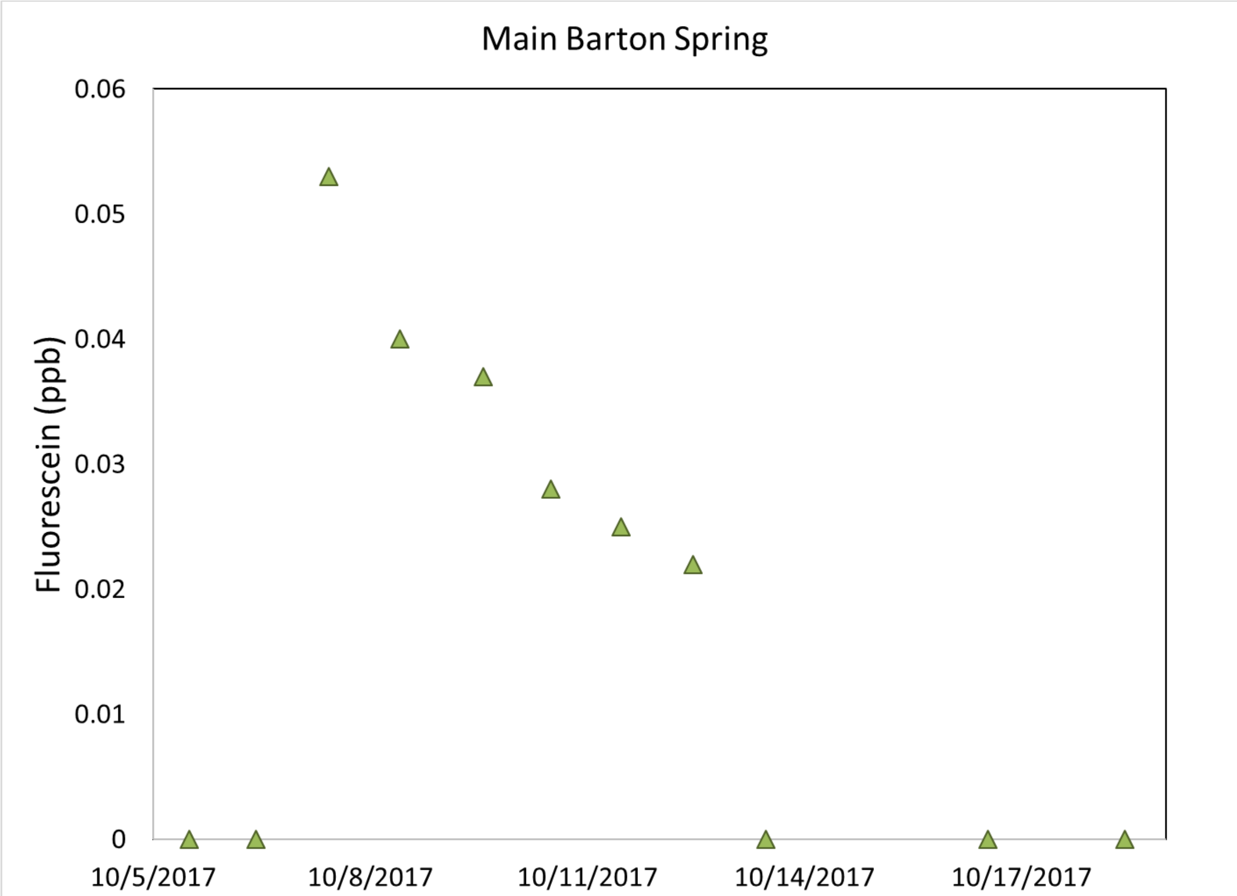

Figure 6. Breakthrough curve of Stoneledge Quarry Fluorescein concentration in water at Main Barton Spring. Sampling occurred only once per day, rather than once per hour as in the previous week.

After the pumping of water at Stoneledge Quarry from the southern ephemeral pond into the perennial northern injection pond on 27 October 2017, the detectable concentrations of Fluorescein at the four Barton Springs continued to decline to non-detectable levels and remained below detection limits. The decline was not measurably different from the declining trend established after the initial Fluorescein injection on 2 October 2017. A depth to water gauge measured 7.8 inches of water added to the northern pond, which was approximately 240,000 gallons (with a surface area of roughly 49,400 ft^2). By 30 October 2017, the water level had dropped 3 inches, and on 2 November 2017 the water in the pond had dropped an additional 1.2 inches. The water in the injection pond retained a visible green color from the Fluorescein tracer dye, though the concentration had likely reduced due to photo-degradation from sunlight. The green coloration was heterogeneous and moved with water currents. Samples of pond water were collected with more and less intense green color during visits between 19 October to 9 November 2017, and the concentration of Fluorescein fluctuated in the range between 0.381 to 36.1 ppb.

Data from the Fluorescein sensor at Main Barton Spring was compared with the laboratory results (Table 5). The sensor was designed and calibrated to detect Fluorescein; however, the method of detecting the other fluorescent dye tracers is similar enough that there seems to be a significant interference from the arrival of the Eosine tracer. The amount of Eosine and

Rhodamine WT that arrived at Main Barton Spring was two to one orders of magnitude greater than the amount of Fluorescein that arrived, respectively, based on the laboratory analyses. The tracer concentrations based on the laboratory analyses are assumed to be accurate based on years of rigorous testing, but the sensor concentrations do not accurately represent the tracer concentrations in the water except in a relative context of presence or absence. The difference in the amount of tracer seems to have overwhelmed the sensor so that the most obvious detection correlates with the Eosine peak concentration, as observed when the data from the Fluorescein sensor was plotted as concentrations over time, similar to the breakthrough curves (Figure 7). A closer inspection of the data curve reveals “shoulders” on the breakthrough recession that align with the peak concentrations of the Rhodamine WT and Fluorescein tracers. The timing of the peak arrival of Eosine matches closely between the water samples analyzed at the lab and the sensor results. The contemporaneous peaks also support the assumption that the Eosine peak concentration was captured in the hourly water samples despite equipment tampering. The “shoulder” arrival of the Rhodamine WT in the sensor data lags behind the peak lab results by about 14 hours, and this could be due to the peak being buried by the overwhelming amount of Eosine or by the fact that this sensor is not designed to specifically detect Rhodamine WT (communication from Joanna Howerton of Eureka and Tom Brumett of Turner Designs). Water samples during the peak arrival of Fluorescein were only collected once a day, so the exact time of arrival can only be estimated within a 24 hour window, and the sensor peak falls within that time period.

Table 5. Comparison between Fluorescein submersible sensor data and water sample analyses from the laboratory. The laboratory results are considered accurate due to more rigorous methods.

Tracer	**Lab Peak Arrival Time**	**Lab Peak Concentration (ppb)**	**Sensor Peak Arrival Time**	**Sensor Peak Concentration (ppb)**
Eosine	10/03/2017 13:20	11.5	10/03/2017 13:40	1.80
Rhodamine WT	10/03/2017 22:30	4.16	10/04/2017 12:10	1.16
Fluorescein	Between 10/06/2017 10:05 and 10/07/2017 10:15	0.053	10/06/2017 17:30	0.51

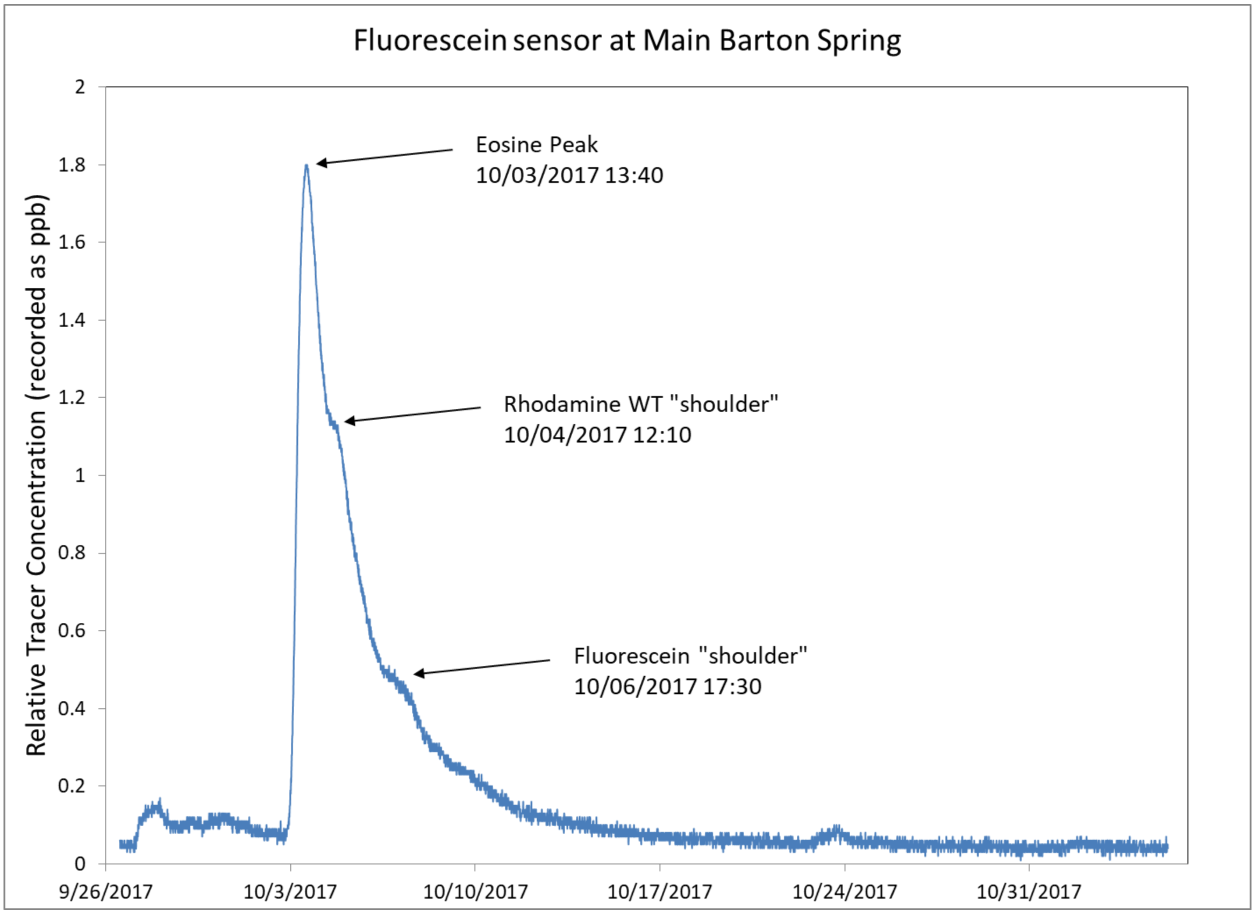

Figure 7. Data curve of tracer concentrations over time from the submersible Fluorescein sensor at Main Barton Spring. These concentrations are for comparison only and do not correlate with the accurate concentrations from the laboratory analyses.

Rhodamine WT was detected at Upper Barton Spring before and after injection at Fenceline Sink (Figure 8). The background detections before the injection occurred indicate a pre-existing source of the tracer in the aquifer, and the different concentrations between duplicate samples reveal variations in the sampling method. The duplicate background detections differ by 4.5 ppb, suggesting a minimum method variability of +/- 4.5 ppb. It is noteworthy that sorption of the tracer onto the charcoal can be impacted by the amount of flow that the receptor is exposed to; for example, a charcoal receptor hidden under a rock is not exposed to as much water, and thus dye, as a receptor located directly in the flow. The measured Rhodamine WT concentrations increased after the tracer injection; however, the increase was low relative to the variability revealed by the duplicate samples. Also, the higher concentrations on the daily charcoal receptor relative to the weekly receptor are suspicious. The daily charcoal receptor deployed 11 – 12 Oct measured 6.2 ppb higher than the closest weekly charcoal receptor, which is questionable because the charcoal deployed for a longer time period should have collected more dye. In addition, many of the Rhodamine WT detections were flagged by the lab as "*A fluorescence peak is present that does not meet all the criteria for this dye. However, it has been calculated as a positive dye result.*" Low detections of Fluorescein were measured during the week of 26 Sep – 3 Oct (background relative to the Stoneledge Quarry injection on 2 Oct) and the week of 13 – 20 Dec, and these were also flagged by the lab as "*A fluorescence peak is present that does not meet all the criteria for a positive dye result. However, it has been calculated as though it was the tracer dye.*" Other sources of background dye include human activity and remnant dye stored within the aquifer from previous traces. One way that previous tracer dye can be mobilized from aquifer storage and transported to a spring is via rain and the resulting stormwater pulse, such as the two inches of rain that fell on 26 Sep 2017, the day before dye was injected at Fenceline Sink. Upper Barton Spring receives a high volume of visitation, and the charcoal receptors were handled by curious visitors. Usually, it was evident that a charcoal receptor had been handled and returned to the sample site, though occasionally the receptor was left dry on shore or disappeared entirely. The results from Upper Barton Spring should be interpreted with caution, as discussed further in the next section.

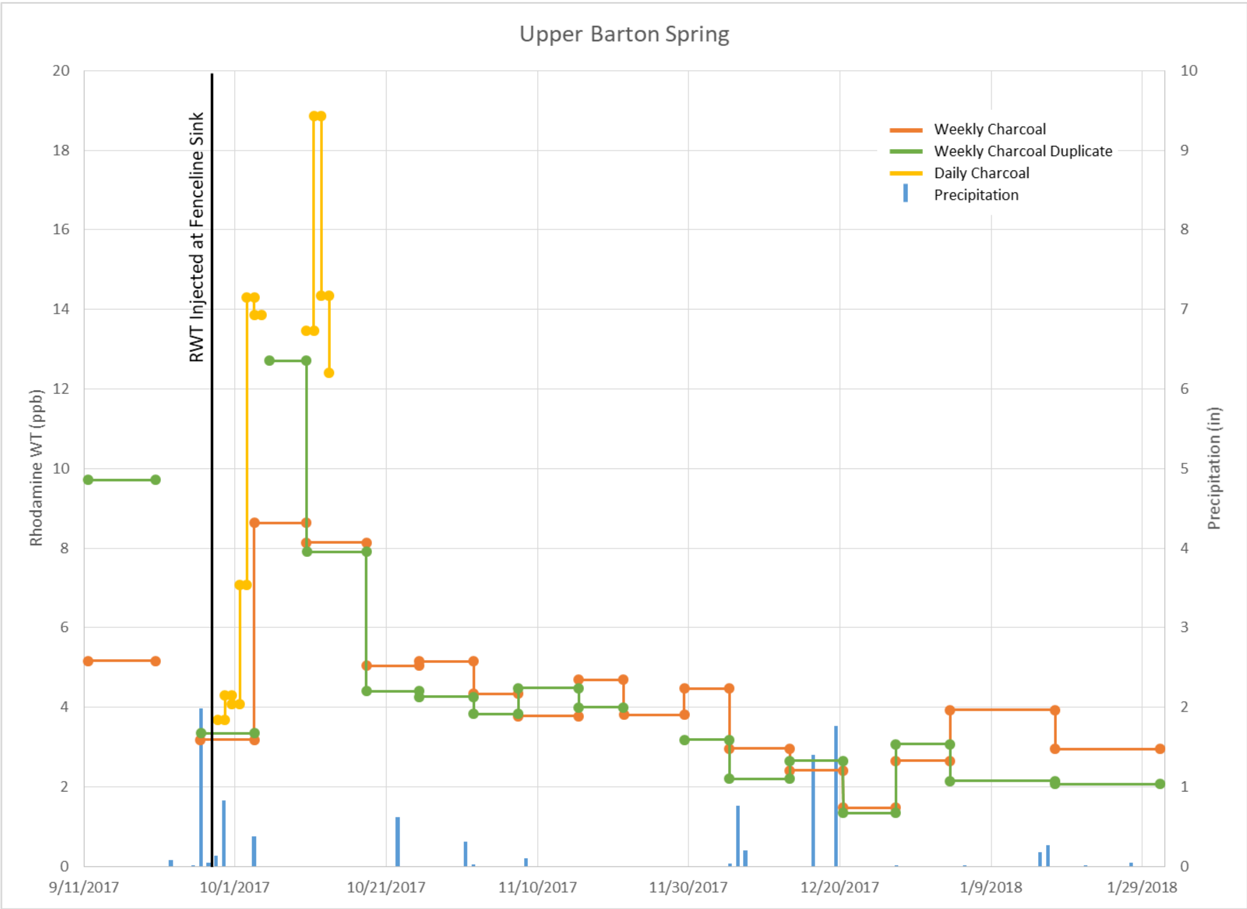

Figure 8. Rhodamine WT (RWT) concentrations at Upper Barton Spring. Concentrations derived from charcoal receptors were normalized to the daily average for each period of deployment. Weekly charcoal receptors were deployed for about 7 days, and daily charcoal receptors were deployed for about 24 hours.

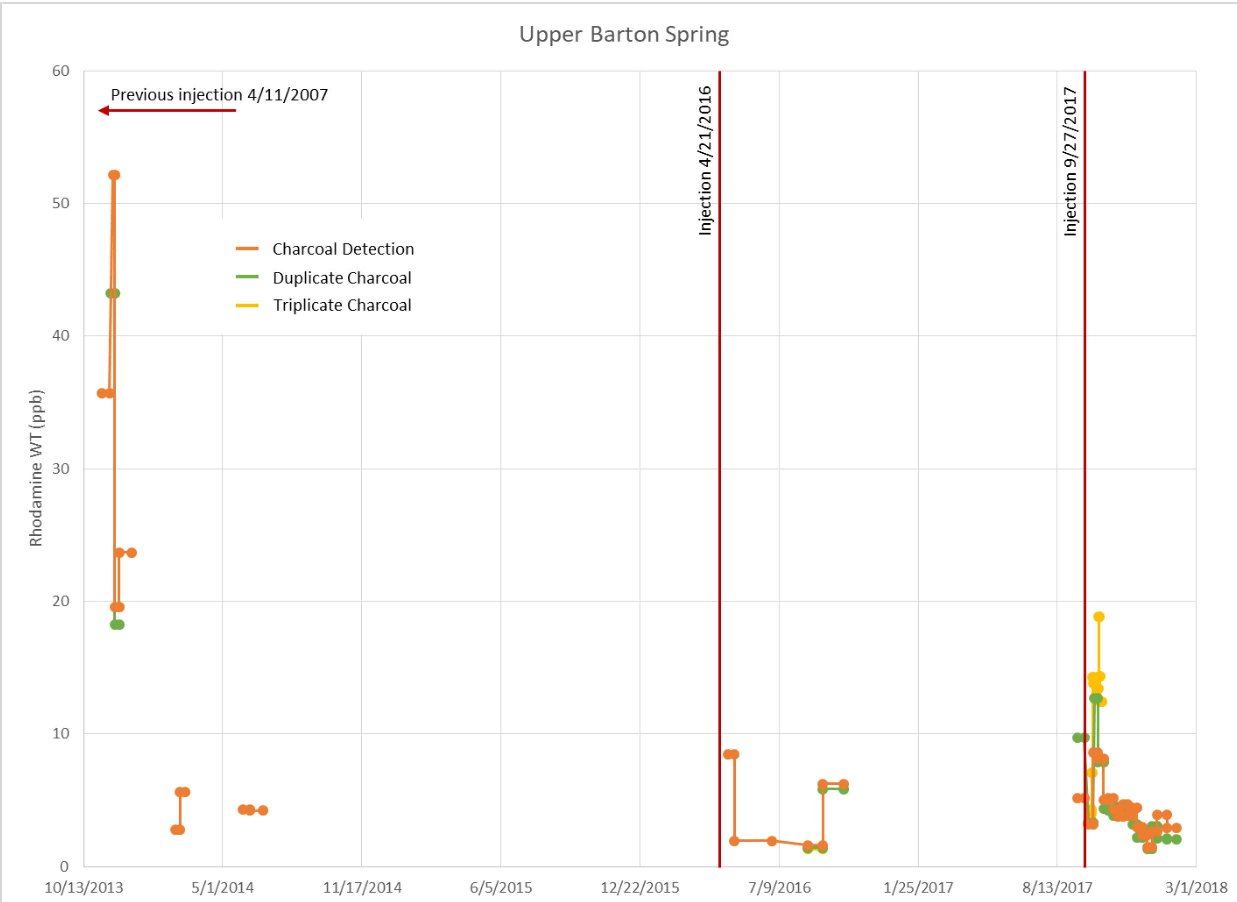

Figure 9. Persistent concentrations of Rhodamine WT (RWT) at Upper Barton Spring from 2013-2018. Samples collected during 2000-2010 had no detections of RWT tracer. RWT was injected in 2007 in Sandbur Cave (Bear Creek watershed) (Hauwert 2012) and in 2016 in F157a SH45 Cave (Slaughter Creek watershed). Injections of RWT occurred prior to 2007, but the 2007 injection, while not expected to reach Upper Barton Spring, was the most recent injection before the first detection of RWT at Upper Barton in 2013.

Discussion

The anticipated arrival of the groundwater tracers at the Barton Springs complex verifies the groundwater flow directions delineated by the last two decades of groundwater tracing in the Barton Springs Edwards Aquifer. While the velocity and specific paths of groundwater flow may vary with aquifer level and other temporal conditions, the convergence and general direction of flow in this region is reproducibly northeast towards Barton Springs. A summary table comparing the 2017 groundwater trace to the earlier traces in the vicinity (Crooked Oak Cave in 2000, Crippled Crawfish in 2002 and 2005, and Dahlstrom Cave in 1999) is included in Table 6. During the 2017 injections the aquifer level was relatively high, and during the 1999 and 2000 traces the aquifer level was at or near drought conditions. The tracer moved more quickly from all three injection sites to Barton Springs in 2017 than in 1999/2000. The fastest tracer arrivals occurred from Crippled Crawfish Cave during high aquifer conditions in 2002 and 2005. The percent of the tracer recovered was much higher from Crooked Oak Cave in 2017, despite similar volumes of Eosine tracer injected during both drought conditions and high aquifer levels. The percent recovered from Fenceline Sink was higher than that recovered from Dahlstrom Cave, while that recovered from Stoneledge Quarry was lower, but the types and volumes of dye tracer varied among all three sites. Since fluorescence intensities vary among the dyes, one dye is not equivalent to an equal amount of another (Aley 2002).

Table 6. Comparison summary with earlier traces near the 2017 injection sites. Eos = Eosine, Fl = Fluorescein, RWT = Rhodamine WT. [1]Water level elevation at the Barton Springs Edwards Aquifer benchmark Lovelady Well. [2]Combined springflow as reported by USGS gage 08155500. *Hauwert et al (2004). **Hunt et al (2004). ***Smith et al (2006).

Site	**Tracer Type & Amount**	**Watershed**	**Year**	**Aquifer Level[1] (ft above NAVD88)**	**Barton Springs Flow[2] (cfs)**	**Initial Arrival Velocity (mi/day)**	**Tracer Recovery (%)**
Crooked Oak Cave	Eos 25 lbs	Onion Creek	2000	464.9	28	0.8*	13*
Crooked Oak Cave	Eos 30 lbs	Onion Creek	2017	522.7	86	3.3	44.7
Crippled Crawfish Cave	Eos 35 lbs	Onion Creek	2002	512.6	99	5.0**	1**
Crippled Crawfish Cave	Eos 35 lbs	Onion Creek	2005	531.3	104	7.3***	5.2***
Dahlstrom Cave	Eos 10 lbs	Little Bear Creek	1999	480.4	37	0.7 – 1.1*	0.7*
Fenceline Sink	RWT 30 lbs	Little Bear Creek	2017	522.7	86	2.5	7.7
Stoneledge Quarry	Fl 50 lbs	Little Bear Creek	2017	522.3	86	2.5	0.17

In addition to different fluorescence intensities, the various dyes also sorb differently within natural aquifer conditions. In general, Fluorescein is the most resistant to sorption, followed by Eosine, and then Rhodamine WT which is much more prone to sorption (Aley 2002). The rapid travel time and high percentage of Eosine recovered indicates a strong connection between Crooked Oak Cave and Barton/Eliza/Old Mill Springs, and the Rhodamine WT recovery may demonstrate a comparably strong connection when the dye properties are taken into account. The low recovery of Fluorescein may indicate a weaker connection between Stoneledge Quarry and Barton Springs and/or an increase in local storage in the aquifer, or the low recovery may simply be due to Fluorescein entrapment within the pond sediments. The dye was expected to degrade due to sunlight and biological activity, and while some degradation may have occurred, the dye was still visible in the pond four and a half months after injection.

Pumping 240,000 gallons of water into the perennial northern pond in Stoneledge Quarry was an attempt to “push” more water and dye through to monitoring sites by increasing the hydraulic head. The subsequent drop in the water level over the course of six days equated to roughly 130,000 gallons of water, which either infiltrated into the ground or evaporated. The lack of additional Fluorescein detection at Barton Springs after the water was pumped into the pond likely reflects a combination of local storage in the aquifer and dye degradation. The Fluorescein dye may have degraded to concentrations that were too low to travel to Barton Springs despite high enough levels for a persistently green color. The highest concentration measured in the pond water (after presumed degradation) was 36.1 ppb, and the highest concentration detected at Barton Springs after the initial injection (before potential degradation) was 0.053 ppb. The low concentration detected at the springs indicates that a very high concentration of the tracer was needed to travel through the aquifer and arrive at the springs at a detectable level.

The faster tracer arrival from Crooked Oak Cave at Barton Springs in 2017 relative to 2000 may be due to the higher aquifer level, the excavation and exposure of deeper limestone conduits at the bottom of the cave, or a combination of both. Hauwert et al (2004) noted both that hydraulic connection is influenced by blockage from sediment fill and that travel rates were significantly higher during high groundwater-flow conditions. On one hand, the impermeable clay-rich fill removed from Crooked Oak Cave may have been a significant barrier to water flow along important conduits; while on the other hand, the water may have simply been flowing around the barrier to find alternative pathways to the conduits. The nature of the creek bed supports the hypothesis that water may have simply flowed around the barrier. Widespread dissolution joints are visible in the limestone bedrock in the bed of Onion Creek near Crooked Oak Cave with continuous karstic porosity, much like a natural sieve in the creek bed. Contrary to the hypothesis that water was simply flowing around barriers, some caves in Onion Creek form whirlpools which indicate the importance of discrete recharge features. Karst aquifers are heterogeneous with rapid water movement through enlarged conduits and slower movement through matrix porosity. Creeks over karst terrain also have varying recharge capacity into the underlying aquifer with some areas recharging significantly higher volumes of water than others, so discrete recharge features are frequently important to the overall function of the system. The comparison of tracing at different locations under different aquifer levels reveals generally faster arrival times during higher aquifer levels (Table 6). As a discrete feature, Crooked Oak Cave continues to demonstrate high levels of tracer recovery. During this trace, the tracer arrived more rapidly from Crooked Oak Cave than from Fenceline Sink or Stoneledge Quarry and a greater amount of tracer was recovered (Table 6). Additional groundwater tracing at different aquifer levels may shed more insight on which variable had a greater impact on the increased speed of tracer arrival from this cave.

Demonstrating the strong connection between Fenceline Sink on Little Bear Creek and Barton Springs supports the City's work to purchase and protect water quality protection lands in that area. Development is one of the biggest threats to water quality, and increased sediment transport to waterways as a result of development activity can plug recharge features in creeks. The citizens of Austin have supported the purchase and protection of undeveloped land in creeks over the recharge zone for the purpose of protecting water quality in the aquifer. Over 2,800 acres of the Little Bear Creek watershed is water quality protection land, a mix between conservation easements and fee simple lands, protected from development impacts by the City.

The results of the current trace at Upper Barton Spring should be interpreted with caution. Upper Barton Spring has previously been traced and connected to the Sunset Valley groundwater basin (Hauwert et al 2004), so a connection to the Manchaca groundwater basin area traced during this study would be a new interpretation for the system. If a connection exists, it may be an upper-level pathway that is active only during high aquifer levels. Background Rhodamine WT levels indicate an error margin of +/- 4.5 ppb which encompasses most of the range of concentrations detected at the site. The Rhodamine WT concentrations detected at Upper Barton Spring were about two orders of magnitude smaller than the concentrations detected at Main Barton, Eliza, and Old Mill Springs. Rhodamine WT detections at Upper Barton Spring have been persistent since 2013, and the concentrations have been similar for the last 4 years from 2014-2018 (Figure 9). The most recent Rhodamine WT tracer injection before 2013 was six years prior at Sandbur Cave in 2007 in the Bear Creek watershed; however, this site was not expected to contribute to Upper Barton Spring. The most recent Rhodamine WT tracer injection before this trace in 2017 was during 2016 at F157a SH45 Cave in the Slaughter Creek watershed, but the dye concentration did not obviously increase after that injection. The first injection of Rhodamine WT in the Barton Springs Edwards Aquifer was 17 years earlier in 1996 at the Mopac Bridge at Barton Creek, and the geographically closest injection was in 2006 at Skunk Hollow Tributary. Rhodamine WT was used as a tracer at nine different sites prior to 2013, and none of those injections occurred in the Sunset Valley groundwater basin. Persistent detections are not unusual, as established by White et al (2015) who detected Rhodamine WT in a karst aquifer 18 years after the dye was injected for a groundwater tracing study. The Rhodamine WT at Upper Barton Spring probably sorbed to sediments (like cave mud) during earlier groundwater traces by COA and BSEACD and is slowly releasing from those sediments in the aquifer. The dye detected at Upper Baron Spring during this trace almost certainly did not result from the current trace. The small and lab-flagged detections of Fluorescein at Upper Barton Spring were also two orders of magnitude smaller than the detections at the other three springs. The Fluorescein detections could be due to visitor activities in the spring, such as laundry washing, which has been observed during monitoring visits.

Few detections were observed at wells during this groundwater trace, and this was similar to past tracing studies (Hauwert et al 2004). The Barton Springs are the major resurgence for this groundwater system, and the evidence indicates direct conduit transport with preferential flow from the recharge zone to the springs. Current and historical tracing indicate that most of the sampled wells do not lie directly on the main conduits within the aquifer. Since conduits occupy a smaller footprint than the surrounding bedrock matrix, the probability that a well will intercept one of the conduits or preferential flow-paths is low. Well 58-50-7DF may be one of the few wells located near a direct groundwater conduit. Tracers from Crooked Oak Cave and Stoneledge

Quarry were detected with confidence in this well. No well detected all three tracers. Tracers were recovered from this well in 2000 and thought to be residual from the 1999 injection at Dahlstrom Cave on Little Bear Creek. Hauwert et al (2004) found that tracers typically arrived more slowly at wells than at the springs, and this has implications for dispersion and diffusion within the aquifer. Dispersion and diffusion inform the evaluation of potential storage in the aquifer. Identifying wells near preferential groundwater flow-paths is helpful for mapping the aquifer flow, could indicate that these wells are more sensitive to contamination, and assists with choosing valuable monitoring points for groundwater studies.

Background levels of tracers detected at San Marcos Springs (Crater Bottom, Diversion, Weissmueller, and the Spillway), Well 58-57-3DO, and Well 58-57-512 were present before dye was injected for this project, and the dye concentrations did not reflect any trends during the sampling period. Tracers at Well 58-57-3DO and Well 58-57-512 are likely remnants of previous traces by COA and BSEACD. The background tracers at San Marcos Springs are also probably derived from earlier traces, and could come from tracing studies aimed at delineating the shifting groundwater divide between the Barton Springs segment and the San Antonio segment of the Edwards Aquifer by COA, BSEACD, and EAA or from tracing studies further south in the San Antonio segment by EAA. Since the dyes used for groundwater tracing are not perfectly conservative, some sorption occurs into sediments in the aquifer (Aley 2002). The accumulated dye tracers may then release over time, such as those observed at Upper Barton Spring and in the White et al study (2015). The background tracer presence at San Marcos Springs, Well 58-57-3DO, and Well 58-57-512 are of unknown duration, and additional investigation may yield more information about the source or behavior (response to aquifer levels, storms, etc.) of the tracers at these sites.

Conclusions

Tracers from all three injections were conclusively detected at Barton Springs. Tracers moved through the aquifer at rates between 2.4 and 3.3 miles per day (12,700 to 17,400 ft/d). These rates are comparable to other injections in the BSEA during relatively high aquifer levels. Crooked Oak Cave on Onion Creek is connected to Barton Springs via a direct conduit flow-path as indicated by rapid migration and large tracer recovery volume. Fenceline Sink on Little Bear Creek is also directly connected to Barton Springs via a conduit flow-path as indicated by rapid migration, although at a slightly slower velocity than from Crooked Oak and with relatively large tracer mass recovery. Stoneledge Quarry connects to Barton Springs via a rapid flow-route as indicated by the fast migration time, but the small amount of tracer recovered indicates either a high level of sorption in the sediments of the pond, a significant potential for storage in that portion of the aquifer, and/or that the volume of water movement out of the quarry lake is fairly small during steady state (non-flood) conditions.

Background tracer concentrations were observed at several sites. The Rhodamine WT at Upper Barton Spring has been persistent for the last 5 years. The low level tracers at San Marcos Springs, Well 58-57-3DO, and Well 58-57-512 may warrant additional investigation. These dyes are probably present in the system due to groundwater tracing studies performed in previous years by COA, BSEACD, and EAA. Accumulated dye tracers are likely releasing from aquifer sediments. The long-term presence of dye tracers in an aquifer system indicate the potential for contaminant storage and flow retardation (White et al. 2015).

Groundwater flow data from tracing studies are used to evaluate locations of potential recharge enhancement projects, delineate regional water budgets, assess impacts of stormwater runoff, and prepare emergency management plans in case of hazardous spills. For example, observations from this study will inform the potential recharge enhancement project at Stoneledge Quarry. Information gained from this phase of tracing demonstrates the sensitivity of the Little Bear Creek watershed, the Onion Creek watershed, and the Barton Springs Edwards Aquifer to acute and chronic contamination and catastrophic spills. , Protection of this critical resource also helps to protect Lady Bird Lake and the Colorado River downstream of Barton Springs.

One of the primary tools for protecting water quality is the management and protection of open lands in source-water areas. Undeveloped land provides a valuable natural service by filtering and collecting high quality water in streams and recharge features where present. Accurate information about the location and extent of recharge areas and groundwater basins is best obtained via groundwater tracing studies (Hauwert 2016), and studies like this one continue to improve our knowledge about where the water feeding the springs comes from.

Recommendations

The next step in applying the results of this groundwater trace will be to fine-tune and reevaluate the delineation of specific flow-paths using the previous two decades of tracing results, the results of this study, the local geology, and the mapped potentiometric surface of the aquifer. Future application of this data may also include groundwater modeling for the Barton Springs Edwards Aquifer. The knowledge gained from this study will be used in management of the natural water resources in the Barton Springs Zone of Austin and planning for future needs. While Barton Springs is the most famous of Austin's springs, all of our springs are valuable resources which provide baseflow to creeks and aquatic ecosystems, so understanding the transport and storage of water within the aquifer is an important component to understanding our overall natural water resources.

As described above, aquifer dynamics vary with different conditions such as aquifer level, and additional tracing would constrain the causes of variations in travel time and direction. A useful follow-up groundwater tracing study would evaluate aquifer behavior during storm events, which has not been examined in this aquifer before. Understanding the dynamics of high-volume water transport through the aquifer during storm events will improve our ability to protect aquifer resources and downstream resources.

Continued consideration of open space conservation is suggested as an ongoing strategy for protection of downstream resources. Rapid development in central Texas continues to threaten the quality and quantity of our water resources, while simultaneously removing open spaces and their natural services (like water filtration) from the landscape. Ongoing high quality management of existing water quality protection lands and education about this vital program is recommended for continued success.

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