January 2005

Dye tracing recharge features under high-flow conditions, Onion Creek, Barton Springs Segment of the Edwards aquifer, Hays County, Texas

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technical paper

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Abstract

The Barton Springs/Edwards Aquifer Conservation District, in cooperation with the City of Austin, injected non-toxic organic dyes into two caves within the Barton Springs segment of the Edwards aquifer to trace groundwater flow paths and determine groundwater-flow velocities. Antioch and Cripple Crawfish Caves are located about 14.0 and 17.5 miles south, respectively, of Barton Springs, the primary discharge point from the aquifer. Twenty-five pounds of sodium fluorescein were injected into Antioch Cave on August 2, 2002 and arrived at Barton Springs between 7 to 8 days after the injection. Thirty-five pounds of eosine were injected into Cripple Crawfish Cave on August 6, 2002 and arrived at Barton Springs in less than 3.5 days after the injection. Under high spring flow conditions, groundwater-flow velocities from Antioch Cave and Cripple Crawfish Cave to Barton Springs are estimated to be 2.0 and 5.0 miles per day, respectively. Detections of dye at water-supply wells indicate a karst system composed of multiple diverging flow paths from these caves that, while recharging surface water, create mounds in the potentiometric surface. Groundwater flow then re-converges as it flows northeast, before discharging at Barton Springs. Interpreted flow paths generally coincide with troughs in the potentiometric surface in the hydraulically unconfined zone and ridges in the potentiometric surface in the hydraulically confined zone of the aquifer. Most interpreted flow paths are oriented normal to potentiometric surface contours. However, some interpreted flow paths are oriented parallel to potentiometric surface contours, indicating a highly anisotropic flow system. Groundwater flow was traced in wells along paths that are parallel to the N40E (dominant) and N45W (secondary) fault and fracture trends presented on geologic maps. Rapid groundwater flow velocities to springs and detections at wells indicate that conduits are an important component of flow, and the bimodal structural grain has influenced the development of conduits in the Edwards aquifer.

Introduction

The Barton Springs segment of the Edwards aquifer (Barton Springs aquifer) is an important groundwater resource for municipal, industrial, domestic, recreational, and ecological needs. Approximately 50,000 people depend upon water from the Barton Springs aquifer as their sole source of drinking water, and the various spring outlets at Barton Springs are the only known habitats for the endangered Barton Springs Salamander. The Barton Springs aquifer is located south of the Colorado River, extending south to the City of Kyle, and generally between Interstate 35 and FM 1826 (Figure 1).

For this study dyes were injected in two caves and traced to numerous wells and to Barton Springs. This document summarizes groundwater dye tracing studies that have led to a better understanding of groundwater flow paths and velocities in the Barton Springs aquifer.

Purpose and scope

The Barton Springs/Edwards Aquifer Conservation District (District), in cooperation with the City of Austin, injected non-toxic organic dyes into two caves within the Barton Springs aquifer in August 2002. The objectives of this groundwater tracing study were to determine the time-of-travel, direction, and destination of groundwater flow and to better delineate the groundwater divide between the Barton Springs and San Antonio segments of the Edwards aquifer south of Onion Creek.

Previous tracing investigations

The Edwards Aquifer Research and Data Center successfully detected groundwater tracers several miles from their injection points within the San Marcos Springs area of the adjacent San Antonio segment of the Edwards aquifer (Ogden and others, 1986).

A small amount of tracer was injected by the U.S. Geological Survey in a well about 200 feet southwest of the main Barton Springs outlet in the pool. The tracer initially appeared about 10 minutes after injection and peaked about one hour after injection (Slade and others, 1986).

Between 1996 and 2001 the District, in cooperation with the City of Austin, performed 20 injections of dye into 17 different features, including features on Onion Creek (Hauwert and others, 2002). Those traces delineated several groundwater basins and rapid groundwater flow velocities of 0.5 to 7.0 miles per day depending on spring flow conditions in the aquifer (Hauwert and others, 2002; BSEACD, 2003).

Hydrogeologic setting

The Edwards aquifer is composed of the Cretaceous-age Edwards Group (Kainer and Person formations) and the Georgetown Formation, which consist primarily of limestone and dolomite about 500 feet thick (Rose, 1972; Small and others, 1986). The Edwards aquifer of central Texas is a dissolution-modified, faulted, karst aquifer composed of three hydrologically distinct segments: the southern (San Antonio) segment, the Barton Springs segment (Barton Springs aquifer), and the northern segment.

Geologic studies in central Texas have delineated faults (Small and others, 1996) and several informal stratigraphic members of the Kainer and Person formations of the Edwards Group (Rose, 1972), each having distinctive hydrogeologic characteristics. Faulting is related to the Balcones Fault system with bimodal trends of N40E (dominant) and N45W (secondary), with total offset of about 1,100 feet across the Barton Springs aquifer (Alexander, 1990).

The areal extent of the Barton Springs aquifer is about 155 square miles (Figure 1). The primary discharge for the Barton Springs aquifer occurs at Barton Springs, located within Barton Creek near the confluence with the Colorado River, near the center of Austin. Barton Springs is a complex of springs that are a major recreational attraction for the city and sustain base-flow to Town Lake (Colorado River). The long-term average spring flow of Barton Springs was 53 cubic feet per second (cfs) (City of Austin analysis of U.S. Geological Survey water resources data from 1917 to 1995). The lowest flow measurement recorded for Barton Springs was 9.6 cfs in 1956 (Brune, 2002).

The eastern boundary of the aquifer is known as the saline-water zone, characterized by a sharp increase in dissolved constituents (greater than 1,000 mg/l total dissolved solids) and a decrease in permeability (Flores, 1990). The western boundary of the aquifer is poorly defined and is delimited by Balcones Faulting and saturated thickness. The southern hydrologic divide between the Barton Springs and the San Antonio segments is estimated to occur between Onion Creek and the Blanco River based on potentiometric-surface elevations and recent dye tracing information (LBG-Guyton, 1994; Hauwert and others, 2004). The injection sites are located close to the approximated location of the groundwater flow boundary separating the Barton Springs and San Antonio segments.

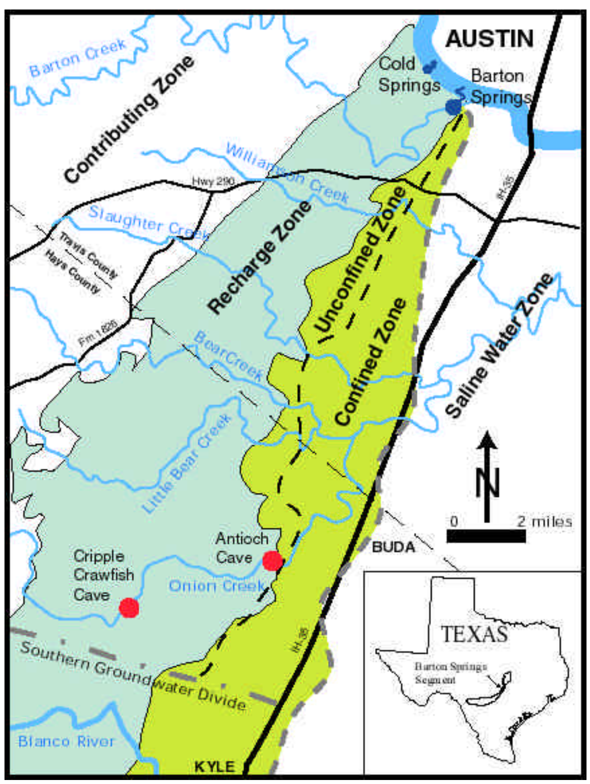

Figure 1. Location map of the study area.

The San Antonio segment is the largest and most prolific water-producing segment of the Edwards aquifer. The segment extends south and southwest from the City of Kyle in Hays County to Brackettville in Kinney County, a distance of greater than 180 miles. The two largest springs in this segment are Comal and San Marcos springs with mean flows reported by the U.S. Geological Survey of 264 cfs and 159 cfs, respectively. San Marcos Springs is located in the City of San Marcos, Hays County. The springs are a complex of several large and numerous small springs that discharge into Spring Lake, forming the headwaters of the San Marcos River. Previous investigators have divided the springs into a northern and southern group, each displaying unique flow patterns and chemistry. From groundwater tracing studies, the northern cluster of springs in Spring Lake is known to discharge groundwater that is recharged north of San Marcos Springs (Ogden and others, 1986). Antioch and Cripple Crawfish caves are located 13.4 and 11.4 miles north of San Marcos Springs, respectively.

Groundwater tracing in the Barton Springs aquifer has defined two groundwater basins with flow toward Barton Springs and a third smaller groundwater basin with flow toward Cold Springs. No dyes injected in Onion Creek or further north have been traced to San Marcos Springs (Hauwert and others, 2002). Groundwater generally flows west to east across the recharge zone and then converges with northeast-trending preferential groundwater flow paths parallel to major faulting, and then flows toward Barton Springs. Preferential flow paths were traced along troughs in the potentiometric surface, indicating zones of high permeability. Rates of groundwater flow determined from dye tracing were very rapid under high flow conditions (4 to 7 miles per day) and less rapid (up to 1 mile per day) under low spring flow conditions (Hauwert and others, 2002; Hauwert and others, 2004). Spring flow conditions are considered high if discharge exceeds 70 cfs and low if below 35 cfs.

Most of the water that recharges the Barton Springs aquifer infiltrates via discrete features such as caves, sinkholes, fractures, and solution cavities within the primary stream channels that cross the recharge zone. Onion Creek is the largest contributor of recharge to the aquifer. The remaining recharge enters the upland areas and the tributary channels within the recharge zone (Slade and others, 1986; BSEACD and COA, 2001).

Two large-capacity recharge features, Antioch and Crippled Crawfish caves, were injected with dyes as part of this study. Both caves are located near the lowest portion of the stream cross section of Onion Creek. Antioch Cave is the largest-capacity recharge feature documented in the Barton Springs aquifer and is located at the eastern edge of the recharge zone, near the City of Buda. Antioch Cave is a shaft developed in the Georgetown Formation that penetrates into the Edwards Group (Person Formation). The District constructed and maintains a water-quality structure consisting of a large concrete vault with a 36-inch pneumatic valve controlling the entry of water from Onion Creek (Figure 2). During one period of high stream flow, flow into the structure was reported to have averaged about 46 cfs with a peak of 94 cfs. Cripple Crawfish Cave is developed within the Kirschberg member of the Kainer Formation of the Edwards Group. Recharge from the upper two-mile stretch of Onion Creek on the recharge zone, which includes Cripple Crawfish Cave, accounts for one-third of the total flow loss (recharge) from Onion Creek on the basis on several flow surveys (BSEACD and COA, 2001).

Figure 2. **Concrete vault and valve system above Antioch Cave within Onion Creek (left). Sodium fluorescein dye being poured into the top of the vault (right).**

Methods of study

Groundwater tracing techniques are recognized as the only direct method of locating groundwater flow paths and determining travel times in karst aquifers. Groundwater dye tracing involves the introduction of non-toxic, organic dyes into the subsurface via injection points, such as caves, sinkholes, and wells, and analyzing charcoal receptors and water samples taken from discharge points such as wells and springs. Alexander and Quinlan (1992) discuss the methodology of groundwater tracing with dyes in karst terrains.

Groundwater tracers (dyes) and injection sites

Two traditional, well-documented, and distinct organic dyes were injected into the two natural recharge features within Onion Creek using creek water that was naturally recharging the aquifer. The dyes used in this study were sodium fluorescein (Acid Yellow 73, D&C Red, 45350) and eosine (Acid Red 87, D&C Red No. 22, 45380). Eosine and sodium fluorescein mixtures containing approximately 75 percent dye equivalent and 25 percent diluent were purchased as a powder. These dyes have been evaluated to be suitable for this and other studies due to their physical characteristics, safety for drinking water supplies and aquatic habitats, and low background concentrations (Smart, 1984; Field and others, 1996).

Twenty-five pounds of sodium fluorescein were injected into Antioch Cave on August 2, 2002. Dye was injected by pouring the dye mixture directly into the top of the vault while the side valve was open, allowing recharge into the structure and cave (Figure 2). Thirty-five pounds of eosine were injected into Cripple Crawfish Cave on August 6, 2002. The District and the City of Austin injected dye into Cripple Crawfish Cave through a PVC pipe inserted into the feature from the bank (Figure 3).

Sample collection

To monitor the movement of the dyes, charcoal receptors were placed in springs and many accessible wells. Receptor sites were monitored using a combination of charcoal receptors, which contain adsorbent activated charcoal in mesh packets, and water samples. Grab samples provide information on the instantaneous dye concentrations in the water. Charcoal receptors adsorb dye from the water and allow detection of dyes over extended periods of time. Charcoal receptors were placed at springs (Figure 4) and wells and collected periodically to determine a positive or negative result.

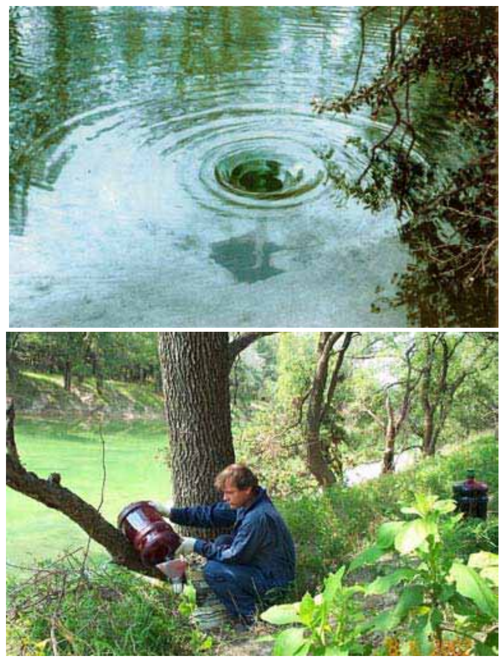

Figure 3. Vortex formed above Cripple Crawfish Cave (top). Nico Hauwert pouring eosine into a pipe inserted into Cripple Crawfish Cave on Onion Creek (bottom).

Figure 4. Brian Hunt retrieving receptors at San Marcos Springs (diversion outlet).

Spring sampling locations include Barton Springs (Main, Eliza, Upper, and Old Mill spring outlets) and San Marcos Springs (Crater Bottom, Salt and Pepper, Weismueller, Diversion, and Deep Hole spring outlets and the spillway of the dam forming Spring Lake). Spring sites were monitored for nine days with charcoal receptors before dye injection to detect background presence of dyes for Barton Springs. Spring receptors and grab samples were analyzed at the Ozark Underground Laboratory in Missouri. Sampling supplies were provided by the laboratory, and sampling procedures outlined by the laboratory were followed. After injection of the dye, charcoal receptors were collected daily along with grab samples at Barton Springs. Daily receptors were collected beginning August 9, 2002 and stopped September 19, 2002 and weekly receptors began thereafter at Barton Springs until November 4, 2002. Water samples were taken from an ISCO 3700 Automatic Compact Sampler at 4-hour intervals at Barton Springs from August 13, 2002 to October 8, 2002. Receptors and grab samples were collected at San Marcos Springs every three to four weeks starting August 1, 2002 until August 14, 2003.

Fifty-three wells were monitored for the presence or absence of dyes in groundwater. These wells had charcoal receptors within a perforated PVC pipe attached to a spigot allowing untreated groundwater to pass through the receptor each time the well pump cycled on. Charcoal receptors were collected about every three weeks starting July 16, 2002 until January 22, 2003. Charcoal receptors placed at wells were assembled by the District with supplies provided by the Edwards Aquifer Authority.

Preparation and analyses of samples

Charcoal and grab samples from San Marcos and Barton Springs were sent to Ozark Underground Laboratory for quantitative analyses on a spectrofluorophotometer. The laboratory's instrumentation analyses, protocols, and procedures are outlined in Aley (1999, 2000). The laboratory's detection limits for sodium fluorescein and eosine are 10 and 35 parts per trillion (ppt) for receptors and 5 and 8 ppt for water samples.

Charcoal receptors from wells were analyzed for qualitative results at the Edwards Aquifer Authority following procedures outlined by Geary Schindel and Steve Johnson (personal communication) and are only generally described here. Charcoal receptors were eluted in a solution containing 95 percent of a 70 percent solution of isopropyl alcohol in water and 5 percent of ammonium hydroxide or sodium hydroxide. The elutant was then placed in a glass vial for analysis. These samples were analyzed using a Perkin Elmer Model LS50B scanning spectrofluorophotometer. The spectrofluorophotometer performs a series of scans (ranging from 460 to 560 nanometers[nm]) exposing the samples to a known wavelength of light and monitors for emissions of light from the dye. Each of the dyes fluoresces at a known wavelength. Sodium fluorescein and eosine fluoresce around 490 nm and 520 nm, respectively (Figure 5). The detection limit for the receptors is approximately 12 parts per trillion (Geary Schindel and Steve Johnson, personal communication).

Positive dye recovery interpretation

The procedures and criteria for a quantitative analysis and positive detection of spring grab and charcoal samples are described in detail by Aley (1999, 2000). A certificate of analysis for each group of samples analyzed by Ozark Underground Laboratory contain analytical results from the laboratory's spectrofluorophotometer and laboratory interpretation of the results.

Criteria for determining a qualitative positive detection from charcoal samples from wells were generally as follows:

1) the fluorescence peak lies within the normal emission wavelength for the specific tracer;
2) the shape of the fluorescence peak is typical of the specific tracer;
3) the fluorescence amplitude (intensity) is greater than background intensity; and
4) other factors do not overwhelmingly suggest that the fluorescence did not result from the injected dye.

Analytical results were evaluated with the four criteria above to interpret the recovery of dye (Table 1).

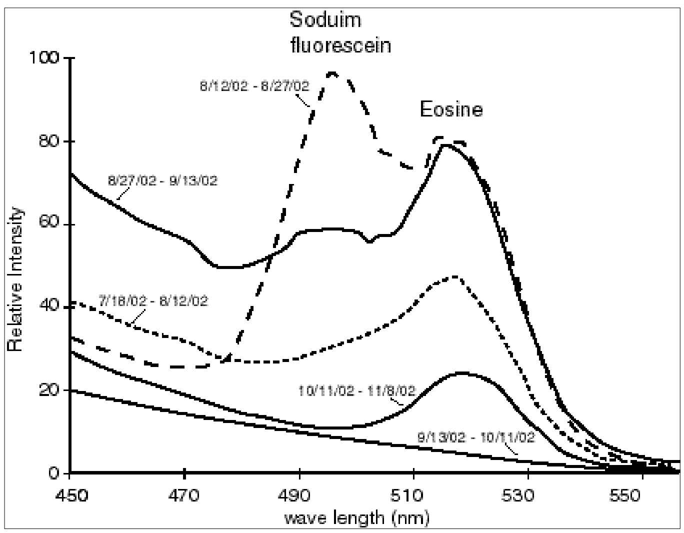

Figure 5. Example of charcoal sample analysis from well 5850511 (Johnson domestic well). Sodium fluorescein and eosine fluoresce around 490 nm and 520 nm, respectively.

Table 1. Interpretation of dye (EAA) results.

Abbreviation	Interpretation	Criteria
ND	Below Quantitation Limit	Fluorescence is below the quantitation limit and none of the criteria are met.
B	Background	Criteria #1 and #2 only.
+	Positive	Aspects of all four criteria are partially met, and as a whole indicate a positive dye recovery.
++	Very Positive	All four criteria are met.
+++	Extremely Positive	All four criteria are met with dye amplitude (concentration) greater than 10 times above background.

Mass recovery

Recovery of the injected tracer mass is calculated by using measured spring concentrations and spring discharge outlined in Field (2002). The percent recovery of dye is the ratio of recovered tracer mass to the mass of tracer injected. Tracer mass described in this report refers to pure dye mass and not dye mixture amounts. Breakthrough curves from the tracer tests were evaluated with spreadsheets and the numerical program Q-Tracer (Field, 2002) to determine mass recovered and some hydraulic parameters. Spring flow for each Barton Springs orifice was assumed to be 81 percent, 9 percent, and 10 percent for Main, Eliza, and Old Mill springs, respectively, of the total spring flow reported by the U.S. Geological Survey (David Johns, personal communication).

Quality control

Each dye receptor was handled following standard chain-of-custody protocols. Trip blanks, consisting of charcoal packets handled by field personnel during the course of sampling, were analyzed. These samples test for cross contamination between sites or contamination from other materials, to which field personnel might have been exposed.

Eluent and charcoal blanks were analyzed for quality control measures. Sodium fluorescein, eosine dye standards, and tap water were also analyzed on the Edward Aquifer Authority's spectrofluorophotometer to confirm operation and consistency of the instrument.

Results

Groundwater dye tracing results from samples collected at Barton Springs are presented in Table 2. No positive recoveries attributed to these injections were made at San Marcos Springs. Groundwater dye tracing results from samples collected at wells are summarized in Tables 3 and 4. Estimated and inferred groundwater flow paths between dye injection and recovery sites were created using potentiometric surface (water level) maps and structures from geologic maps (Figure 6). Detections of dye at water-supply wells indicate a karst system composed of multiple diverging flow paths from these caves, which re-converge as groundwater flows to the northeast, discharging at Barton Springs. Flow paths were observed within the unconfined zone and within the hydraulically confined portion of the aquifer.

Breakthrough curves and mass recovery

Breakthrough curves were prepared from the laboratory results, from which the initial travel time, duration, and peak concentrations were calculated. Breakthrough curves, which are graphs displaying dye concentrations over time, were evaluated to characterize the dye response at the springs (Figure 7).

Recovery of the dye mass was calculated using spreadsheets and the program Q-Tracer (Field, 2002). Both methods resulted in nearly identical mass recovery estimations for sodium fluorescein (Table 2). Eosine dye mass recovery is a minimum value, because the initial arrival was not sampled.

Recovery of dye mass at Barton Springs represents a minimum of mass recovered. Potentially more dye mass could have discharged to the Barton Springs complex below the detection limit or through other springs (such as upper Barton Springs). Adsorption of the dye on sediment could also account for the low mass recovered.

Background florescence and potential contamination

Low levels of background eosine were detected at Upper Barton Springs prior to injection and throughout the duration of the study. Accordingly, no positive dye trace recovery at Upper Barton Springs was noted from this study. No background eosine was detected at the remaining spring orifices. Sodium fluorescein was not detected at background levels at any of the spring orifices.

Table 2. Barton Springs dye recovery data.

Injection site	**Antioch Cave**	**Cripple Crawfish Cave**
Trace ID	M"	S
Dye	Sodium fluorescein 25 lbs	Eosine 35 lbs
Injection Date	8/2/2002	8/6/2002
Spring Flow (cfs) at time of injection	99	98
Minimum Distance from injection to springs	14.0 mi 22.6 km	17.5 mi 28.2 km
Distance corrected for sinuosity (1.3x)**	18.3 mi 29.4 km	22.8 mi 36.6 km
Dye First Arrival (hrs)**		
Main	170	<84.2
Eliza	169	<83.5
Old Mill	168	<83.2
Time to peak tracer concentration (hrs)**		
Main	311	
Eliza	286	
Old Mill	339	N/A
Mean tracer transit time (hrs)**		
Main	413	
Eliza	261	
Old Mill	373	N/A
Mean Tracer Velocity (km/d)**		
Main	1.7	
Eliza	2.7	
Old Mill	1.9	N/A
Maximum tracer velocity (km/d)**		
Main	4.2	
Eliza	4.2	
Old Mill	4.2	> 10.8
Maximum tracer velocity (mi/d)	2.0	5.0
Dye Mass Recovered (grams):		
Main	77.7	157.4
Eliza	1.90	4.80
Old Mill	7.00	40.4
Minimum Dye Mass Recovery	0.8 %	1.3%*

*First arrival of the dye was not sampled; therefore, time and mass parameters represent minimum values.
**Result using the program Q-Tracer (Fields, 2002).

Table 3. Eosine recovery at wells.

Map No.	SWN*	DD lat	DD long	Site name	Result	Qualitative recovery	No. days for first detection
1	5850511	30.17159	-97.82578	Johnson	Eos	++	up to 6
2	5850703	30.13813	-97.85522	Marbridge	Eos	++	up to 6
3	5857606	30.04773	-97.88367	Cindy Barton	Eos	+++	22 to 45
4	5857913	30.03389	-97.89111	Hays HS	Eos	+++	111 to 118
5	58507DF	30.14830	-97.84378	Figueroa	Eos	+	6 to 21
6	58575T4	30.05853	-97.92112	Ruby #4	Eos	+++	6 to 24
7	58576RH	30.04560	-97.89873	Ray Holt	Eos	+++	up to 1

*State Well Number

Table 4. Sodium fluorescein recovery at wells.

Map No.	SWN*	DD lat	DD long	Site name	Result	Qualitative recovery	No. days for first detection
1	5850511	30.17159	-97.82578	Johnson	Fl	++	10 to 25
8	5850845	30.12383	-97.82638	Arroyo Double	Fl	++	10 to 26
9	5857307	30.09986	-97.88229	Dahlstrom	Fl	+	98 to 129
10	5857903	30.03850	-97.88617	Negley	Fl	++	5 to 12
11	5858111	30.12319	-97.87226	City of Hays	Fl	++	10 to 25
12	5858121	30.10503	-97.86236	Leisurewoods #5	Fl	+++	up to 12
13	5858128	30.08725	-97.85361	Wright	Fl	+++	up to 12
5	58507DF	30.14830	-97.84378	Figueroa	Fl	+	42 to 70
14	58507PL	30.14581	-97.84589	Guajado	Fl	++	10 to 25
15	5850835	30.14671	-97.81308	Onion Creek C.C.	Fl	+	98 to 129
16	58573ES	30.11153	-97.88165	Swanson	Fl	++	10 to 25
17	58581DL	30.08587	-97.85644	Levin	Fl	+++	up to 12
18	58581JK	30.08645	-97.85426	Kortan	Fl	++	up to 12
19	58581KM	30.09347	-97.84483	Marks	Fl	+++	25 to 45
20	5858209	30.11934	-97.81612	Onion Creek Meadows	Fl	+	76 to 115
21	58584DD	30.07717	-97.86132	Dement	Fl	+++	up to 12
22	58584L	30.07083	-97.87473	Shackelford	Fl	++	up to 12

*State Well Number

No background concentrations of eosine were detected in any of the well samples collected prior to the injection. In addition, no false positive detections of eosine were encountered in well samples. Several well samples did have false positive detections of sodium fluorescein that appear to have been the result of contamination or sampling error. Additionally, several trip blanks (control samples) beginning on August 12, 2002 had false positive sodium fluorescein detections. These control samples appear to have been exposed to sodium fluorescein during the washing procedure intended to remove the black charcoal dust from the dry charcoal control samples. Control samples that were not washed did not have any false positive results.

Discussion

Injection of dyes into Antioch and Cripple Crawfish caves occurred during high spring flow conditions of 98 and 99 cfs at Barton Springs, respectively. Maximum groundwater flow velocities were calculated by the first arrival of the dye. Since the first arrival of eosine arrived before the first sampling event, the flow velocity reported in Table 2 is a minimum value. Additionally, dye travel times and recoveries may underestimate the actual groundwater flow rates and character of groundwater flow due to adsorption of the dye underground, the complexity of the actual flow paths (tortuosity), saturated and unsaturated flow paths, frequency of sampling, and the amount of dye used.

Breakthrough concentrations peak soon after initial arrival, suggesting an aquifer system strongly influenced by conduit (rapid, pipe-like) flow rather than diffuse (slow) flow. Several sodium fluorescein breakthrough peaks on Figure 7 suggest arrival of dye via different (conduit) pathways.

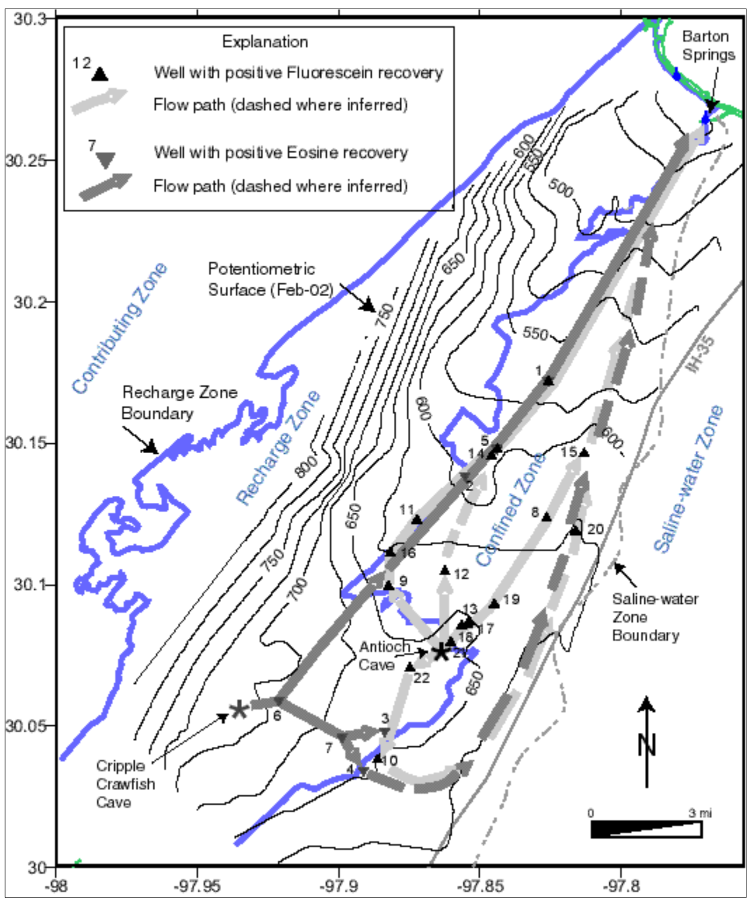

Figure 6. **Map of groundwater flow paths and potentiometric surface lines from a period of similar high-flow conditions (February 2002). The potentiometric surface was created using 175 groundwater elevation measurements throughout the study area.**

A potentiometric surface map constructed from water-level measurements in about 175 wells during February 2002 represents high flow aquifer conditions, similar to flow conditions of this study (shown on Figure 6). A mound in the potentiometric surface around Antioch Cave and Onion Creek is apparent on the potentiometric surface under these conditions. Dye was injected into the two caves as recharge was occurring. Under these conditions the dyes diverged from the caves and flowed in multiple directions away from the injection points. Flow from Antioch Cave generally followed the mound in the potentiometric surface in the confined zone and the trough in the potentiometric surface in the unconfined zone. Flow is interpreted to re-converge at some point or points up-gradient from Barton Springs (Figure 6). These flow paths are interpreted to be parallel to potentiometric lines in some areas, reflecting anisotropic flow in the aquifer or perhaps a lack of water-level control data.

Dyes from each injection site were detected in the same two wells (5850511 and 58507DF), indicating that groundwater flow converges into preferential flow paths (Hauwert and others, 2002). These wells are generally located within a broad potentiometric-surface trough in the unconfined zone (Figure 6).

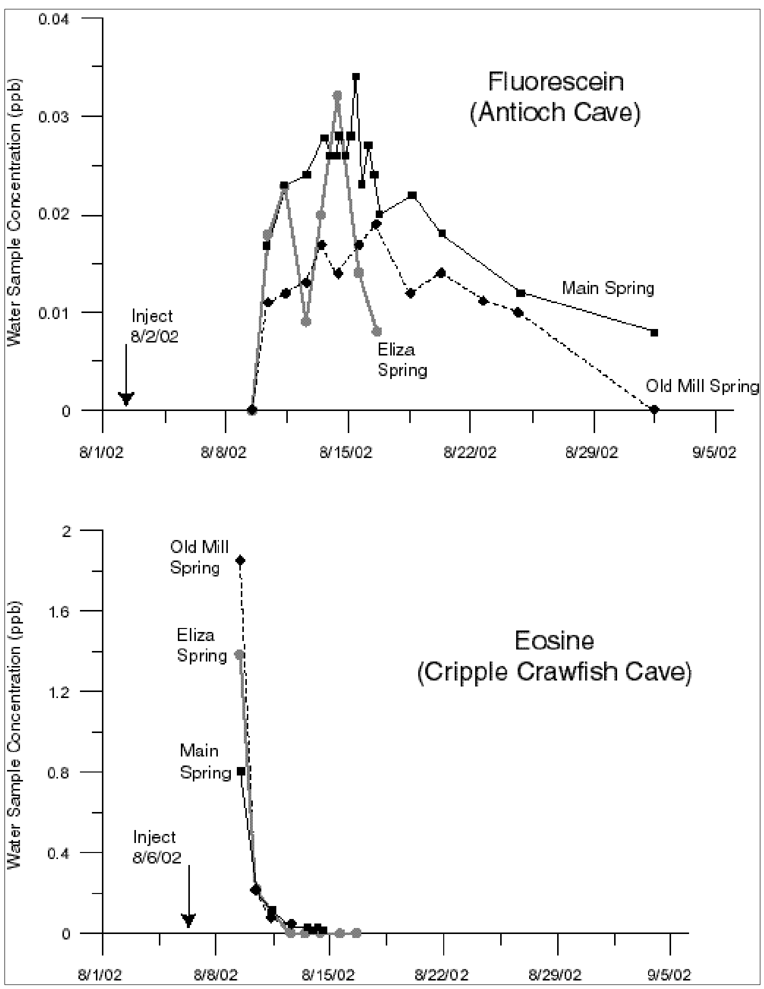

Figure 7. **Breakthrough curves of sodium fluorescein and eosine at Barton Springs.**

These data demonstrate the dynamic nature of this karst aquifer system with some aspects of flow reversing under different hydrologic conditions when compared to previous dye trace studies (Hauwert and others, 2002). Under average flow conditions, groundwater flow is predominantly from west to east and then northeast. This study also shows that under active recharge conditions some additional components of flow from these large recharge features can be to the northwest, southeast, and to the south.

Dye was recovered from wells south of Onion Creek in Mountain City, although no dye was recovered from San Marcos Springs during the year of monitoring associated with this study. Hauwert and others (2004) proposed a saline-water flow route along the eastern boundary of the aquifer to Barton Springs, which could be the flow path for water mounding during recharge and initially flowing to the south (shown as dashed or inferred flow paths in Figure 6). Positive recovery of sodium fluorescein in wells 5858209 and 5850835 near the saline-water zone many weeks after injection (Table 4) could support such a path, although these results should be verified in future traces due to the relatively low qualitative recovery of dye at these wells.

Rapid groundwater flow was traced in wells along paths that are parallel to the dominant and secondary fault and fracture trend presented on geologic maps (Small and others, 1996) and lineament studies (Alexander, 1990). Therefore, conduit flow within the aquifer appears to be strongly influenced by the bimodal fault and fracture system with trends of N40E (dominant) and N45W (secondary) (Figure 8).

Conclusions

- Groundwater flow velocities from Antioch and Cripple Crawfish caves to Barton Springs under high spring flow conditions are 2.0 and 5.0 miles per day, respectively. These rapid velocities indicate that conduits are an important component of groundwater flow.
- Tracer testing of Antioch and Cripple Crawfish caves reveals a groundwater flow system composed of multiple diverging flow paths from the caves as they recharge surface water. Flow then appears to re-converge as it flows northeast before discharging at Barton Springs.
- Flow paths appear to coincide with troughs in the potentiometric surface in the hydraulically unconfined zone and with ridges in the potentiometric surface in the hydraulically confined portion of the aquifer.
- Conduit flow within the aquifer appears to be strongly influenced by the bimodal fault and fracture system.

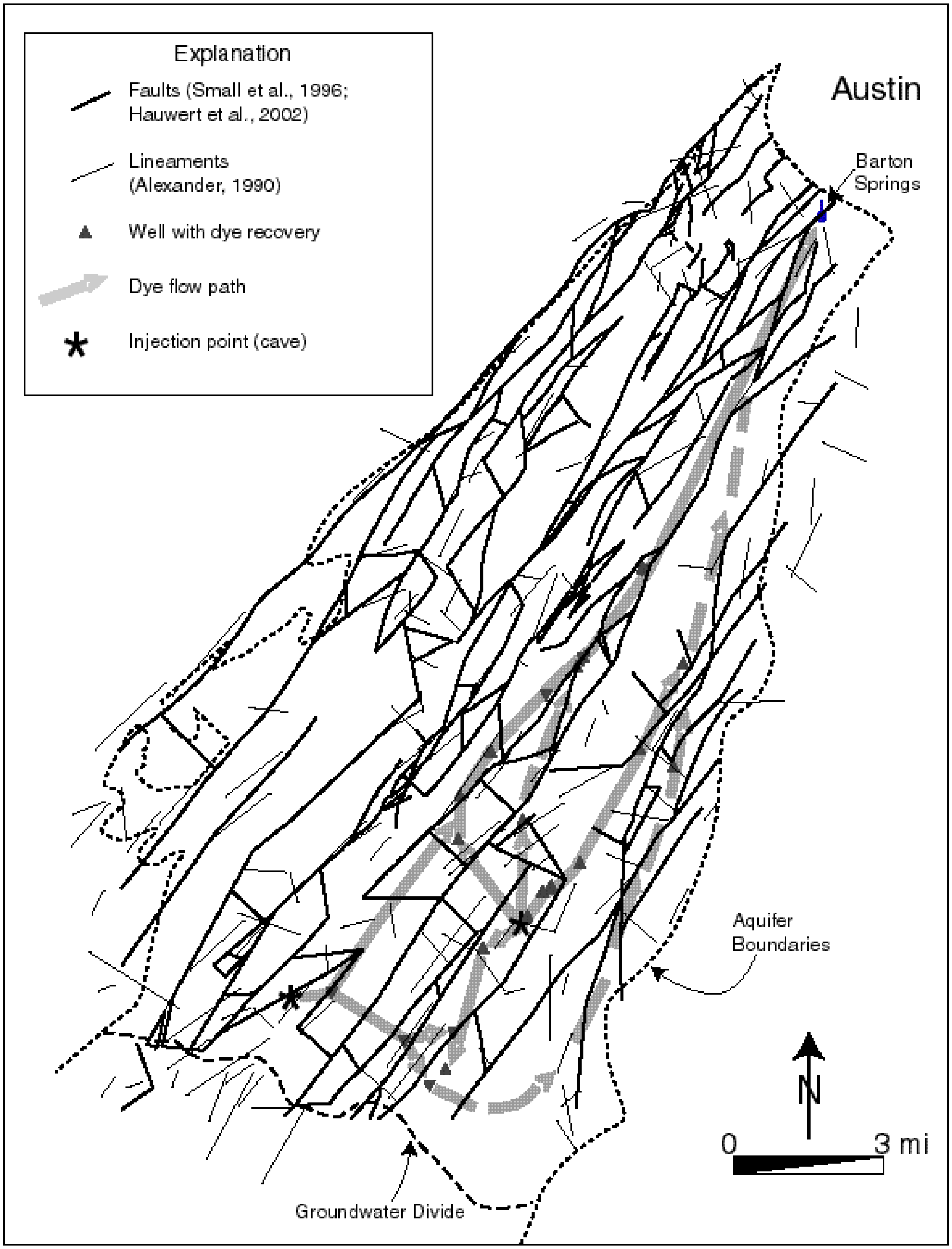

Figure 8. Map showing faults and lineaments with flow paths drawn from the potentiometric map (figure 6) superimposed. Note the flow paths generally follow structural trends.

Acknowledgments

This work was done in close collaboration between the District and the City of Austin and is an extension of dye tracing work performed from 1996 to 2001. Results of this study were initially presented at the Geological Society of America: South-Central Meeting in San Antonio, April 1, 2005. Nico Hauwert (City) injected eosine dye into Cripple Crawfish Cave. David Johns (City) retrieved samples from Barton Springs. Mark Mathis (District) injected sodium fluorescein dye into Antioch Cave; Joe Beery (District) collected receptors from wells; Brian Smith (District) and Brian Hunt (District) retrieved samples from San Marcos Springs; and Stefani Campbell (District) and Brian Hunt extracted and analyzed receptors at the Edwards Aquifer Authority.

Thanks goes to Geary Schindel and Steve Johnson of the Edwards Aquifer Authority for support of this effort with supplies, analytical equipment, training, and advise. Scott Wood, Bridget Clark, and Ron Coley of San Marcos Springs Aquarena Center supported our monitoring efforts. Tom Aley and Ozark Underground Laboratory staff provided advice and guidance. The District would like to extend its gratitude to all well and landowners and other participants in this study.

Special thanks goes to Jim Sansom, Steve Johnson, and Kirk Holland (District) for reviewing this paper.

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