Barton Springs
Edwards Aquifer
CONSERVATION DISTRICT

Evaluating the Hydrologic Connection of the Blanco River and Barton Springs Using Discharge and Geochemical Data

BSEACD Report of Investigations 2013-0701

Barton Springs/Edwards Aquifer Conservation District
1124 Regal Row
Austin, Texas

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Cover Photos. Top: Flow in the Blanco River on Halifax Ranch (4/1/2010). Bottom: Barton Springs Pool during pool cleaning with lowered water levels (2/18/2003).

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ABSTRACT

Barton Springs issues from the karstic Edwards Aquifer in drought-prone central Texas. The Edwards Aquifer provides public water supply and springflow for endangered species and recreation. Delineating source areas and flow paths in karst aquifers is important for understanding water availability. Historic data and recent dye-trace studies indicate that the Blanco River is the hydrologic divide between the Barton Springs and San Antonio segments of the Edwards Aquifer during dry hydrologic conditions, contributing recharge to both segments and their associated springs, such as Barton and San Marcos Springs. This study evaluated historical discharge and geochemical data to characterize and quantify the hydrologic connection between recharge from the Blanco River and Barton Springs, the main discharge point for the Barton Springs segment. Hydrologic data, including stream discharge, spring discharge, and stream recharge estimates (1987 through 2012) during extremely dry hydrologic time periods, when it is inferred that there was no recharge occurring internally within the Barton Springs watershed, were identified and evaluated. A hydrologic connection is considered to exist when estimated recharge from the Blanco River increases and there is a time-lagged increase in discharge and gage height at Barton Springs. Sixteen events with increased recharge from the Blanco River with an associated, time-lagged increased in discharge at Barton Springs were identified. The average increase in recharge from the Blanco River for these 16 events was 2.7 ft^3/s (range 0.2 to 13.8 cfs), while the average increase in discharge at Barton Springs was 1.4 ft^3/s (range 1-2 cfs). The data indicate that the increase in Barton Springs discharge is likely attributable to Blanco River recharge for 4 of the 16 events, and potentially attributable for another 6 events. The 6 remaining events of increased discharge at Barton Springs are within instrument uncertainty and cannot be attributed with confidence to an increase in recharge from the Blanco River. Results of the geochemical analyses were inconclusive because variations in the specific conductance of discharge at Barton Springs were within instrumental error, and the lack of temporal consistency between major ion data and the time periods of interest.

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INTRODUCTION

The Edwards Aquifer in central Texas (**Figure 1**) is a karst aquifer that supplies water for nearly two million users. Increasing population and intermittent droughts can stress the water supply for humans as well as area ecosystems. The primary natural discharge point for the Barton Springs segment is located at Barton Springs in Austin, TX, while the major discharge points for the San Antonio segment are San Marcos Springs in San Marcos, TX, and Comal Springs in New Braunfels, TX. Both segments of the aquifer are sole-source water supplies and the springs provide habitat for endangered and threatened species (Edwards Aquifer Research and Data Center, 2010). The Barton Springs and San Antonio segments are subdivisions of the aquifers based upon their primary discharge points and hydrologic divides (**Figure 2**; Slade et al., 1985; Slagle et al., 1986; Stein, 1995). The divide is defined by a potentiometric ridge where groundwater flows north-northeast through the Barton Springs segment of the Edwards Aquifer (Barton Springs segment), and a portion flows south through the San Antonio segment of the Edwards Aquifer (**Figure 1**).

Recent studies have demonstrated that the hydrologic divide shifts between Onion Creek and the Blanco River depending on surface hydrologic conditions (**Figure 2**; Smith et al., 2012). Dye trace studies have proved that a hydrologic connection exists between the Blanco River and Barton Springs under drought conditions (Johnson et al., 2012). Recent studies also suggest that the majority of water discharging from Barton Springs during drought conditions is from the Blanco River (Hauwert, 2011b).

This study evaluates the hydrologic connection of the Blanco River and Barton Springs using discharge and geochemical data. The focus of the approach is on storm-driven increases in recharge from the Blanco River than can be observed as the source of increased springflow (and gage height) at Barton Springs. Geochemical changes during these periods are also evaluated. This investigation focuses on "extremely dry hydrologic conditions," when only the Blanco River could potentially be contributing recharge. This type of data could give a more quantitative characterization of the hydrologic connection of the Blanco River and Barton Springs.

HYDROGEOLOGIC SETTING

The Edwards Aquifer is a karst aquifer developed in faulted and fractured Lower Cretaceous limestones and dolomites. The Edwards Aquifer is composed of the Edwards Group and Georgetown Formation (Rose, 1972; Ryder 1996). The aquifer has unconfined portions as well as confined portions overlain by the Del Rio Clay, while the Upper Glen Rose Limestone underlies the aquifer (Smith and Hunt, 2009).

The majority of recharge to the aquifer is derived from streams originating in the contributing zone, located up-gradient and primarily west of the recharge zone (Slade et al., 1986). Seeps and springs contribute to baseflow in the contributing streams and originate from rocks of the Trinity Group, which host the Upper and Middle Trinity Aquifers in this area. Water flowing onto the Edwards recharge zone sinks into numerous caves, sinkholes, and fractures along several losing streams. For the Barton Springs segment, Slade et al. (1986) estimated that as much as 85% of recharge to the aquifer is from water flowing in these losing streams. The remaining recharge (15%) occurs as infiltration through soils or direct flow into recharge features in the upland areas of the recharge zone. Recent studies hypothesize that upland recharge might be somewhat larger than 15% (Hauwert, 2009). Regardless, the majority of recharge to the Edwards Aquifer is from flow in the creeks that cross the recharge zone.

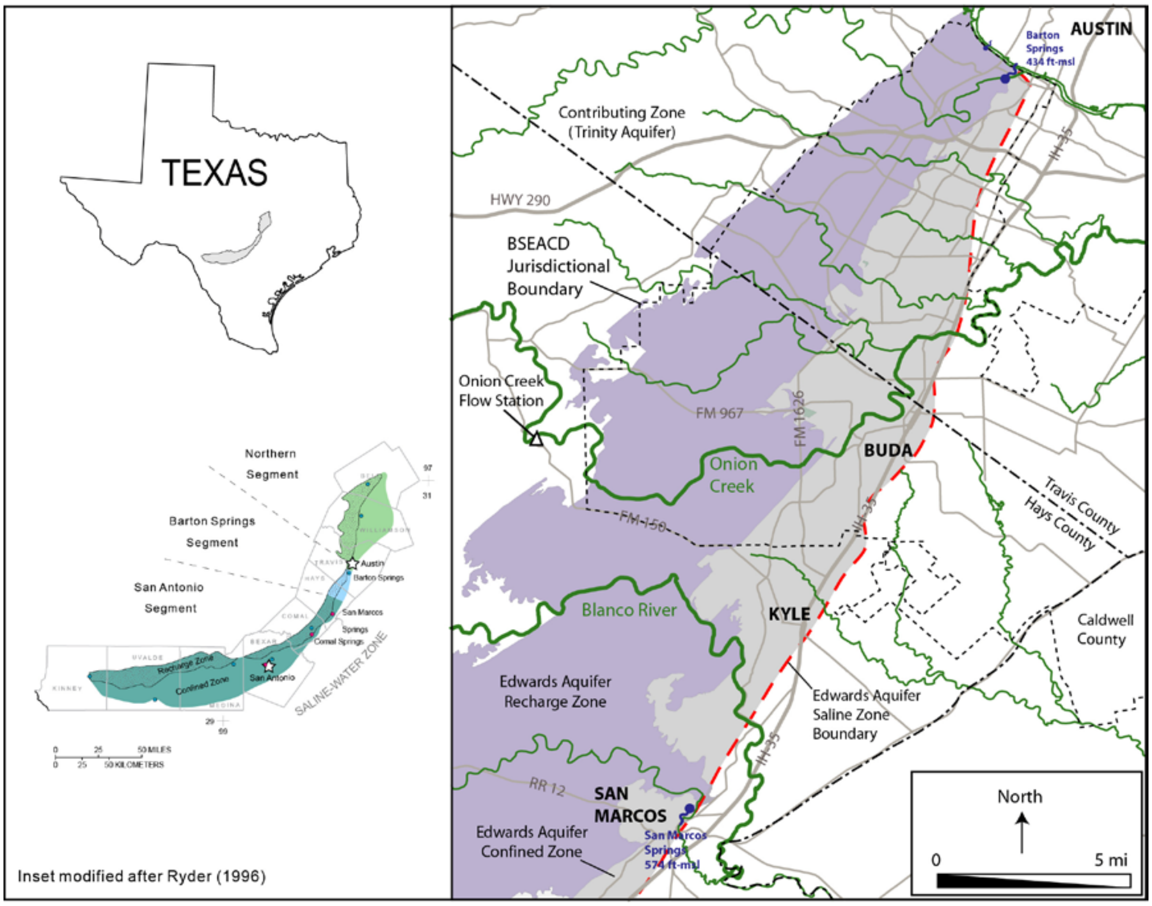

Figure 1. *(Left) Location map of the Edwards Aquifer in central Texas. The aquifer is divided into three segments. (Right) This study is geographically focused on the Blanco River and the Barton Springs and San Antonio segments (modified from Smith et al., 2012). The confined zone includes the area that has confined (artesian) fresh water aquifer conditions or confining units present at the surface.*

The Edwards Aquifer is heterogeneous and anisotropic, characteristics that strongly influence groundwater flow and storage (Slade et al., 1985; Maclay and Small, 1986; Hovorka et al., 1996 and 1998; Hunt et al., 2005). The Edwards Aquifer can be described as a triple porosity and permeability system consisting of matrix, fracture, and conduit porosity (Hovorka et al., 1995; Halihan et al., 2000; Lindgren et al., 2004) reflecting an interaction between rock properties, structural history, and hydrologic evolution (Lindgren et al., 2004).

In the Barton Springs segment groundwater generally flows from west to east across the recharge zone, converging with preferential groundwater flow paths sub-parallel to major faulting, and then flowing northerly toward Barton Springs. In the San Antonio segment, groundwater similarly flows down-dip in the recharge zone then along strike in the confined zone toward the major springs of Comal and San Marcos (Hamilton, et al., 2006; Pettit and George, 1956).

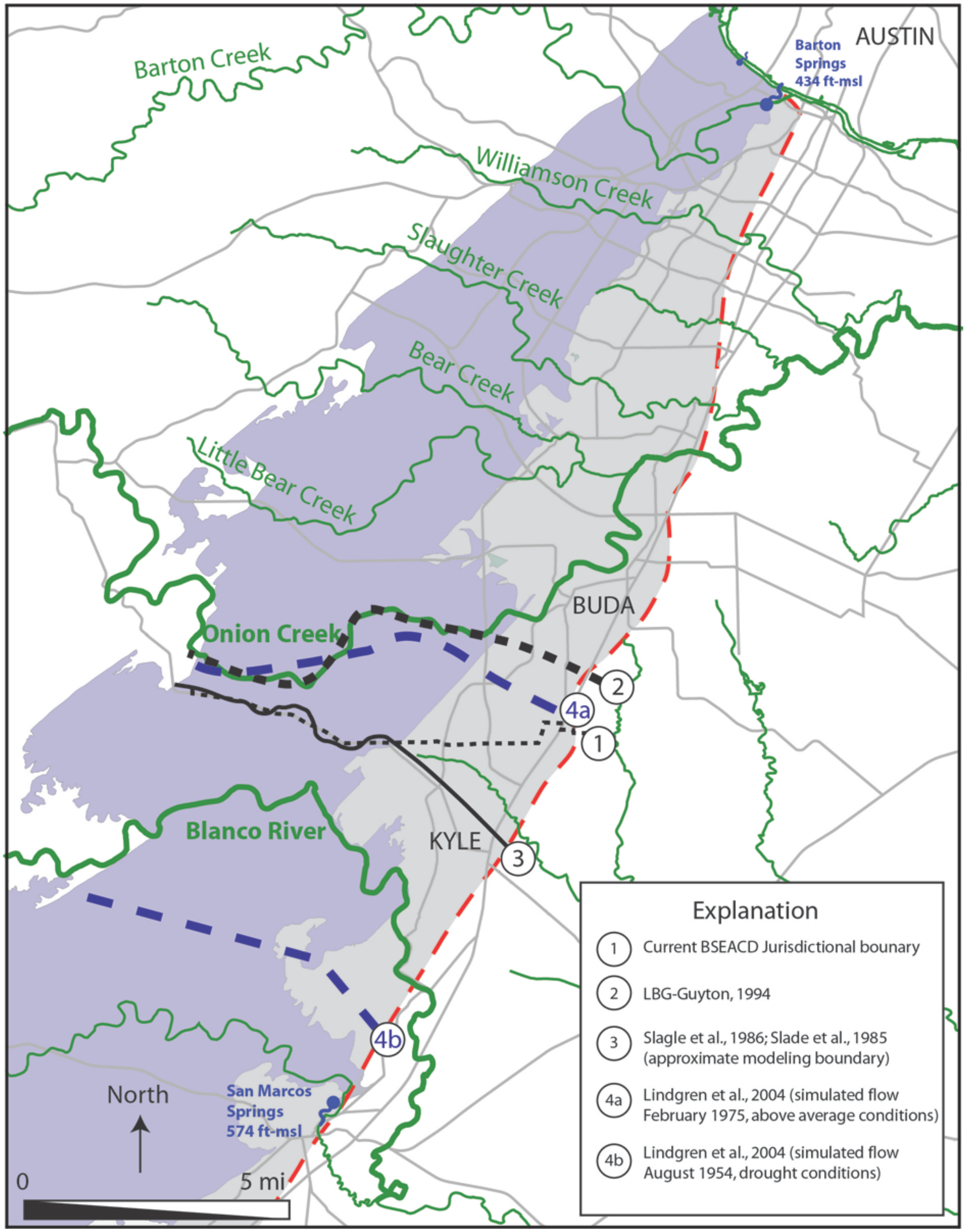

Figure 2. *Map showing various published locations of the hydrologic divide between the Barton Springs and San Antonio segments of the Edwards Aquifer (from Smith et al., 2012).*

Hydrologic divide and recharge to the Barton Springs segment of the Edwards Aquifer

Numerous studies involving potentiometric maps and dye-trace studies have been used to refine and understand the location of the hydrologic divide between the two segments (**Figure 2**; Pettit and George, 1956; DeCook, 1960; Slagle et al., 1986; Slade et al., 1986; Ogden et al., 1986; LBG-Guyton, 1994; Hunt et al., 2005, 2006; Hamilton et al., 2006; Johnson and Schindel, 2008; Hauwert, 2011a; Land et al., 2011). These studies are summarized in Smith et al., 2012. During normal- to wetter-than-average periods the hydrologic divide is located in proximity to Onion Creek, where high capacity recharge can be attributed to discrete points of origination in the creek, such as Antioch, Cripple Crawfish, and Crooked Oak caves (**Figure 3**). A potentiometric mound forms under Onion Creek, and water flows to Barton and San Marcos Springs (Hunt et al., 2006; Smith et al., 2012). During wet periods the majority of groundwater discharge at Barton Springs is attributed to the five major contributing streams: Barton Creek, Williamson Creek, Slaughter Creek, Bear Creek, and Onion Creek (Slade et al., 1986). When flowing, Onion Creek is the largest source of recharge to the Barton Springs segment, with an estimated contribution of ~34% (Slade et al., 1986; Barrett and Charbeneau, 1997; Passarello et al., 2012).

During drought conditions the major contributing streams of the Barton Springs segment have little to no flow and contribute minimal to no recharge to Barton Springs. Under these conditions the hydrologic divide shifts farther south towards the Blanco River which provides recharge during these dry periods (**Figure 2**; Lindgren et al., 2004; Smith et al., 2012). Potential sources of recharge to Barton Springs during drought conditions, when the major streams are not flowing, are: (1) localized recharge events due to rainfall that do not result in creek flow (upland recharge); (2) urban recharge (Sharp, 2010; Passarello et al., 2012); (3) regional, deep groundwater flow from the San Antonio segment (Johnson and Schindel, 2008; Land et al., 2011; Smith et al., 2012); (4) lateral inflows from the Trinity Aquifer (most likely Upper Trinity Aquifer); and (5) recharge from the Blanco River that flows northerly across the nominal groundwater divide (**Figure 3**; Johnson et al., 2012; Smith et al., 2012). This last possibility is the focus of this study.

The contribution of Blanco River recharge to Barton Springs discharge is poorly understood. However, recent studies suggest that during dry time periods, when Barton Springs discharge is <40 ft^3/s, the Blanco River is a significant source of recharge (Hauwert, 2011b). This is supported by recent dye-trace studies during drought conditions that established a hydrologic connection of the Blanco River to Barton Springs (Johnson et al., 2012). Tracers from the Blanco River region generally took three months to reach Barton Springs (Johnson et al., 2012).

Blanco River recharge and discharge at San Marcos Springs

The Blanco River is understood to be a minor source of recharge to the San Antonio segment of the Edwards Aquifer and to San Marcos Springs discharge (Pettit and George, 1956; LBG-Guyton Associates, 2004; Johnson and Schindel, 2008; Musgrove and Crow, 2012). Using geochemical data Musgrove and Crow (2012) estimated that the Blanco River may contribute as much as 30% of discharge at San Marcos Springs, but is more typically less than 10% depending on moisture conditions. It is not clear from their study the extent to which the Blanco River might contribute to Barton Springs discharge.

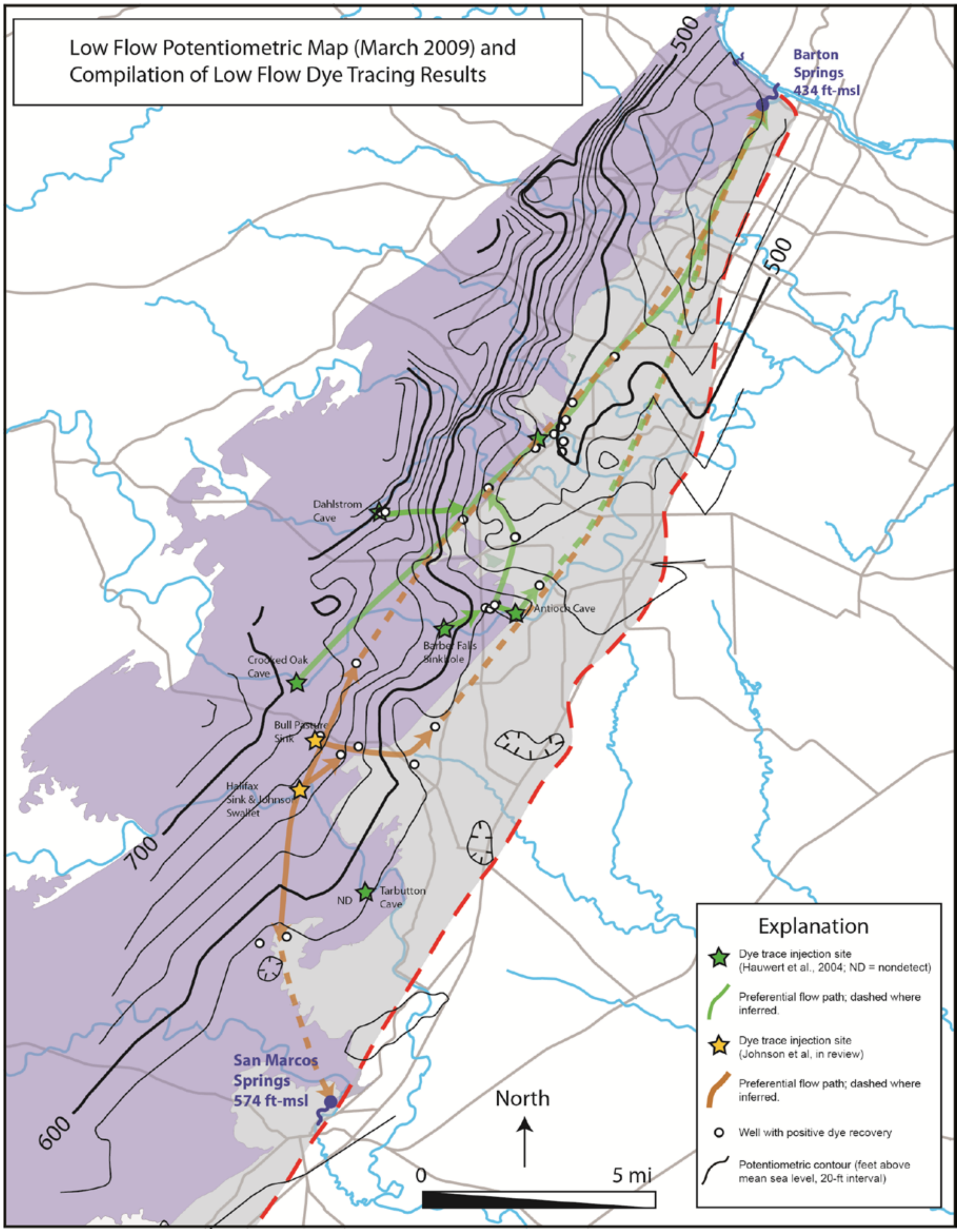

Figure 3. *Groundwater flow from the San Antonio segment to the Barton Springs segment during extremely dry conditions (From Smith et al., 2012).*

Geochemical distinctions within the Edwards Aquifer region

Previous studies have addressed general geochemical distinctions between groundwater from the Edwards Aquifer and the Trinity Aquifers (Smith and Hunt, 2009). In general, the Trinity Aquifers are characterized by deeper groundwater of longer residence time with higher overall concentrations of Ca, Mg, Na, Cl, K, SO_4, and TDS relative to the Edwards Aquifer, and also typically a higher concentration of sulfate than bicarbonate.

During dry intervals Barton Springs's specific conductance peaks at ~700 µS/cm/cm and reaches a low of ~600 µS/cm during wet intervals (Massei et al., 2007). This reflects more of a conduit fed, surface water recharge component during wet intervals and more of a saline-water zone and/or aquifer matrix component during dry intervals (Senger 1983; Hauwert et al., 2004; Johns, 2006). The Blanco River at Wimberley has an average specific conductance of ~460 µS/cm. The differences in specific conductance between Barton Springs and the Blanco River could be useful for assessing the extent of Blanco River recharge contributing to discharge at Barton Springs. A recharge input from the Blanco River conceptually would be reflected by a decrease in specific conductance at Barton Springs.

Other studies have used geochemical data to characterize stream recharge and spring discharge in an attempt to determine if increasing recharge is evidenced geochemically in spring discharge. Mahler et al. (2006) demonstrated that increases in recharge during drought (defined in that study as Barton Springs discharge of < 40 ft^3/s) can be traced geochemically as contributing to discharge at Barton Springs. During drought conditions, as discharge increases at Barton Springs, specific conductance decreases and, in general, major ion concentrations such as Ca and Sr decrease in concentration (Mahler, 2006). Garner and Mahler (2007) also demonstrated that specific conductance can be used as an indicator of increased recharge as pulses of recharging water will decrease the specific conductance of Barton Springs discharge.

APPROACH

In order to investigate the hydrologic connection between the Blanco River and Barton Springs this study focused on data from time periods with extremely dry hydrologic conditions. Historical hydrologic and geochemical data were evaluated to determine time periods when there was (a) no flow in the major contributing streams to Barton Springs, and (b) no rainfall in the Barton Springs segment of the Edwards Aquifer. These are the type of conditions in which the Blanco River is believed to be the sole source of surface water input (Smith et al., 2012). If these conditions were satisfied, we examined the extent to which instances of increased recharge from the Blanco River correlated with increased gage height and discharge at Barton Springs. For these same time periods we also investigated the potential relationship of geochemical parameters (i.e., specific conductance and major ions) at Barton Springs resulting from recharge from the Blanco River.

Discharge data for the upstream and downstream portions of major contributing streams and the Blanco River as well as discharge and gage height data for Barton Springs are available from the U.S. Geological Survey (USGS) National Water Information System (NWIS) database. Recharge along the Blanco River was calculated by subtracting the downstream discharge (ft^3/sec) near Kyle, TX from the upstream discharge near Wimberley, TX (**Table 1**). Geochemical data were available from the USGS, the Guadalupe Blanco River Authority (GBRA), the Texas Water Development Board (TWDB), and the Barton Springs/Edwards Aquifer Conservation District (BSEACD). Rainfall data were procured from the National Climatic and Data Center (NCDC) as well as the City of Austin (COA) rainfall gauges for sites in the Barton Springs segment. Stream discharge stations and rainfall gauge locations are identified in **Tables 1 and 2**, respectively, and on **Figure 4**. All raw data used in the evaluations are provided in **Appendix A**.

Figure 5 is a flow chart of the steps taken to evaluate the data. Hydrologic data were isolated to periods of time when there was no discharge occurring in the upstream locations of the major contributing streams to Barton Springs (n = 583 days). These time periods are referred to as “no flow conditions”. Discharge data from the major contributing streams were initially used in lieu of calculated recharge data. This is because data for the upstream portions of the major contributing streams are much more temporally extensive (7/8/87 to 5/16/12) than the discharge data concurrent for both the upstream and downstream portions (10/01/03 to 12/08/10), which are needed to calculate recharge. The 583 days of no flow conditions in the upstream portions of the major contributing streams were then filtered into instances when there were increased flows at both the Blanco River (Wimberley) and at Barton Springs. Recharge and rainfall data were used to further refine these time periods into those in which it is inferred that only increased recharge from the Blanco River was contributing to increased gage height and discharge at Barton Springs. This resulted in 16 occurrences when there was no discharge or recharge in the contributing streams, no rainfall in the Barton Springs segment, and an increase in recharge from the Blanco River and an increase in discharge at Barton Springs. The time it took for discharge to increase after recharge is called “lag time.” Lag time (in days) was calculated by determining the number of days between an initial increase in recharge from the Blanco River and the first occurrence of increased gage height and discharge at Barton Springs.

Descriptive statistics were used to characterize trends in the data and to infer contribution of flow from the Blanco River to Barton Springs during the selected extremely dry hydrologic conditions. Correlation analyses were conducted to determine the relationship between recharge at the Blanco River and discharge at Barton Springs during dry conditions.

Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) was developed as a measure of the moisture deviation from “normal” (Palmer, 1965). To assess the severity of drought, the index calculates a weighted average of temperature, rainfall, and soil moisture for the current and preceding 12 months to determine the dryness of the system. The scale ranges from “extremely moist” (+4 or above) to “extreme drought” (-4 or below) with divisions for severe drought (-3 to -3.99), moderate drought (-2 to -2.99), and mid-range (1.99 to -1.99). Data for Texas Climate Region 7 were used to assess the hydrologic conditions for central Texas. The PDSI was used as an indicator of antecedent moisture conditions during the time periods of interest. It serves to characterize the conditions under which increased recharge from the Blanco River would be expected to contribute to increased discharge at Barton Springs.

Table 1. *Station identification information for the upstream and downstream USGS gaging stations.*

Map ID	USGS station ID	Site name	Type	Station name	Gage Location
1	8158810	Bear 1826	Stream	Bear Creek below FM 1826 near Driftwood, TX	Upstream
2	8158700	Onion Driftwood	Stream	Onion Creek near Driftwood, TX	Upstream
3	8158827	Onion Twin Creeks	Stream	Onion Creek at Twin Creeks Road near Manchaca, TX	Downstream
4	8158840	Slaughter 1826	Stream	Slaughter Creek at FM 1826 near Austin, TX	Upstream
5	8158860	Slaughter 2304	Stream	Slaughter Creek at FM 2304 near Austin, TX	Downstream
6	8158920	Williamson Oak Hill	Stream	Williamson Creek at Oak Hill, TX	Upstream
7	8158930	Williamson Manchaca	Stream	Williamson Creek at Manchaca Road, Austin, TX	Downstream
8	8155200	Barton 71	Stream	Barton Creek at SH 71 near Oak Hill, TX	Upstream
9	8171000	Blanco River near Wimberley, TX	Stream	Blanco near Wimberley	Upstream
10	8171300	Blanco near Kyle, TX	Stream	Blanco near Kyle	Downstream
11	8158819	Bear Brodie	Stream	Bear Creek near Brodie Lane near Manchaca, TX	Downstream
12	8155400	Barton Above	Stream	Barton Creek above Barton Springs at Austin, TX	Downstream
	8170000	San Marcos Springs	Spring	San Marcos Springs	
	8155500	Barton Springs	Spring	Barton Springs	

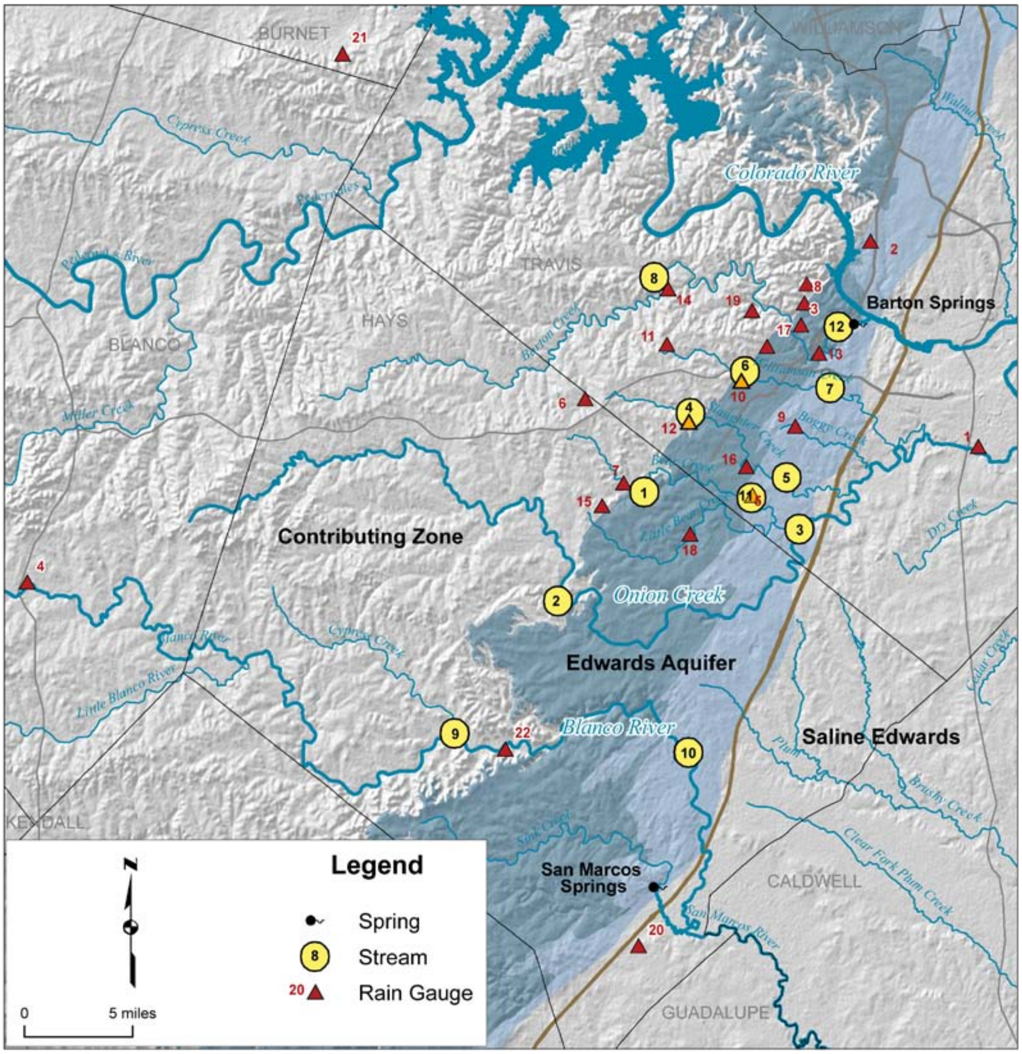

Figure 4. *Location map of spring and stream discharge measurement sites and rain gage locations. The numbers correspond to the sampling sites, which can be found in Tables 1 and 2.*

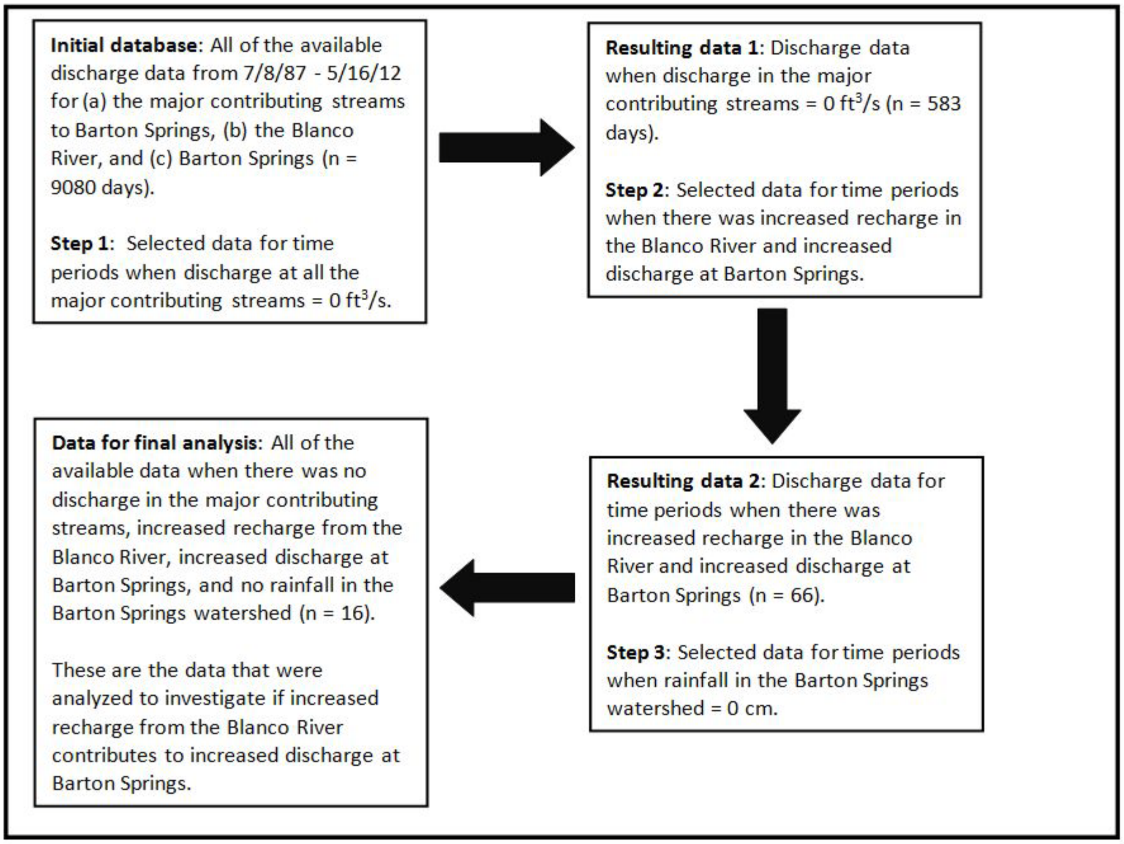

Figure 5. *A flow chart of the steps taken to evaluate and condense the data from the entire database of discharge rates to those used in this study.*

Geochemical data

Geochemical data for streams and springs were compiled from the USGS and the Guadalupe-Blanco River Authority (GBRA). Geochemical data for the Blanco River, Onion Creek, and Barton Springs were summarized and compared to each other to determine if significant differences exist. The constituents of interest were specific conductance and selected major ions: calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), and sulfate (SO_4). All raw data used in the evaluations are provided in **Appendix A**. Geochemical constituents might be expected to vary with various sources of recharge, varying amounts or proportions of recharge, and antecedent moisture conditions (Mahler et al., 2011). For instance, higher specific conductance values suggest that older, more saline water is discharging at Barton Springs, while lower specific conductance values suggest a younger, fresh water source such as recharge from rainfall (Mahler et al., 2011). Geochemical data were examined to (1) distinguish differences between recharge sources and spring discharge for extremely dry versus wetter conditions; and (2) for instances when Blanco River recharge was correlated with Barton Springs discharge, to determine if increased discharge at Barton Springs was accompanied by a geochemical signal.

Table 2. *Rainfall gauge site name, identification number, location, extent of data, and data source.*

Map ID No.	Rainfall Gage Site Name	Station ID	Latitude	Longitude	Source
1	Austin, TX (Bergstrom)	USW00013904	30.17944	-97.68056	NCDC
2	Austin, TX (Camp Mabry)	USW00013958	30.28333	-97.7	NCDC
3	BBQ	7	30.2631988	-97.81567787	COA
4	Blanco, TX	USC00410832	30.1	-98.4167	NCDC
5	BLE	5	30.14990992	-97.85572951	COA
6	Dripping Springs, TX	USC00412585	30.21667	-97.98333	NCDC
7	FBU	1	30.1597694	-97.95524021	COA
8	FEWS0700	11	30.27791087	-97.81257771	COA
9	FEWS0920	18	30.19546053	-97.82148604	COA
10	FEWS1120	20	30.23544657	-97.86014975	COA
11	FEWS1140	21	30.25191712	-97.91949857	COA
12	FEWS1180	23	30.20947372	-97.90355226	COA
13	FEWS1210	25	30.24414587	-97.80202351	COA
14	FEWS1300	26	30.28891945	-97.91778618	COA
15	FEWS2600	50	30.14480001	-97.97200001	COA
16	FEWS2750	52	30.16925273	-97.85984505	COA
17	FSU	2	30.24942558	-97.84239405	COA
18	LBR	9	30.12486161	-97.90427904	COA
19	LGA	4	30.27343877	-97.85329587	COA
20	San Marcos, TX	USC00417983	29.85000	-97.95000	NCDC
21	Spicewood, TX	USC00418531	30.45	-98.16667	NCDC
22	Wimberley, TX	USC00419815	29.98333	-98.05	NCDC

RESULTS

Discharge results

Extremely dry conditions were defined as time periods when discharge in the upstream portions of Onion Creek, Williamson Creek, Slaughter Creek, Little Bear Creek, and Bear Creek were all 0.0 ft^3/s (n = 583 days; **Table 3**). Discharge data encompass the time period from 7/8/1987 to 5/16/2012. Conditions of no flow at all of the major contributing streams listed above did not occur until 9/6/2000, when there were 32 days of no flow (5.5% of the no flow data) from 9/6/2000 to 10/14/2000. No-flow conditions did not occur again until 11/4/2005. From 11/4/2005 to 5/16/2012 there were 551 days of zero flow (94.5% of the no flow data). During these 583 days of no flow in the five major contributing streams, there was continuous flow in the upstream portion of the Blanco River and 486 days of no flow in the downstream portion of the Blanco River (83%).

During these intermittent, extremely dry conditions from 9/6/2000 to 5/16/2012 (n = 583 days) average discharge occurring at the Blanco River near Wimberley, TX was 15.1 ft^3/s (ranging from 4.6 to 208 ft^3/s), while calculated recharge using the downstream discharge station near Kyle, TX, was 12.7 ft^3/s, on average. The corresponding average discharge at Barton Springs was 23.2 ft^3/s (range 13 to 44 ft^3/s). There were 66 instances of no recharge in the major contributing streams and increased discharge at Barton Springs. Occurrences of rainfall in the Barton Springs segment were examined to eliminate time periods when there was rain in the Barton Springs contributing zone. This filtering resulted in 21 occurrences of increased discharge at Barton Springs.

Five of the 21 occurrences of increased discharge at Barton Springs were not associated with increased recharge from the Blanco River. We eliminated these 5 occurrences from analysis. A total of 16 occurrences of increased recharge from the Blanco River are associated with increased discharge at Barton Springs (**Figure 6**; **Table 4**). For these 16 occurrences average recharge from the Blanco River was 12.5 ft^3/s (range 7.2 to 22.7 ft^3/s), the average increase in recharge from the Blanco River was 2.7 ft^3/s (range 0.2 to 13.8 ft^3/s), average discharge at Barton Springs was 21 ft^3/s (16 – 44 ft^3/s), and the average increase in discharge at Barton Springs was 1.4 ft^3/s (range 1 to 2 ft^3/s; **Table 4**). The average lag time from an increase on the Blanco River to an increase from Barton Springs was 4.8 days (range 2 to 10 days; **Table 5**). An important consideration is the uncertainty associated with the discharge measurements at Barton Springs, especially considering the relatively small average increase in discharge at Barton Springs of 1.4 ft^3/sec. Using a conservative estimate of 10% uncertainty for discharge measurements at Barton Springs we determined that 7 of 16 occurrences of increased discharge at Barton Springs are higher than instrumental uncertainty. This is inferred to indicate that, in at least these 7 occurrences, increased discharge at Barton Springs can be attributed to increased recharge from the Blanco River.

An increase in gage height at Barton Springs was reviewed as a second indicator of recharge coming from the Blanco River, in an attempt to determine if the small increases in discharge at Barton Springs were valid. Barton Springs discharge is calculated from a stage-discharge relationship developed by USGS from a nearby well (state well number 58-42-903). There were 12 increases in gage height during the 16 occurrences of increased discharge at Barton Springs. Seven of the 12 increases are higher than or equal to the instrumental uncertainty of 0.02, and correspond to increases in discharge at Barton Springs and the Blanco River. The 7 increases in gage height have a mean of 0.04 ft. and a range of 0.02 – 0.07 ft. **Table 6** presents a summary of the results of increase in gage height and discharge at Barton Springs owing to recharge on the Blanco River.

Table 3. *Descriptive statistics for recharge and discharge for the Blanco River and discharge for Barton Springs. Discharge for Barton Creek, Williamson Creek, Slaughter Creek, Bear Creek, and Onion Creek equals 0 ft^3/s (n = 583 days).*

n = 583	**Blanco River recharge** (**ft^3/s**)	**Blanco River discharge (ft^3/s)**	**Barton Springs discharge (ft^3/s)**
Mean	12.7	15.1	23.2
Range	4.6 – 208	4.6 – 208	13 – 44
Standard deviation	9.2	11.9	6.6

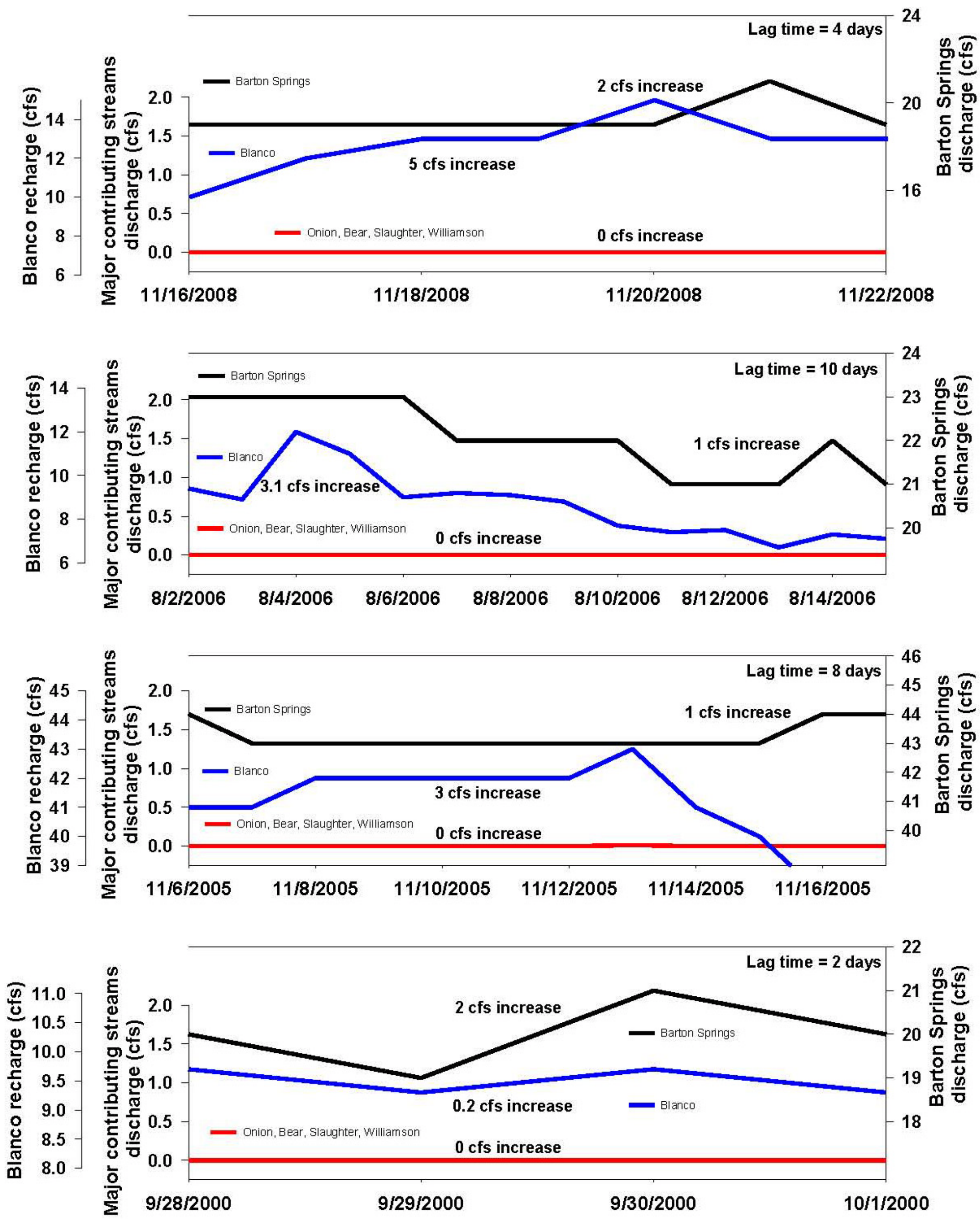

Figure 6. *Hydrographs showing discharge at Barton Springs, recharge from the Blanco River, and discharge at the major contributing streams to Barton Springs. Lag time is the amount of time it takes to see an increase in discharge at Barton Springs once there is increased recharge from the Blanco River. The graphs are 4 of the 16 occurrences of increased recharge from the Blanco and a corresponding (lagged in time) increased discharge at Barton Springs.*

Table 4. *Descriptive statistics for time periods when there is recharge only from the Blanco River and no rainfall in the Barton Springs segment and no recharge from the major contributing streams.*

n = 16	**Blanco River recharge (ft^3/s)**	**Blanco River discharge (ft^3/s)**	**Barton Springs discharge (ft^3/s)**	**Lag time: Blanco River to Barton Springs**	**Recharge increase Blanco River (ft^3/s)**	**Springflow increase at Barton Springs (ft^3/s)**
Mean	12.5	13.5	21.4	4.8 days	2.7	1.4
Range	7.2 – 22.7	6.6 - 41	16.4 - 43.5	2 – 10 days	0.2 – 13.8	1 – 2
Standard deviation	3.5	4.6	6.2			

Table 5. *The 16 time periods from 9/29/2000 to 10/4/2011 when recharge from the Blanco River increased and there was a corresponding, time-lagged increase in discharge at Barton Springs.*

Event	**Time period**	**Lag time (days)**	**Average recharge Blanco River (ft^3/s)**	**Recharge increase Blanco River (ft^3/s)**	**Springflow increase at Barton Springs (ft^3/s)**	**PDSI**
1	9/29/00 – 9/30/00	2	9.5	0.2	2	-4.1
2	11/7/05 - 11/16/05	8	22.7	3	1	-2.4
3	8/3/06 - 8/14/06	10	10.5	3.1	1	-4.9
4	8/19/06 - 8/26/06	7	7.2	0.5	1	-4.9
5	9/21/06 – 9/30/06	8	13	2	1	-4.1
6	10/6/06 - 10/8/06	2	11.5	1	2	-3.6
7	9/20/08 – 9/24/08	3	12	1	1	-3.1
8	11/9/08 - 11/15/08	6	10.7	2.3	2	-3.6
9	11/17/08 - 11/21/08	4	12.6	5	2	-3.6
10	12/2/08 - 12/6/08	2	13	2	2	-4.0
11	12/23/08 - 12/30/08	6	13.5	1	1	-4.0
12	12/30/08 - 1/2/09	2	14.5	4	2	-4.5
13	1/19/09 - 1/24/09	4	14	2	2	-4.5
14	1/26/09 - 1/31/09	4	14	2	1	-5.3
15	6/18/09 - 6/22/09	4	8	0.3	1	-5.9
16	9/28/11 – 10/4/11	5	13.1	13.8	1	-5.8

Table 6. *Summary of confidence of interpretation of results of increase in gage and discharge at Barton Springs due to recharge on the Blanco River; and the increase in gage height and percent increase in discharge at Barton Springs. A "+" represents when both gage height and discharge increase by more than analytical uncertainty; a "0" represents when either gage height or discharge increase; and a "x" represents when neither gage height nor discharge increase.*

Event	Occurrence date	Increase in gage height (ft.)	Increase in Barton Springs discharge (%)	Inferred increase (x = no; 0 = maybe; + = yes)
1	9/29/00 – 9/30/00	n/a	11.1	0
2	11/7/05 - 11/16/05	0.03	2.4	0
3	8/3/06 - 8/14/06	0.01	4.6	x
4	8/19/06 - 8/26/06	0.01	4.9	x
5	9/21/06 – 9/30/06	0	5.1	x
6	10/6/06 - 10/8/06	0	10.3	0
7	9/20/08 – 9/24/08	0.01	4.4	x
8	11/9/08 - 11/15/08	0.04	10.9	+
9	11/17/08 - 11/21/08	0.04	11.5	+
10	12/2/08 - 12/6/08	0.02	11.6	+
11	12/23/08 - 12/30/08	0.02	5.1	0
12	12/30/08 - 1/2/09	n/a	11.3	0
13	1/19/09 - 1/24/09	0.03	11.8	+
14	1/26/09 - 1/31/09	0.01	5.9	x
15	6/18/09 - 6/22/09	0.01	6.5	x
16	9/28/11 – 10/4/11	0.07	6.0	0

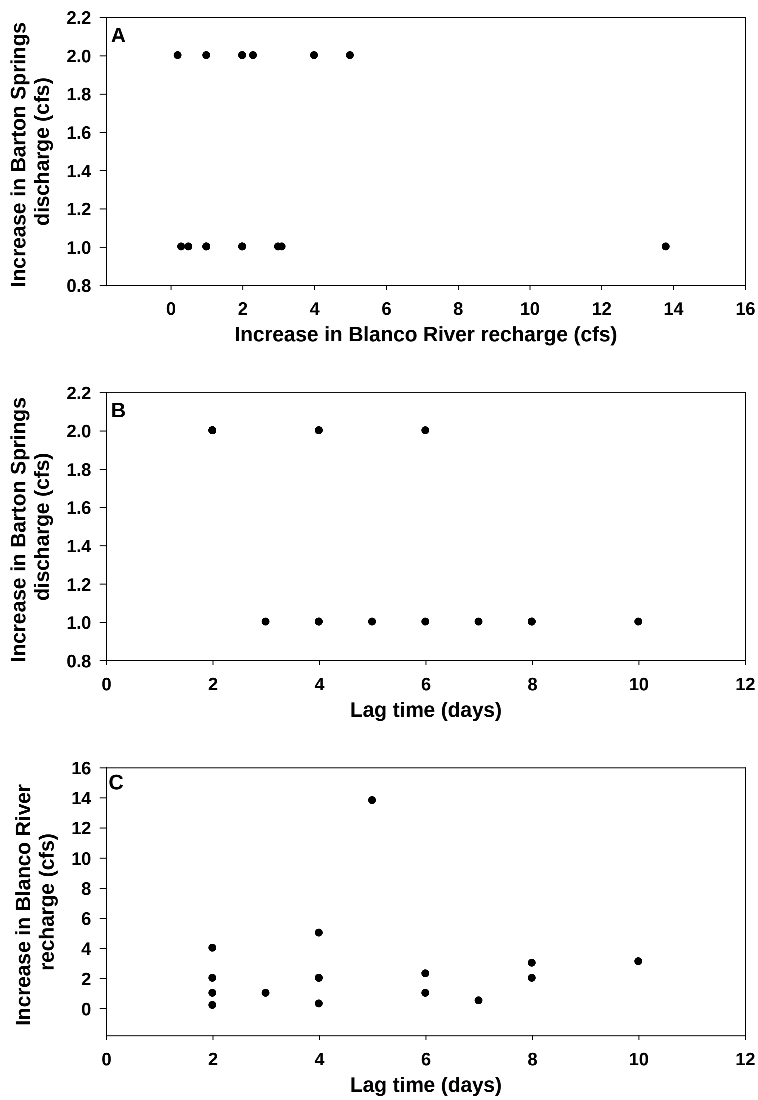

Figure 7A-C. *(A) Comparison of the increase in Blanco River recharge versus the increase in Barton Springs discharge; (B) comparison of lag time versus the increase in Barton Springs discharge; (C) comparison of lag time versus the increase in Blanco River recharge. Lag time is defined as the amount of time it takes for an increase in Blanco River recharge to be evidenced by an increase in Barton Springs discharge.*

Lag time and discharge correlations

There was no significant correlation between the amount of increased recharge from the Blanco River and the amount of increased discharge at Barton Springs (**Figure 7A**). There was no significant correlation between lag time (during the 16 events) and either (1) the increase in discharge amount at Barton Springs (**Figure 7B**) or (2) the increase in recharge amount along the Blanco River (**Figure 7C**).

Geochemical results

Geochemical data were examined for the 16 events when the Blanco River increased in recharge and there was a correlated increase in Barton Springs discharge. One of the 16 events was not examined because there were no geochemical data of any type available. Except for the specific conductance data, there was a lack of temporal matching between geochemical data (Ca, Mg, Na, K, Cl, and SO_4) and the 16 events. Therefore, we compared variations in specific conductance of discharge at Barton Springs *versus* the timing of recharge along the Blanco River and increases in discharge at Barton Springs. Furthermore we copared other geochemical parameters from extremely dry *versus* wetter time periods to determine if differences in discharge geochemistry at Barton Springs exist.

Table 8 lists average geochemical values for selected major ions and specific conductance for Onion Creek, the Blanco River, and Barton Springs. In general, groundwater from the Edwards Aquifer has higher Ca, Mg, and SO_4 and lower Na and Cl *versus* Onion Creek (Smith and Hunt, 2009). The concentrations of Ca and specific conductance are similar for Onion Creek and the Blanco River. The concentrations of Na, K, Cl, and SO_4 are higher in Onion Creek than the Blanco River while Mg is higher in the Blanco River. Barton Springs has higher Ca, Mg, Cl, Na, SO_4, and specific conductance compared to the Blanco River.

There are no geochemical data available for major ions during the 16 events of interest. However, specific conductance data are available for these events. Average specific conductance of the Blanco River is 473 µS/cm/cm (n = 295), which is significantly lower than the average specific conductance of Barton Springs, 631 µS/cm/cm (n = 407; **Table 7**). In 12 of the 15 time periods investigated, there is slight variation (within analytical uncertainty) in average daily specific conductance at Barton Springs after an increase in recharge along the Blanco River. After recharge from the Blanco River increased but before discharge at Barton Springs increased, the average specific conductance at Barton Springs was 704 µS/cm. After recharge from the Blanco River increased there was a slight increase in Barton Springs average daily specific conductance (mean increase = 2.2 µS/cm/cm), typically one day prior to a decrease in Barton Springs average daily specific conductance (mean decrease = 4.0 µS/cm/cm). The decrease in average daily specific conductance at Barton Springs correlates with increased discharge at Barton Springs. However, the change in average daily specific conductance at Barton Springs is within the error of the instrument, therefore, no significant conclusions can be drawn from these data.

The remaining geochemical data (i.e., major ion data) were not available for the 16 time periods of interest. Therefore, geochemical data from Barton Springs were separated into two groups: 1) periods of no flow in the major contributing streams, and 2) periods of flow in the major contributing streams (**Table 8**). On average, specific conductance, Mg, Na, and Cl are higher in the no flow group; Ca is lower in the no flow group; and K and SO_4 are similar.

Table 7. *Geochemical data for Onion Creek, the Blanco River, and Barton Springs. For streams the sampling point is the upstream site.*

Water source	**Ca (avg. ppm)**	**Mg (avg. ppm)**	**Na (avg. ppm)**	**K (avg. ppm)**	**Cl (avg. ppm)**	**SO_4 (avg. ppm)**	**Specific conductance (avg. µS)**	**pH**	**Time frame (sample size)**
Onion Creek[2]	62	11	29	2.9	36	35	514	7.9	10/13/76- 8/27/01 (107)
Blanco River[1]	n/a	n/a	n/a	n/a	14	36	482	8.1	10/28/96 – 12/7/11 (183)
Blanco River[2]	64	16	7.8	1.3	13	26	458	7.7	4/4/62 - 12/9/08 (141)
Barton Springs[2]	87	21	17	1.5	29	33	631	7.1	11/5/69 - 4/4/12 (407)
Bear Creek[2]	76	16	11	1.5	22	42	528	7.8	3/1/78 - 12/22/11 (145)
Slaughter Creek[2]	90	23	24	1.3	46	78	639	7.8	6/9/83 -4/17/10 (111)
Williamson Creek[2]	62	17	11	1.8	18	31	357	7.8	1/11/74 - 6/22/11 (222)

[1]GBRA
[2]USGS

Table 8. *Geochemical data for Barton Springs discharge during no flow conditions in the major contributing streams versus flow conditions.*

	Ca (avg. ppm)	**Mg (avg. ppm)**	**Na (avg. ppm)**	**K (avg. ppm)**	**Cl (avg. ppm)**	**SO_4 (avg. ppm)**	**Specific conductance (avg. µS)**	**pH**	**Sample size**
No flow conditions	82	25	28	1.7	45	41	721	7	n = 14 sp. cond. n = 12 others
Flow conditions	94	20	14	1.4	26	40	644	7	n = 61 sp. cond. n = 47 others

DISCUSSION

Correlation analyses demonstrated that there is not a significant relationship between the amount of increased recharge from the Blanco River and the amount of increased discharge at Barton Springs (**Figure 7**). Furthermore, there is no significant correlation between lag time and (a) the amount of increased recharge from the Blanco River as well as (b) the amount of increased discharge at Barton Springs (**Figure 7**). These results indicate that (a) the amount of increased recharge from the Blanco River does not proportionally reflect the amount of increased discharge at Barton Springs; and (b) the amount of increased recharge from the Blanco River does not affect how long it takes Blanco River recharge to affect Barton Springs discharge. These results are possibly indicative of conduit groundwater flow routes from the Blanco River to Barton Springs reaching maximum capacity after which groundwater is then routed elsewhere, such as to San Marcos Springs and/or to pumping groundwater wells. Evidence for this re-routing hypothesis emerges when comparing the amount of increased recharge from the Blanco River and the amount of discharge at Barton Springs. The average increase in recharge from the Blanco River for these 16 events is 2.7 ft^3/s with a range of 0.2 – 13.8 ft^3/s, while the average increase in discharge at Barton Springs is 1.4 ft^3/s with a range of 1-2 ft^3/s. The larger magnitude range of increased recharge at the Blanco River does not seem to affect the magnitude of increased discharge at Barton Springs. This suggests that if recharge from the Blanco River is the source of increased discharge at Barton Springs there might be an upper limit on the amount of water that is sourced from the Blanco River to Barton Springs. Furthermore, not all of the water recharging along the Blanco River is accounted for as discharge at Barton Springs. There is flow to San Marcos Springs and a certain amount must go into storage.

Comparison to dye trace studies along the Blanco River

Dye-tracing investigations in the Blanco River suggests that, on average and during drought conditions, the general travel time for dyes injected in the Blanco River to arrive at Barton Springs was three months (Johnson et al., 2012). These travel time results are much longer than the average of 4.8 days suggested by this study. Possible reasons for the discrepancies between the two studies include:

- The dye study targets specific recharge points, which may or may not be connected to flow paths that reach Barton Springs the quickest, whereas this study is able to examine the contribution of all flowpaths at once by estimate of total recharge from the Blanco River watershed and comparing it to discharge at Barton Springs;
- Dye traces did not target periods of increased recharge along the Blanco; thus, there were no specific recharge events in which pulses of water were flowing towards Barton Springs. It is expected that a pulse of recharging water would reach Barton Springs quicker than sustained recharge and/or decreasing recharge as there would be increased hydrostatic pressure along the flow paths during periods of increasing recharge;
- This study characterizes a pressure pulse, where recharging water can provide a piston-like effect where groundwater is pushed through the aquifer. Dye-tracing must detect the appearance of a physical particle. The appearance of a physical particle will inherently take a longer period of time versus the detection of a pressure pulse that quickly results in increased discharge.

Geochemistry

In general the average specific conductance of the Blanco River (472 µS/cm) is significantly lower than Barton Springs (631 µS/cm). Furthermore, there are differences in specific conductance in Barton Springs discharge for no flow (in terms of streams and recharge) versus flow conditions, 721 µS/cm versus 644 µS/cm, respectively. This difference is inferred to be a result of more geochemically evolved groundwater from deeper within the aquifer and/or mixing with the saline-water zone dominating discharge during extremely dry hydrologic conditions, while less evolved conduit-fed groundwater dominates discharge during wetter conditions (Senger, 1983; Hauwert et al., 2004; Mahler et al., 2011). There are also differences in major ion data where Ca, Mg, Na, Cl, and SO_4 are lower in the Blanco River versus Barton Springs discharge. Therefore, it would be expected that if Blanco River water is contributing directly to Barton Springs discharge then concentrations of these constituents would decrease as Barton Springs discharge increases.

During 12 of the 16 events we examined, there were increases in the average daily specific conductance at Barton Springs approximately one day prior to an increase in discharge at Barton Springs and a subsequent decrease in specific conductance at Barton Springs. The initial increase in specific conductance prior to an increase in discharge at Barton Springs could be attributed to a pulse of dilute recharge water from the Blanco River displacing more geochemically evolved water (e.g., water from the saline-water zone; see Senger, 1983; Hauwert et al., 2004). This can be thought of as a piston-like effect. The higher conductivity water is discharged at Barton Springs, resulting in a spike in specific conductance. Typically one day after this spike in specific conductance, less evolved recharging water from the Blanco River discharges at Barton Springs and leads to a decrease in the specific conductance at Barton Springs. However, this mechanism is not able to be definitively demonstrated because the increases and decreases in specific conductance are within analytical uncertainty. Fluctuations in specific conductance are noted to occur without variations in discharge at Barton Springs. This makes interpretation of the specific conductance data as a proxy for increased recharge from the Blanco River not possible for this study.

For the other geochemical parameters (Ca, Mg, Cl, K, Na, and SO_4) there are no time periods in which there are geochemical data to associate with the 16 events in which recharge along the Blanco River is hypothesized to contribute to Barton Springs discharge. This temporally limited data set makes determining the extent to which Blanco River recharge contributes to Barton Springs discharge not possible. However, differences in Barton Springs discharge geochemistry exist between drier versus wetter intervals. These differences presumably arise during drought conditions because (a) there is a larger component of groundwater derived from more evolved matrix flow to discharge at Barton Springs; and (b) the influence of water from the saline zone becomes a larger component of discharge at Barton Springs (Garner and Mahler, 2007). This is important for future studies as a pulse of less evolved recharge water can potentially alter the “drier time period” values for Barton Springs and allow for the geochemical tracing of groundwater flow from the Blanco River to Barton Springs.

CONCLUSIONS

Discharge conclusions

Our results support the previously established conclusions from dye tracing studies (Johnson et al., 2012; Smith et al., 2012) regarding the dynamic nature of the hydrologic divide. The hydrologic divide shifts from Onion Creek towards the Blanco River during dry time periods. Recharge along the Blanco River produces a corresponding, time-lagged increase in discharge at Barton Springs.

Geochemical conclusions

Existing geochemical data are insufficient to differentiate between the Blanco River and the major contributing creeks as source areas. Thus, it was not possible to distinguish geochemical changes that could be the result of recharge from the Blanco River issuing at Barton Springs. Specific conductance data are inconclusive as the variations in the specific conductance of discharge at Barton Springs are within instrumental error, and also variations in specific conductance are noted to occur without an increase in Blanco River recharge and/or an increase in Barton Springs discharge.

FUTURE INVESTIGATIONS

Although hydrologic conditions varied from wet to dry between 1987 and 2012, there were no time periods before 2000 when all contributing streams in the Barton Springs zone ceased to flow. The initial onset of zero flow conditions did not occur until September of 2000. The next period of no flow conditions did not occur until November of 2005, but became more frequent thereafter.

Questions arise as to why there was consistent flow in the contributing streams from July 1987 until September of 2000 and then again from late 2000 until November of 2005. Several hypotheses may account for the consistent creek discharge early in the record and lack of flow in more recent times: (a) rainfall may have been higher and/or more uniform during the consistent flow periods; (b) population growth and increased groundwater demand in the contributing zone may account for the decreased flow in more recent times; and (c) changes to base flow, which may arise from all of the preceding factors, may account for the decreased flow in more recent times. A preliminary examination of PDSI data suggests that drought conditions correspond to the periods of no stream flow. PDSI for the time period of 1987 to 1999 averaged 0.32 (average conditions). For the year 2000, PDSI averaged -1.84 (approaching moderately dry conditions). For 2001 to 2004 conditions were wetter and averaged 0.95. From 2005 to 2011 conditions became drier as PDSI averages -0.88. This is a very preliminary analysis and there are some statistical issues that need to be examined, such as the larger data set for 1987-1999 *versus* only for the year 2000. These are questions that could be investigated in the future, but are beyond the scope of this report.

Future geochemical investigations would need to utilize samples collected during periods when there is increased recharge along the Blanco River and corresponding increased discharge at Barton Springs. It would also be useful for additional dye-tracing studies originating at the Blanco River to be conducted at such times. Future studies might also target specific time periods of interest in a manner similar to Musgrove and Crow (2012).

The potential for groundwater geochemistry to help determine if there is flow across the Kyle area in the confined zone needs to be evaluated. Land et al. (2011) document the potential for flow to bypass San Marcos Springs toward Barton Springs under extremely dry conditions, and then from the Buda area back toward San Marcos Springs under wet conditions. Within the Kyle area however, there appears to be a significant change in the permeability structure of the aquifer, which is termed the “Kyle discontinuity” (Land et al., 2011). Preliminary evaluations of geochemical data in the Kyle area suggest an anomaly exists in comparison to surrounding Edwards groundwater geochemistry. This could have bearing on the actual volume of groundwater thought to be flowing through the Kyle area toward Barton Springs.

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The final scope of work was discussed at a technical meeting held at the Sierra Club Offices, Austin TX on February 24, 2012. Attendees included: Brian Hunt (BSEACD), Brian Smith (BSEACD), Marylynn Musgrove (USGS), Barbara Mahler (USGS), Geary Schindel (EAA), Sylvia Pope (City of Austin), Myron Hess (NWF), Jennifer Walker (Sierra Club), and Tyson Broad (Sierra Club). Marylynn Musgrove wrote the initial scope of work for this project.

Robin Gary assisted in construction of the site location map. Kirk Holland, MaryLynn Musgrove, Barbara Mahler, Tyson Broad, Myron Hess, David Johns, and Sylvia Pope reviewed the manuscript.

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Appendix A.

The raw data will be attached to the final report as a CD. It will also be kept in the BSEACD network and is available upon request.

Rainfall data:

- NCDC
- City of Austin

USGS discharge data:

- Slaughter
- Williamson
- Onion
- Bear
- Barton Creek
- Barton Springs
- San Marcos Springs
- Blanco River

Geochemical data:

- GBRA
  - Blanco River
- USGS
  - Slaughter
  - Williamson
  - Onion
  - Bear
  - Barton Creek
  - Barton Springs
  - San Marcos Springs
  - Blanco River