Flow Systems of the Edwards Aquifer Barton Springs Segment Interpreted from Tracing and Associated Field Studies

Nico Hauwert and David Johns
City of Austin Watershed Protection and Development Review Department
PO Box 1088
Austin, Texas 78767

Brian Hunt, Joseph Beery, and Dr. Brian Smith
Barton Springs/Edwards Aquifer Conservation District Assessment Program
1124 Regal Row
Austin, Texas 78748

Dr. John M. Sharp, Jr.
Department of Geological Sciences
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
Austin, Texas 78712

Abstract

Dye tracing and field studies conducted from 1996 to 2002 by the Barton Springs/ Edwards Aquifer Conservation District and City of Austin have delineated the groundwater basins and flow routes of the Barton Springs segment of the Edwards aquifer. The methodologies used included: 1) detection of injected tracers at springs and wells; 2) evaluation of potentiometric troughs and mounds; 3) distinguishing groundwater basins by their discharge sites; 4) offset dye arrival times and peaks at different spring discharge outlets; 5) spring water chemistry as an indication of source area; 6) geological structure and hydrostratigraphic unit influences on groundwater flow; and 7) observations of groundwater flow routes from within caves. These approaches and their analysis have refined the understanding of the Barton Springs flow system.

Three groundwater basins have been delineated (Cold, Sunset Valley, Manchaca) in the Barton Springs segment, each with a network of flow routes. Most of the flow within the Barton Springs segment occurs along the preferential flow routes, which are strongly influenced by faulting. Groundwater flow in the Manchaca basin follows two principal flow routes, the Manchaca flow route and the Saline-Line flow route. Groundwater flow within the Sunset Valley groundwater basin converges along the Sunset Valley flow route. The Cold Springs groundwater basin discharges to Cold and other springs along the Colorado River.

The four major Barton Springs outlets (Main, Eliza, Old Mill, and Upper) have distinctive concentrations of chloride and sulfate that reflect different water quality of the major source water flow routes. Upper Barton Springs is relatively low in chloride and sulfate, which increase along a different slope than in the other three Barton Springs. Main, Eliza, and particularly Old Mill Springs receive chloride and sulfate-enriched waters from the Saline-Line flow route. The

contribution of the Saline-Line flow route to Barton Springs is about 10 to 20% of the USGS-reported Barton Springs flow.

The Sunset Valley/Manchaca groundwater basin divide was delineated in part using observations from a flowing cave stream over 200 ft below the surface. Available data indicate that the southern divide for the Barton Springs segment lies near the watershed divide between the Onion Creek and Blanco River watershed divide. Groundwater-tracing data suggest that Onion Creek does not contribute to San Marcos Springs to the south.

Introduction

The Barton Springs segment of the Edwards aquifer is located south of the Colorado River at Austin extending south to the Kyle area, east to Interstate 35, and west to FM 1826. The aquifer provides water supplies for domestic, municipal, commercial, industrial, agricultural, recreational, and ecological needs. It is estimated that more than 50,000 people depend on the aquifer as a sole source of water.

The Barton Springs/Edwards Aquifer Conservation District (BSEACD), in cooperation with the City of Austin (COA), injected non-toxic organic dyes into caves, sinkholes, and wells within the Barton Springs segment of the Edwards aquifer to trace groundwater flow routes and determine groundwater-flow velocities (Hauwert, Johns, Aley, and Sansom, 2002; BSEACD, 2003). These studies, conducted between 1996 and 2002, have provided new insight into groundwater flow for this karst aquifer by establishing groundwater basins, preferential groundwater flow routes, and groundwater flow velocities. Groundwater tracing is recognized as the only direct method to measure groundwater flow routes and travel times in karst aquifers. However, additional field data are used to provide a better understanding of the overall karst flow system.

This paper presents results from a comprehensive data analysis to understand the flow system of the Barton Springs segment of the Edwards aquifer. Data include findings from dye tracing, potentiometric maps, water chemistry, and geologic and cave maps.

Hydrogeologic Setting

The Barton Springs segment of the Edwards aquifer discharges in South Austin primarily from Barton Springs, Cold Springs, and, to a lesser extent, smaller springs along the Colorado River and lower Barton Creek. Detailed hydrogeologic settings for this aquifer are described in Slade et al. (1986) and Small et al. (1996) and are only briefly described here. Barton Springs consists of four spring outlets: Main, Eliza, Old Mill, and Upper Barton Springs. The discharge of Barton Springs reported by the U.S. Geological Survey includes only the flows from Main, Eliza, and Old Mill Springs. Discharge in Upper Barton and other springs on lower Barton Creek, ceases when USGS reported flows decline below about 40 cubic feet per second (cfs). For the purposes of this paper, low groundwater flow conditions (low flow conditions) are defined as when the USGS reported flow for Barton Springs is about 35 to 40 cfs. Moderate groundwater flow conditions (moderate flow conditions) are defined to be from 40 to 75 cfs. High groundwater flow conditions (or high flow conditions) are defined for flow exceeding 75 cfs. The average USGS reported flow of Barton Springs is 53 cfs (COA analysis, 1998). In this paper we will focus discussion on Barton Springs. Additional information on Cold Springs and other springs of the Barton Springs segment is presented in Hauwert, Johns, Aley, and Sansom (in press).

Methods (Approach)

Characterizations of groundwater flow systems involving multi-disciplinary investigations, including groundwater dye tracing, are well-documented (Quinlan and Ray, 1981; Thrailkill, 1985; Atkinson et al., 1973). Ogden et al. (1986) showed that San Marcos Springs was fed by two separate groundwater basins based on the appearance of tracers at different sets of spring outlets, differences in groundwater chemistry, and potentiometric-surface elevations. A number of studies were conducted cooperatively since the 1990's by the BSEACD, City of Austin Watershed Protection and Development Review Department, U.S. Geological Survey, and the University of Texas Department of Geological Sciences. These studies involve groundwater tracing, potentiometric-surface mapping, and water-quality sampling. Concentrations of dissolved chloride and sulfate, collected by the USGS and COA from July 1978 to January 2004 were examined to delineate source areas and proportions. Geologic mapping by the U.S. Geological Survey (USGS) and the BSEACD provided the hydro-stratigraphic and fault relationships (Small et al, 1996). Mapping of caves in the Barton Springs segment by the Texas Speleological Survey have also contributed to a better understanding of recharge and groundwater flow (Russell, 1975; Russell, 1996).

Analysis

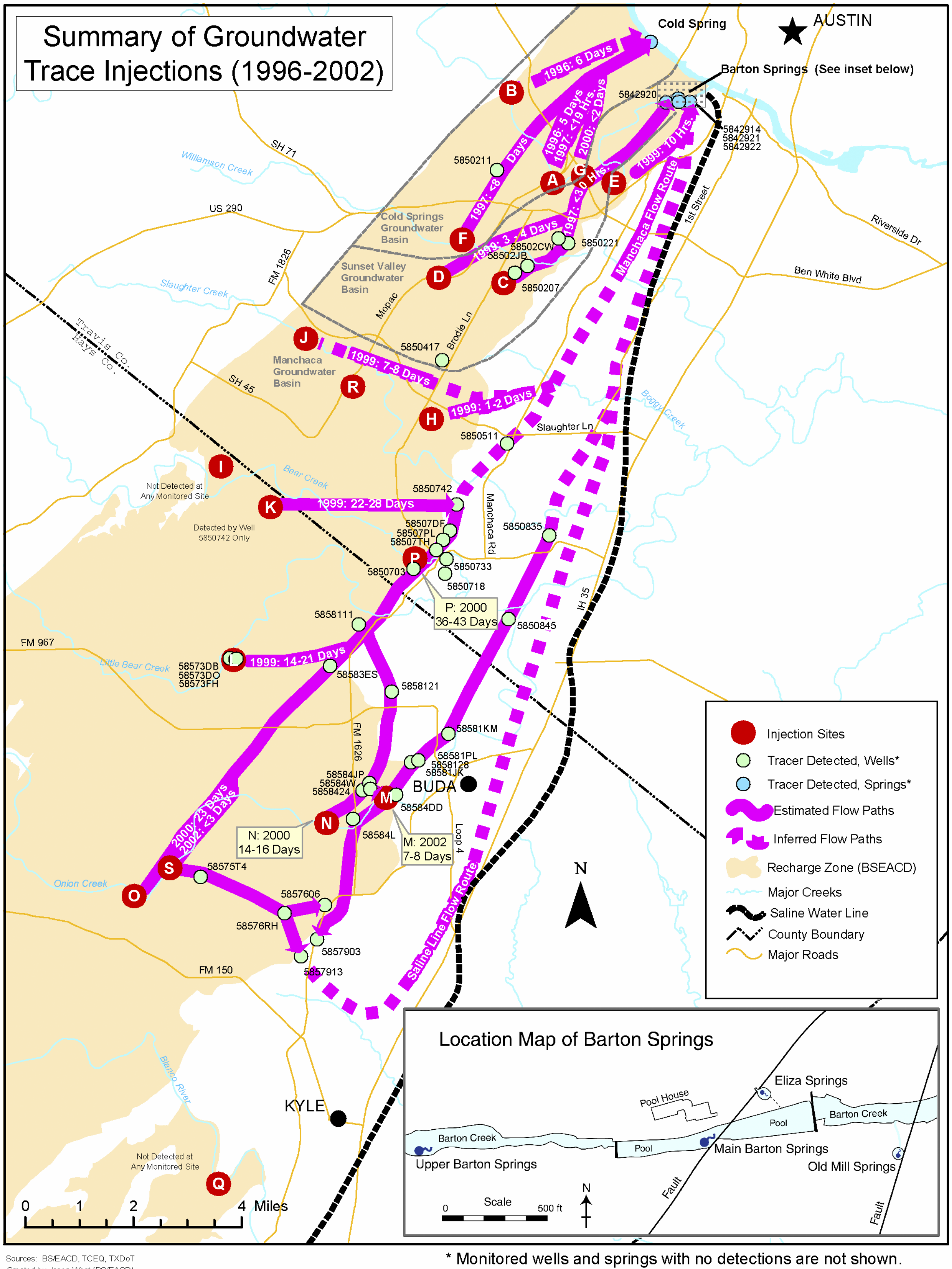
Identification of the Groundwater Basins from Discharge Spring Sites

Three groundwater basins were identified in the Barton Springs segment **(Figure 1)**. These are the Cold Springs, Sunset Valley, and Manchaca groundwater basins. The presence of three groundwater basins is based largely on groundwater dye tracers injected across the Barton Springs segment that discharged from specific spring outlets:

1. The Cold Springs groundwater basin includes areas where tracers appeared at Cold Springs or other unidentified springs near Cold Springs on the Colorado River.

2. The Sunset Valley groundwater basin was defined as areas where tracers discharged from Upper Barton Springs and Main Barton Springs, but not Eliza or Old Mill Springs.

3. The Manchaca groundwater basin was identified as those portions of the Barton Springs segment where tracers were injected in recharge features and subsequently discharged from Main, Eliza, and Old Mill outlets of the Barton Springs, but not Upper Barton Springs.



* Monitored wells and springs with no detections are not shown.
** All travel times are to the Springs (Cold Spring and Barton Springs).

Figure 1. Summary of groundwater traces conducted from 1996 through 2002 within the Barton Springs segment. Prepared by Jason West of the Barton Springs/Edwards Aquifer Conservation District.

The groundwater basins defined in Figure 1 are well defined, by the tracer tests and other field data. The divides are subject to refinement by future studies. Data, in addition to presence of tracers at monitored sites, were used to examine the divides between groundwater basins, and are described in greater detail below.

Delineation of major preferential groundwater flow routes using tracers and potentiometric surfaces

Prior to the 1996 groundwater tracing within the Barton Springs segment, potentiometric surfaces in the Sunset Valley area (Hauwert and Vickers, 1995) suggested the presence of convergent preferential groundwater flow routes, such as those observed in karst areas of Kentucky (Quinlan and Ray, 1981; Thrailkill, 1985). Master conduits associated with preferential groundwater flow routes can be sufficiently solution-enlarged to transmit groundwater as fast as the recharge sources can supply it. Consequently, groundwater moves along the preferential flow route analogous to a pumping well's cone of depression. In fact, pumping wells or other large discharges of water from the Edwards Aquifer typically have an anisotropic cone of depression that reflect local preferential groundwater flow routes. Slade (et al, 1986) described the anisotropic cone of depression created by the draining of Barton Springs pool during low flow periods. The cone of depression from major pumping wells within the Barton Springs segment tend to be strongly anisotropic to reflect preferential flow routes near the well (Hauwert, Johns, and Sharp, 2002). It can be expected that for periods where the recharge source exceeds the capacity of the master conduit, the preferential flow route will be expressed as a mound on potentiometric surface maps of sufficient detail (Palmer, 2004) (**Figure 2**).

The most definitive indicator of the presence of preferential groundwater flow route is the recovery of a tracer far downgradient of the injection site. Tracers recovered from well 58-50-742 had been injected in widely separated sites within the Bear, Little Bear, and Onion Creek watershed, demonstrating convergent flow to a preferential flow route (Figure 1).

Water quality is also influenced by preferential flow routes and is an indication of preferential flow routes. Wells located very close to the identified preferential flow routes tend to have a relatively poor water quality for at least two reasons. First, the rapid flow rate found along the preferential flow routes allows for transport and internal erosion of sediment within the aquifer. Anomalously high levels of sediment were observed along the Sunset Valley flow route (Hauwert and Vickers, 1995). Groundwater flow rates of 4 to 8 miles per day that were measured along preferential flow routes by tracers in the BS/EACD and COA study. These velocities are sufficiently rapid to promote internal erosion and transport of sediment. The second reason that higher levels of contaminants are found along preferential flow routes than in adjacent portions of the same aquifer is that the master conduits normally drain a relatively large portion of the groundwater basin. As an indication of this phenomenon, levels of indicator bacteria in Barton and Cold Springs are almost always higher than wells sampled in the source area (Texas Groundwater Protection Committee, 1998; BSEACD Annual Reports 1994-1999). Many existing wells currently used for water-quality monitoring that are not positioned on preferential groundwater flow routes may have a limited source area, experience relative small flow through its screened or open interval, and/or have a complicated source area not representative of the overlying or nearby surface land use.

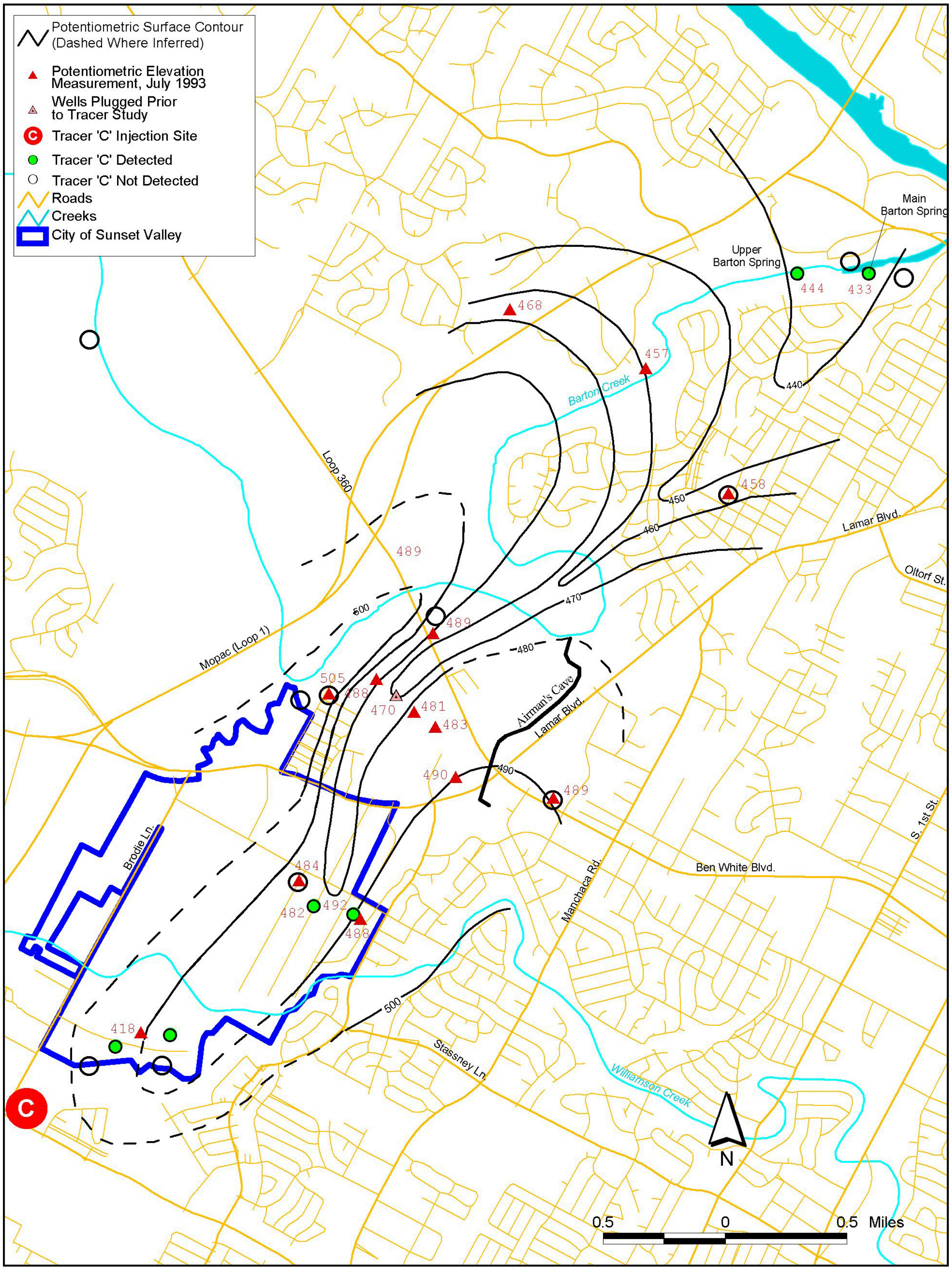


Figure 2. Potentiometric-surface trough in the Sunset Valley area, defining the Sunset Valley Flow Route to Barton Springs. Tracer C, injected in 1997, appears to follow this flow route to the Upper and Main Barton Springs outlets. Modified from Hauwert and Vickers (1993) by Jason West of the Barton Springs/Edwards Aquifer Conservation District.

Delineation of the Sunset Valley and Manchaca Groundwater Divide

The groundwater divide for the Sunset Valley and Manchaca groundwater basins were based largely on the results of dye traces H and J from the Slaughter Creek watershed under high flow conditions (Figure 1). Both traces were recovered from Main, Eliza, and Old Mill outlets of Barton Springs, but not Upper Barton Springs. During this tracing phase, the Sunset Valley groundwater basin had a relatively high number of monitored wells, including a few on or very near the preferential flow route that had detected tracers from previous injections within the Sunset Valley groundwater basin. The Manchaca groundwater basin, from Slaughter Creek to Barton Springs, has few accessible wells that could be monitored. The Manchaca groundwater basin has a deep potentiometric trough that runs parallel to and just east of Manchaca Road in South Austin and is visible on several maps in the literature (Slade et al., 1986, Hauwert and Vickers, 1995; Hauwert, Johns, Aley, and Sansom, in press).

Cave mapping provides critical data for defining the groundwater basin. About one-half mile north of injection site H is Blowing Sink Cave, located just south of the watershed divide between Slaughter and Williamson Creeks (**Figure 3**). This cave has a southeast-flowing perennial cave stream, Eileen's River, at a depth of 255 feet below the surface (525 feet msl). Nearby well 58-50-411 has a nearly constant water level of 542 feet msl, except around periods of heavy rain when the water level can temporarily rise about 15 feet (Hauwert, Johns, and Sharp, 2002; Hauwert, Johns, Aley, and Sansom, in press). The lower elevation of the cave stream to the nearby well suggests that Eileen's River reflects the water-table gradient in a direction away from its eventual discharge site, Barton Springs. About 15 feet above Eileen's River, Blowing Sink contains a 10-ft diameter, nearly circular, and normally dry passage called Dark Side of the Moon. The Dark Side of the Moon passage trends and dips northeast, towards Barton Springs.

During the injection phase of trace H, well 58-50-417 was monitored for the tracer. No tracer was detected in this well until one month after injection. Positive detections came after several days of rain events in the study area. Low levels of tracer H were measured in two consecutive charcoal receptors placed for two-week intervals in the discharge from this well.

These combined results indicate that recharge from Slaughter Creek watershed flows to Barton Springs from the Manchaca groundwater basin. During periods of heavy rain, potentiometric mounding along Slaughter Creek forces water through the flood overflow passage of Dark Side of the Moon to enter the Sunset Valley groundwater basin, temporarily shifting the location of this groundwater divide.

Delineation of the Southern Divide

Six traces at four sites in Onion Creek from 2000-2002 provide the basis for flow route interpretation at the southern divide. Tracers were injected in creek-bottom caves on Onion Creek under low flow conditions of 2000, as well as under high flow conditions of 2002. Under the contrasting flow conditions, both bifurcation and trifurcation of recharge from Onion Creek was observed. Initial arrival of tracers at Main and Eliza (Barton) Springs occurred as soon as 14 days during low flow conditions and less than 3 days under high flow conditions along the

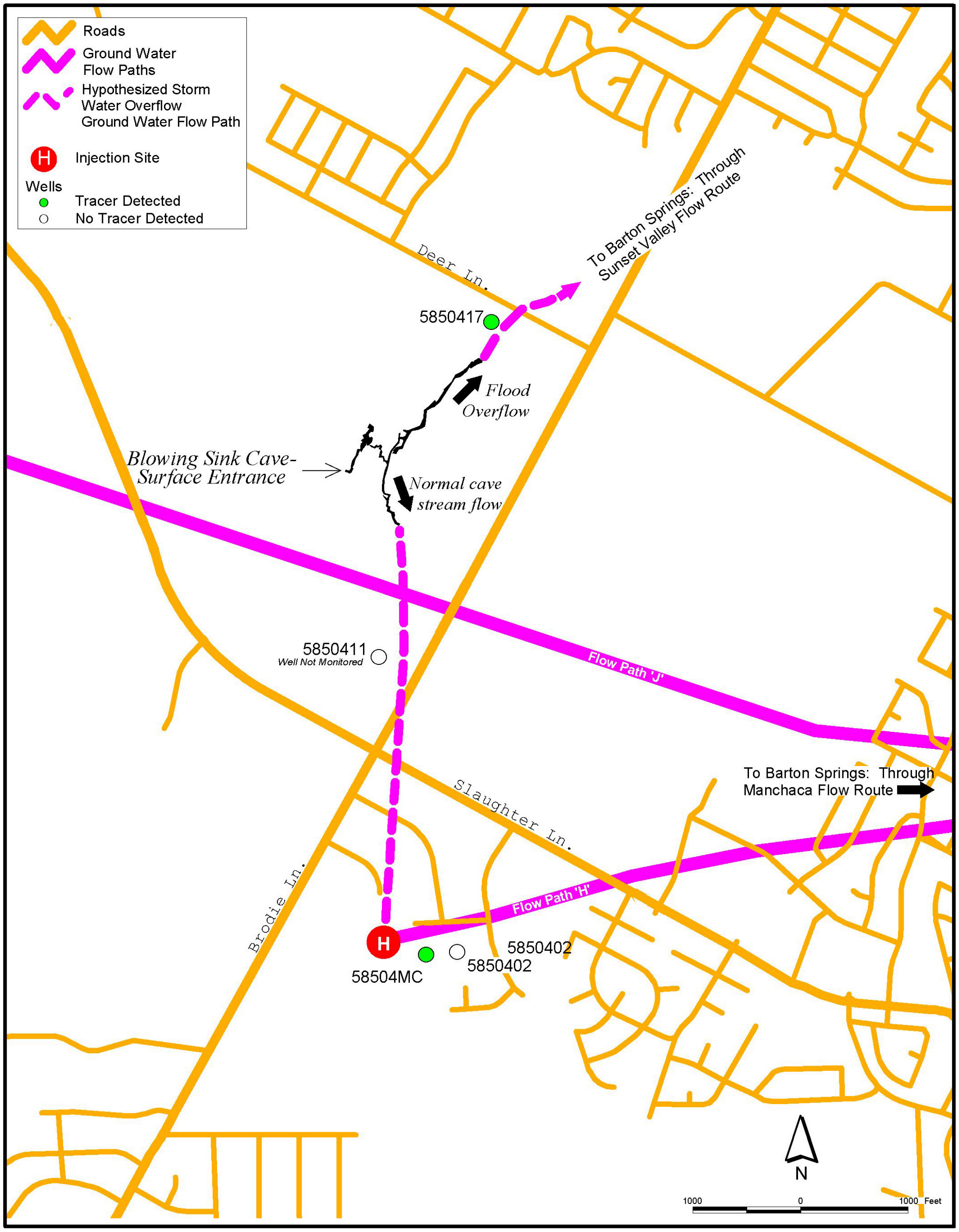


Figure 3. Tracers H and J appear to flow east to the Manchaca Flow Route, discharging from the Main, Eliza, and Old Mill outlets of Barton Springs. The cave stream in Blowing Sink Cave lies below the water table elevation observed in nearby well 58-50-411 and flows southeast -- a direction away from Barton Springs. The presence of flood overflow passages in Blowing Sink trending toward Barton Springs and the late, post-rain appearance of tracer H in well 58-50-417 suggest that under some high-recharge conditions, some recharge from the Slaughter Creek watershed temporarily crosses a normal groundwater divide into the Sunset Valley groundwater basin. Prepared by Jason West of the Barton Springs/Edwards Aquifer Conservation District.

Manchaca flow route. Regardless of where tracers were injected in Onion Creek, some of the tracer was recovered south of Onion Creek near Mountain City during both flow conditions (Figure 1).

No tracers from Onion Creek were recovered at either the City of Kyle municipal supply wells or San Marcos Springs. Both of these sites had previously been identified as possible destinations for portions of Onion Creek recharge (Stein, 1995). The third flow route of recharge from injection site M near Buda trended away from the Manchaca flow route and towards the Saline-Water (Bad-Water) Line. On Trace O, injected in upper recharge zone portion of Onion Creek, the tracer arrived nearly simultaneously at Main Barton and Eliza Springs, but arrived at Old Mill Spring about 10 days after its arrival at Main Barton Spring **(Figure 4).**

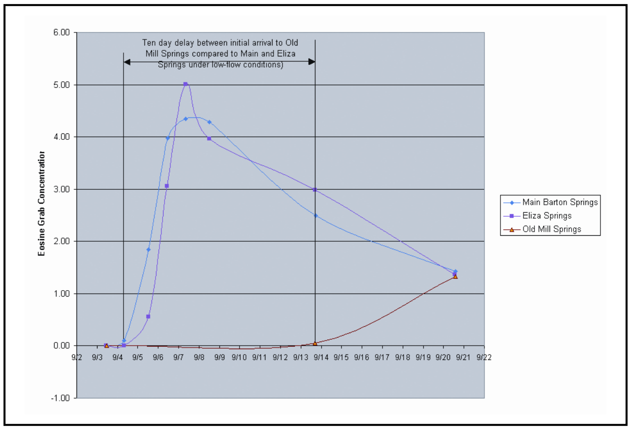


Figure 4. Arrival of eosine tracer from Site O on Onion Creek to Barton Springs, showing a 10-day delay from initial arrival at Old Mill versus the Main Barton Springs outlet.

Trace N, injected in Onion Creek, arrived at Main and Eliza Springs Barton Springs outlets, but was not detected at Old Mill Springs. During high flow conditions, the initial arrival of tracers were essentially simultaneous at Main, Eliza, and Old Mill Springs, but the concentrations of tracers measured at Old Mill Springs were consistently half or less. At least three peaks were evident in the recovery of the 2002 traces at the Main and Old Mill Springs, one of which was associated with a 0.5 inch rain event.

Contribution of Flow Routes to Barton Springs

If Main, Eliza, and Old Mill Springs are commonly fed by the Manchaca flow route within the Manchaca groundwater basin (Onion, Little Bear, Bear, and Slaughter Creeks), we would expect similar tracer concentrations in all three springs. However, the results of Trace J in the Slaughter Creek watershed under high flow conditions, show similar concentrations in Main and Eliza Springs, but significantly lower concentrations in Old Mill (**Figure 5**). Tracer concentrations measured at Old Mill Springs were less than a third of the concentrations measured at Main and Eliza Springs, until late in the breakthrough curve recession for trace J. This suggests that Old Mill receives about 2/3 dilution from another source other than the Manchaca flow route.

Tracer tests conducted in other karst areas have documented multiple peaks. Atkinson (and others, 1973) believed multiple peaks were the results of subsurface oxbow bifurcated flow routes or temporary storage that later releases in the aquifer as result of a recharge pulse.

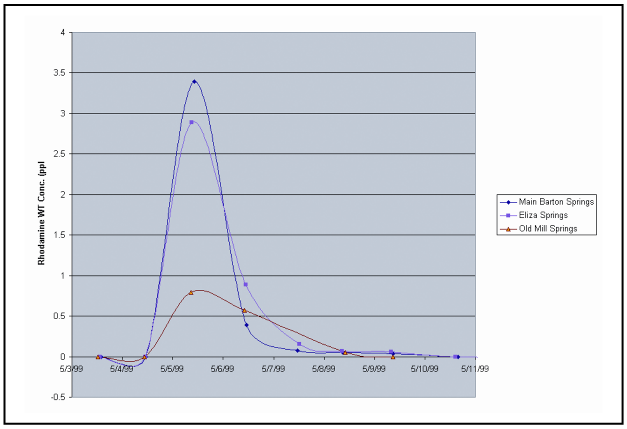


Figure 5. Differences in arrival of tracer J (rhodamine wt) from the Slaughter Creek watershed to the Barton Springs outlets. Although the arrival times are simultaneous, the concentrations at Old Mill Springs are about 1/3 of those at Main and Barton Springs, suggesting that Old Mill receives additional flow from a separate source. No rhodamine wt was detected at Upper Barton Springs during this tracing phase.

Similarly, the delays in arrival and peak tracer concentration times associated with the tracer injections in the Barton Springs segment and water-quality differences between the Barton Springs outlets can be explained by a flow route that extends from the Buda/Kyle area to Old Mill Springs that has not been previously described. This flow route likely corresponds with the position of the Saline-Water Line. This is supported by tracer detections from wells in the confined zone moving east from the Manchaca flow route. Assuming no absorptive, dispersive, or diffusive loss of tracer, about one half to two thirds of Old Mill's contributing flow originates from a subparallel, but separate and slower "Saline-Line" flow route. The Saline-Line flow route shown on Figure 1 also agrees with DeCook's (1963) interpretation of potentiometric surface maps of drought conditions in 1956: that flow in the Buda and Kyle areas moved east and northeast in the direction of the Saline-Water Line.

The water chemistry of Old Mill Springs is distinct from either Main or Eliza Springs, showing significant contribution of chloride, sulfate, and other constituents from the Saline-Water Zone which increase during drought periods (Senger and Kreitler, 1984; City of Austin, 1997). The chloride and sulfate concentrations in Barton Springs waters, collected by the USGS and City of Austin from 1978 to 2004, were examined with Barton Springs flow conditions ranging from 17 to 129 cfs. The concentrations of chloride and sulfate at Upper Barton Spring, Eliza, and Old Mill are fairly distinctive (**Figure 6**). Main Barton Springs, however, shows

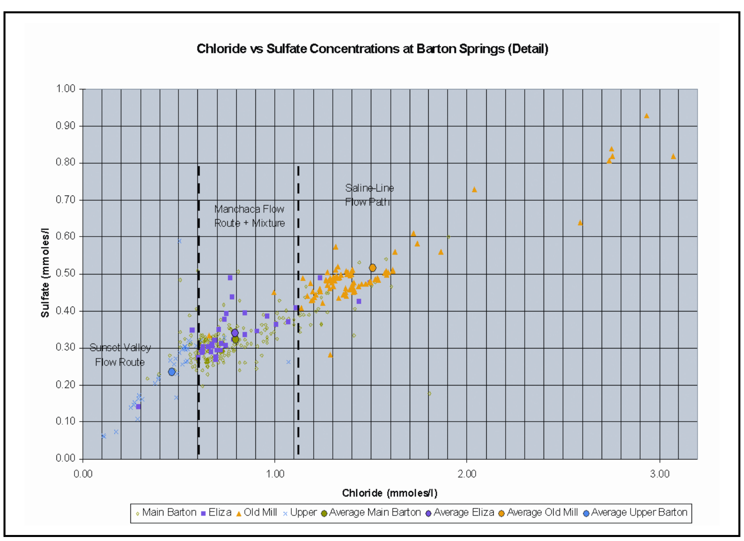


Figure 6. Water chemistry of Barton Springs and Saline-Water Zone. Distribution of chloride and sulfate support the concept that Upper, Eliza, and Old Mill Springs receive groundwater from separate flow routes, while Main Barton receives contributing flows from all three sources, interpreted to be Sunset Valley flow route (Upper and Main), Manchaca flow route (Main, Eliza, and Old Mill), and the Saline-Line flow route (Old Mill with diversion to Main during low-flow conditions). Water-quality results were from samples collected from 1979 to 2004 by COA and USGS.

considerable overlap in chloride and sulfate concentration fields. The chemical distribution of chloride and sulfate support the interpretation of tracing results that Upper Barton, Eliza, and Old Mill receive flows from different sources, while Main Barton receives portions of its flow from a combination of the three sources (Sunset Valley, Manchaca, and Saline-Line flow routes.)

Assuming that: Upper Barton Springs never receives contribution from the Saline-Water Zone and that the shift in sulfate and chloride along a set slope is directly related to changes in Saline-Water Zone contributions, then the shift in range of chloride and sulfate concentrations measured in Old Mill, Eliza, Upper, and Main Springs can be used to estimate the flow contribution from the Saline-Water Zone and proportion of contribution from the Saline-Line flow route to Barton Springs. The reference water quality of the Saline-Water Zone was assumed that of south Travis County well 58-50-301 collected October 26, 1948. However, other Saline Water samples showed similar trends **(Figure 7).**

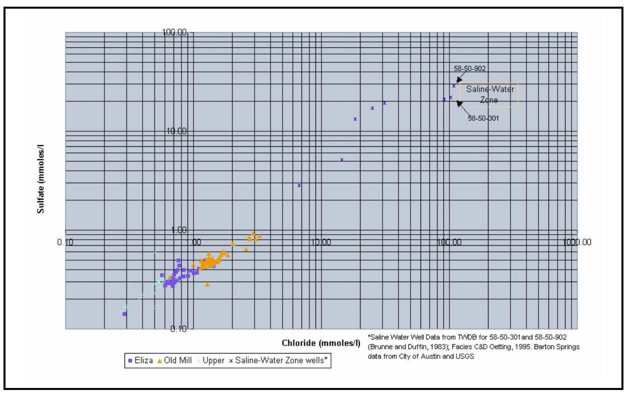


Figure 7. Dissolved sulfate and chloride concentrations from Barton Springs to the Saline-Water Zone. The shift in constituent concentrations for Old Mill from reference point at the Upper Barton maximum line indicates it receives variable contribution from the Saline-Water Zone, but a maximum of 3% under the range of flow conditions (17-129 cfs) sampled here. Barton Springs water quality is derived from City of Austin and USGS data. The Saline-Water Zone water quality is from wells 58-50-301 and 58-50-902 (Brune and Duffin, 1973) and Facies C and D wells from Oetting (1995).

For the highest concentrations represented by the samples and assumed lowest flow conditions, the Saline-Water Zone contributed 3% to Old Mill springs and 0.5% to Main and Eliza Springs outlets combined. Averaging of all the data, Old Mill consisted of 1% Saline Water, while the combined Main and Eliza outlets contained 0.2% Saline Water. The values derived from chloride are consistently about 1% lower than those derived from sulfate, presumably because sulfate also reflects the addition of leakage from the underlying Trinity Group. By comparison Senger (1983) roughly calculated the Saline-Water Zone contribution to be about 5 to 10% using the same Saline Water Zone reference data (well 58-50-301) and water quality of Barton Springs under 20 cfs conditions in 1978. Even though the percent of the saline water is relatively small even under drought conditions, slight increases in the concentrations of dissolved minerals within the Saline Water Zone potentially could be of concern for potability and for aquatic life at Barton Springs.

The geochemical estimate from chloride for the average contribution of the Saline-Line flow route was calculated under the additional assumption that Old Mill Spring consists of 1/3 to 2/3 of Saline-Line flow route source water, as derived from the tracing results, and that the average flow for Old Mill Spring is 6 cfs or 12% of the combined Main and Eliza outlet flows. Under average conditions, the Saline-Line flow route contributes 5 to 11 cfs, or 10% to 20% of the total USGS reported Barton Springs flow.

Influence of Geologic Structure on Groundwater Flow

The main trunks of the flow routes tend follow to closely the fault trends in each groundwater basin. The Manchaca flow route generally follows a line of faulting for nearly 20 miles from Onion Creek to Barton Springs. The Sunset Valley flow route generally follows a separate fault line through the Sunset Valley groundwater basin for at least five miles to the Upper and Main outlets of Barton Springs. Airman's Cave is a normally dry overlying cave that illustrates the influence of faulting on master conduit development (Russell, 1975; Hauwert and Vickers, 1994; Hauwert and Russell, 1996). The main trunk of the Cold Springs flow route extends about five miles along a general trend of faulting from Williamson Creek to Cold Springs.

Tracers injected on the western side of the recharge zone in the Slaughter, Bear, Little Bear Creek watersheds moved east and appeared to initially ignore major northeast fault and fracture trends. Karst studies in other areas suggest that in unconfined portions of karst aquifers, aquifer dip can dictate flow directions (Ford and Ewers, 1978; Dreybrodt and Gabrovsek, 2003; Ginsberg, et al., 2002). DeCook (1963) reported that the Barton Springs segment has a slight regional "dip" of about 20 feet per mile to the southeast. Detailed mapping however, is necessary to distinguish offset due to faulting, fault drag, and ramp-relay structures, from regional dip. Current hydrostratigraphic mapping of the Barton Springs segment has not detected any measurable amount of regional dip in the Edwards Aquifer (Small and others, 1995; BSEACD, 2003a). Geological cross sections across the Barton Springs segment between IH35 and FM 1826 show a net offset of about 1070 near Barton Creek increasing to roughly 1260 feet of net offset near Bear Creek (Hauwert, Johns, Aley, and Sansom, in press). This net offset is interpreted to be due almost entirely to down dropping of fault blocks to the east. It is likely these down-dropped fault block "steps" that juxtaposes units of variable permeability, rather than regional dip, that produces a profound eastward groundwater flow gradient on the western side of the recharge zone. Generally, the eastward-flowing groundwater from the recharge zone of Slaughter, Bear, and Little Bear creek watershed converges with northeast-trending Manchaca groundwater flow route to the Main, Eliza, and Old Mill outlets of Barton Springs. Tracers injected in the channel of Onion Creek flow directly northeast, rather than east, to converge with either the Manchaca or Saline-Line flow routes.

Sparse data on the Saline Line flow route suggest that geologic structure has less influence on its trend. This flow route trends at an angle to the general fault trends, although it is possible that individual faults may influence its master conduits for limited distances. Groundwater in this flow route is interpreted to flow in a general up-thrown fault direction. Downstream of Barton Springs on Barton Creek and the Colorado River, the Edwards Aquifer is overlain with confining units that reduce significant downstream discharge and aquifer circulation. Consequently, the highly mineralized Saline-Water Zone approaches very close to Barton Springs, and reflecting aquifer "stagnation" to the east and north. The Saline-Line flow route flows under artesian conditions along a forced gradient to the regional drain of Barton Springs. The Saline-Line flow route appears to be fed solely by the Onion Creek watershed.

Discussion

The concept of a major groundwater flow route along the Saline-Water Line is reasonable. Preferential groundwater flow routes can act as a hydraulic barrier for cross flow. Mixing of waters from the freshwater zone and Saline-Water Zone is likely to lead to calcite undersaturation and result in chemically aggressive groundwater more likely to result in dissolution and conduit development (Senger and Kreitler, 1984; Thrailkill, 1968).

Tracing test results from Onion Creek during low and high flow conditions establish that Onion Creek contributes recharge to Barton Springs and not to San Marcos Springs. The analysis of tracer tests demonstrate how reliance on potentiometric surfaces from widely-spaced wells to delineate divides in a karst aquifer can result in erroneous conclusions. Potentiometric surface data collected in previous studies (Petit and George, 1952; Guyton, 1956; Garza, 1962; Guyton, 1958, Garza, 1966, McClay, 1980, and Stein, 1995) have been used to infer that during some or all flow conditions, Onion Creek contributes to San Marcos Springs or is intercepted by the City of Kyle cone-of-depression. The mounding in potentiometric surfaces depicted around the lower reaches of Onion Creek are accurate (Stein, 1995). However, direct groundwater tracing shows that the potentiometric surface mounds reflect bifurcation of at least three flow routes to Barton Springs, as shown in Figure 1, rather than a groundwater divide separating the Barton Springs and San Marcos groundwater basins.

The question could be raised that some of the injected tracers and recharge from Onion Creek have arrived at San Marcos Springs below the detection limit? However, no tracers attributed to injection along Onion Creek was ever detected at San Marcos Springs, and an analysis of a hypothetical recovery of a tracer at the dye detection limit for grab samples indicates that any flow to San Marcos Springs, even if it did occur, would be insignificant. Under the low-flow conditions of 2000, 25 lbs of eosine were injected at site O in Onion creek, at least 13% of which was recovered 18 miles away at Barton Springs within 2 months of subsequent detection in grab samples. At the time, San Marcos flowed at a combined rate of about 110 cfs as reported by the USGS. If for 2 months the eosine tracer flowed 8 miles south and discharged from San Marcos at the detection limit of 0.008 ppb, the maximum mass of tracer would be 0.3 lbs, or 1% of the injection mass. This estimate is conservatively high since only a small portion of San Marcos springs originates from the north and no tracer was detected on charcoal receptors placed at San Marcos springs that adsorb tracer continuously and have a much lower detection limit.

During the 2002 tracer tests under high-flow conditions, no tracers attributed to the Onion Creek injections were detected on either grab samples or charcoal receptors placed at San Marcos Springs or the City of Kyle wells. However less than 1% recovery was seen at Barton Springs. The low recovery from Barton Springs of at least one of the tracers from 2002 was caused in part by the surprisingly rapid groundwater velocity so that the first arrival and peak were not collected by grab samples and automatic samplers.

There is no direct evidence to date shows that the Blanco River contributes significantly to Barton Springs. In May 1983, the Edwards Aquifer Research and Data Center injected a tracer in Tarbutton's Cave on the Blanco River (site Q) under high-flow conditions. One year later, under low-flow conditions, the same tracer was detected seven miles to the south at selected San Marcos Springs (Ogden, et al., 1986). No monitoring was performed within the Barton Springs segment over the same period, so a bifurcation of flow from the Blanco River cannot be ruled out. A follow-up tracer retest was in the BS/EACD and COA study in 2000 with relatively intensive monitoring of wells and Barton and San Marcos springs. Between August 3 through August 5, 15 pounds of sodium fluorescein dye mixture were poured into Tarbutton's Showerbath Cave. The tracer from this injection was not detected at any of the monitored sites and consequently this particular trace provides little or no useful information in delineating the groundwater divide. Potentiometric surface maps of low-flow periods produced by DeCook (1963) and Stein (1995) do not eliminate the possibility of recharge from the Blanco River moving north towards Kyle and, possibly, Barton Springs during drought periods. From 1934 to 1971, an estimated annual average of 44 cfs recharged to the Edwards Aquifer from the Blanco River watershed (Klempt and others, 1979). River–bottom recharge of the Blanco River can be approximated by the difference in daily average flow between the USGS flow station upstream of the recharge zone at Wimberly and downstream of the recharge zone near Kyle. From June 1, 1956 to September 30, 1956, the daily average flow difference between the two stations was 18 cfs. This estimates discounts additional recharge occurring in the river bottom that originated within the recharge zone, of loss of potential recharge from river bottom evapotranspiration. It is possible that the Blanco River contributes to Barton Springs during extreme drought conditions, although if occurring such contribution can be expected to be relatively small under these low-recharge conditions. Examination of the groundwater divide by dye tracing of the Blanco River during low-flow conditions would test this hypothesis.

Does the San Marcos area contribute flow to Barton Springs? Some researchers h(Guyton and Associates, 1958; Senger and Kreitler, 1984) have suggested that "during extremely low flow" conditions, groundwater from the San Antonio segment could flow to Barton Springs based on the following data:

1) During the 1950's drought of record, Comal Springs dried for five months while San Marcos and Barton Springs continued to flow, even though Barton and San Marcos Springs had relatively smaller source areas, and
2) Barton Springs is at a lower surface elevation (440 ft or 134 m) than San Marcos Springs (670 ft or 204 m).

Although San Marcos Springs likely receives groundwater flow bypassing Comal Springs (Guyton and Associates, 1979, Ogden and others, 1986), it is not apparent that Barton Springs also does. The drying of Comal Springs during the 1950's drought was largely influenced by well pumping, totaling an annual average of as much as 428 cfs in the San Antonio segment during that period (Guyton and Associates, 1979). During the 1950's, drought pumpage in the Barton Springs segment was estimated to be only 0.6 cfs (Brune and Duffin, 1983). Therefore, the fact that Barton Springs flowed during the 1950's drought does not necessarily indicate that it received flow from the San Antonio or San Marcos areas. Finally, lower surface elevation at Barton Springs does not prove that conduits are present to carry groundwater from San Marcos to Barton Springs or that geologic barriers are not present between the two areas.

Instead, current information indicates that the groundwater divide between the Barton Springs and San Antonio segment lies south of Onion Creek and north of the Blanco River, most likely along the watershed divide and the current path of Highway 150, as mapped by Senger (and Kreitler, 1984) Slade (and others, 1986). Potentiometric surface maps by (Stein, 1995) and existing groundwater tracing results (Ogden and others, 1986) indicate that groundwater flows from the Blanco River to San Marcos Springs, rather than the reverse direction, even under drought conditions. Tracing of Onion Creek under both high and low flow conditions shows that it does not contribute measurably to San Marcos Springs.

Conclusions

We interpreted the groundwater flow system in the karstic Edwards Aquifer, Barton Springs segment, with field data and tracer tests. The three main groundwater basins were identified by the spring outlets where tracers discharged.

Three groundwater basins have been delineated (Cold, Sunset Valley, Manchaca), each with a network of preferential flow routes. Groundwater flow routes in the Manchaca basin follow two principal flow routes: the Manchaca flow route and the Saline-Line flow route. The preferential groundwater flow routes were mapped using tracer recovery locations, potentiometric-surface troughs, and geologic maps. In some areas, cave maps, localized water-quality degradation, and anisotropic cones of depression indicated the groundwater flow routes. Water-quality differences between Upper, Main, Eliza, and Old Mill Springs support the concept that they are fed from different sources. The water quality of source waters from the Sunset Valley flow route, Saline-Line flow route, and Manchaca flow route plus mixed waters can be distinguished by sulfate and chloride concentrations. Based on this analysis, the Saline-Line flow route provides 10% to 20% of the USGS-reported flow of Barton Springs. Based on traces conducted during high and low flow conditions, the location of the southern divide for the Barton Springs segment was verified to be near the surface-water divide for the Blanco and Onion Creek watersheds. Onion Creek does not contribute to San Marcos Springs from the wide range in sites and flow conditions tested. Existing data indicate that the San Marcos area does not contribute to Barton Springs, even under drought conditions, however, further tests are needed to prove whether or not the Blanco River contributes recharge to Barton Springs.

The main trunks of the Cold Springs, Sunset Valley, and Manchaca flow routes are strongly influenced by the location of geologic fault trends with offsets of over 40 feet. Groundwater flow from the unconfined recharge zone to the main trunks appear to be influenced by steeply down-dropping fault block steps to the east. These downdropping fault steps simulate the effects of dipping strata, but the actual structural dip is not negligible. So far, the Saline-Line flow route cannot be associated with structurally-connected fault trends.

Acknowledgments

The council members, and/or board of directors, and staff of the Barton Springs/Edwards Aquifer Conservation District and the City of Austin provided essential support for these studies, particularly James Sansom, Stefani Helmcamp, Jason West, and COA ERM manager, Nancy

McClintock. These studies were funded in part by the U.S. Environmental Protection Agency through the Texas Natural Resource Conservation Commission (now TCEQ). Tom Aley and Ozark Underground Laboratory conducted laboratory analysis of tracing samples and provided valuable advice on the study. Geary Schindel and the Edwards Aquifer Authority provided supplemental analysis of tracer samples.

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