**GROUNDWATER TRACING STUDY OF THE**

# BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER,

**SOUTHERN TRAVIS AND NORTHERN HAYS COUNTIES, TEXAS**


**Barton Springs/Edwards Aquifer Conservation District**

**City of Austin Watershed Protection and Development Review Department**


**September 2004**

Prepared by the Barton Springs/Edwards Aquifer Conservation District
And the
City of Austin Watershed Protection and Development Review Department

PREPARED IN COOPERATION WITH THE TEXAS NATURAL RESOURCE CONSERVATION COMMISSION AND U.S. ENVIRONMENTAL PROTECTION AGENCY

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**COVER:**

Rhodamine WT tracer is visible at Cold Springs on the south bank of the Colorado River on August 20, 1996. The tracer was injected 5 days earlier in a sinkhole (Site A) on Barton Creek just downstream of Mopac Expressway Bridge crossing, about 3.2 miles southwest of Cold Springs. The tracer was strongly visible for about 1 day, and was barely visible on the following day. The visual appearance of tracer at a monitoring site was rare and unintentional. Photograph by David A. Johns.

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## EXECUTIVE SUMMARY

Groundwater tracing conducted in the Barton Springs segment of the Edwards Aquifer from 1996 through 2000, has provided new insight on groundwater flow directions and velocities. A groundwater tracing study performed by the Barton Springs/Edwards Aquifer Conservation District and the City of Austin has measured groundwater velocities and destinations from 17 natural recharge features and one well within the Barton Springs segment. A total of 20 traces were conducted in all the major contributing watersheds supplying water to Barton Springs, including Barton, Williamson, Slaughter, Bear, Little Bear, Onion Creeks, as well as the Blanco River. This study accomplished its data quality objectives by detecting 85% of the traces in at least one monitoring site.

To conduct the traces, up to five distinct organic tracers were used: fluorescein, rhodamine WT, eosine, sulforhodamine B, and pyranine. The tracers were injected into caves, sinkholes, and other recharge features and were generally flushed into the aquifer with about 10,000 gallons of water. In one trace, dye was poured into a well that was flushed with creekwater flowing adjacent to the well. Activated charcoal receptors were placed at wells and springs where tracer arrival was possible, in order to adsorb cumulative concentrations over the placement duration. Grab samples were also collected to measure tracer concentrations at specific times. Potentiometric surface, geological, and cave maps were used to estimate groundwater-flow paths in between the tracer detection sites.

The results of this study demonstrate that groundwater recharging the Barton Springs segment in the Barton and Williamson Creek watersheds travels either north or northeast towards either Barton or Cold Springs. Portions of the upper Recharge Zone of Barton Creek (from the Mount Bonnell Fault down to the Loop 360 crossing) and Williamson Creek (from Highway 290 down to the Brush Country Road crossing) contribute flow to Cold Springs and other springs on the south bank of the Colorado River rather than Barton Springs. The groundwater in this area generally converges to a preferential flow

path called the Cold Springs Flow Route. The Cold Springs groundwater basin within the Barton Springs segment of the Edwards Aquifer is about 11.8 square miles.

Recharge entering into the remaining portions of the Recharge Zone within the Barton and Williamson Creek watersheds generally discharges from the Main outlet of Barton Springs and Upper Barton Springs and is called the Sunset Valley groundwater basin. The Sunset Valley groundwater basin is about 11.7 square miles in size. The primary identified preferential groundwater flow path that feeds Upper Barton Springs is known as the Sunset Valley Flow Route. Upper Barton Springs becomes dry when the other three Barton Springs outlets decline to a combined flow of 40 cubic feet per second (cfs). During these periods of low groundwater levels, all of the source area for Upper Barton Springs discharges solely from the Main and possibly the Old Mill and Eliza spring outlets.

Groundwater recharging the Barton Springs segment in the Slaughter, Bear, Little Bear, and Onion Creek watersheds generally flows east towards a wide potentiometric trough that parallels the east side of Manchaca Road from Manchaca/San Leanna northeast to Barton Springs. The primary identified preferential groundwater flow path for recharge from these watersheds is known as the Manchaca Flow Route. Groundwater recharging these watersheds feeds the Manchaca groundwater basin and discharges from the Main, Eliza, and Old Mill outlets of Barton Springs. Under some conditions, Slaughter Creek watershed may supply Upper Barton Springs through overflow routes, based on cave observations at the water table near the estimated divide separating the Sunset Valley and Manchaca groundwater basins and from detections of tracer moving across this divide following storms.

The traces have shown relatively rapid flow rates for first dye arrivals of about half a mile to 1 mile per day during very low groundwater-flow conditions, to over 4 miles per day from selected injection points during moderate to high groundwater-flow conditions. Even during low groundwater-flow conditions where the injection was performed at one of the more distant injection points, Barber Falls (Site N) on Onion Creek, the tracer traveled at least 15 miles to arrive to arrive at Barton Springs 14 to 16 days later. Most of the traces were conducted under low water-level conditions; consequently, more rapid groundwater velocities can be expected under moderate and high groundwater-level conditions.

Groundwater flow rates vary with (1) the proximity and connection to major preferential groundwater-flow paths and (2) groundwater-flow conditions. Under moderate and high groundwater-flow conditions at Barton Springs (greater than 35 cfs), groundwater generally travels about 4 to 7 miles per day along the major groundwater-flow paths, but moves at a rate of about 1 mile per day to move from the western side of the Recharge Zone to the eastern side. During low flow conditions of less than 35 cfs at Barton Springs, groundwater velocities of about 1 mile per day to 0.6 mile per day across the aquifer were measured. Five tracers injected under low groundwater-flow conditions were not recovered from any discharge spring, although two of these were recovered in nearby wells. The three major preferential groundwater-flow paths appear to be strongly influenced by geological fault trends.

In most cases, the peak concentration reached the discharge spring within hours after the initial arrival of the tracer, suggesting a system with a high component of advection relative to dispersion and diffusion. Tracer recoveries are calculated to range from 0% up to about 77%, with a mean recovery of about 16% and a median recovery of about 4.2%. The amount of tracer recovery did not vary directly with distance from the injection point to the discharge springs. The rapid travel rates and strong tracer recoveries measured during the study suggest that distant groundwater recharge sites, including those in the Williamson, Slaughter, Bear, Little Bear, and Onion creek watersheds, are strongly connected hydraulically to Barton Springs.

The results of this groundwater tracing study provide information necessary to improve wellhead protection, to anticipate the fate of a hazardous material spill on the Recharge Zone, to assist in developing monitoring strategies, to prioritize purchases of water quality/quantity protection lands, and to evaluate sites for potential recharge enhancement. This study has helped identify some preferential groundwater flow paths that are the major sources of Barton and Cold Springs.

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# 1.0 INTRODUCTION

The Barton Springs segment of the Edwards Aquifer is located south of the Colorado River at the City of Austin, Texas and extends south to the Buda and Kyle areas, east to Interstate 35 (IH35) and west to FM 1826 (Figure 1.1). The portion of the aquifer segment south of the Williamson Creek watershed is a federally designated sole source aquifer (53 Federal Register 20897). In 1995, an estimated 44,000 people lived over the sole source area of the Barton Springs segment (BS/EACD, 1997a). The Barton Springs segment of the Edwards Aquifer provides water for municipal, commercial, industrial, agricultural, recreational and domestic uses in the Austin, Sunset Valley, Manchaca, San Leanna, Buda, Hays, Creedmoor, Niederwald, and Mountain City areas. Because groundwater is a relatively inexpensive source of potable water, it serves to support the local economy. The purpose of this report is to present the results of a groundwater tracing study that was performed within the major watersheds that recharge the Barton Springs segment: Barton, Williamson, Slaughter, Bear, Little Bear, and Onion creeks. A trace was performed at one site on the Blanco River to delineate the groundwater divide between the Barton Springs and San Marcos Springs segments. Many natural spring outlets were monitored to identify flow paths from point recharge features. These springs include Barton, Cold, Backdoor, Bee, San Marcos, and Fern Bank Springs.

Barton Springs are located in Zilker Park near the center of Austin (Figure 1.2, Appendix E2 and E3). They contain the largest natural discharge points for the Barton Springs segment. Barton Springs consists of Main (Parthenia) Springs, Eliza (Concession) Springs, Old Mill (Sunken Gardens, Xenobia, or Walsh) Springs, and Upper Barton Springs. The Main Springs discharge directly into Barton Springs pool. Barton Springs pool is a major recreational attraction for the city, receiving about 350,000 paid visits in 1996. Discharge from Barton Springs sustains flow in the lower portion of Barton Creek and contributes to Town Lake, which serves as a source of drinking water for the City of Austin and other municipalities located downstream on the Colorado River. Barton Springs are the only known habitat for the Barton Springs salamander, *Eurycea sosorum*, which has been listed by the U.S. Fish and Wildlife Service as an endangered species (Federal Register, 1997). A second salamander, the blind *Eurycea waterlooensis*, has recently been discovered to inhabit the spring as well.

Figure 1.1 Map of the Study Area

Figure 1.2 Location of Barton Springs in Southwest Austin, Travis County

Springflow rates for Barton Springs are based on water levels measured by the U.S. Geological Survey (USGS) in nearby well 58-42-903, and are correlated by a rating curve to actual flow measurements of the Main, Eliza, and Old Mill Spring outlets combined. Any flow from Upper Barton Springs or other springs further upstream on Barton Creek are not included in the flow reported by the USGS. Upper Barton Springs is located about 400 feet upstream of Barton Springs pool on the south bank of Barton Creek. As an overflow spring, Upper Barton Springs only flow during periods when the USGS-reported flow of Barton Springs exceeds about 40 cfs. As groundwater-flow conditions increase, additional periodic springs can appear on Barton Creek as far upstream as the Loop 360 vicinity.

The long-term average springflow of Barton Springs was 53 cubic feet per second (cfs) from 1917-1995 (COA compilation analysis of USGS Water Resources Data). The lowest flow measurement recorded for Barton Springs was 9.8 cfs in 1956 (Brune, 1981). During the study, the springflow at Barton Springs varied from 17 to 117 cfs (Figure 1.3). For the purposes of this study, low groundwater-flow conditions are defined to be periods when the combined flow of Main, Eliza, and Old Mill Springs is less than 35 cfs. Moderate groundwater-flow conditions are defined in this study when combined Barton Springs flow is between 35 and 70 cfs for extended periods, while high groundwater-flow conditions exist when the combined flows exceed 70 cfs. In general, high groundwater-flow conditions correspond to higher water levels and potentiometric-surface head in wells.

Several smaller springs also discharge directly into the Colorado River from the Barton Springs segment of the Edwards Aquifer, including Cold Springs, Bee Springs, and a previously unidentified “Rollingwood Springs” (Figure 1.4 and Appendix E4). Cold Springs discharges into the Colorado River along the south bank of Town Lake at a point about 1.5 miles upstream of the mouth of Barton Creek. Its flow is partially below the normal level of Town Lake and is difficult to gauge, except during periods when the lake level is low. Consequently, the normal or maximum flow at Cold Springs is not precisely known. Perhaps the most complete measurement of Cold Springs flow was collected by the USGS under drought conditions in August 1918, when measured flow in Town Lake increased 3.7 cfs between points above and below Cold Springs.

Figure 1.3 Barton Springs Discharge from 1996 to 2000

Figure 1.4 Location of Cold and Bee Springs in Southwest Austin, Travis County

The flow of Barton Springs was measured at the mouth of Barton Creek on the same day at 14.3 cfs, or about 28% of its normal flow (Texas Board of Water Engineers, 1960). Brune (1981) presented flow measurements of Cold Springs varying from 2.6 to 4.2 cfs. The documentation of Brune's measurements are not sufficient to determine if they represent only the discharge above the surface of Town Lake or the total water discharging into the lake from Cold Springs. Discharge of the portion of Cold Springs visible above the level of Town Lake was measured by City of Austin staff to be about 4.5 to 6.8 cfs on November 6, 1997, at a time when Barton Springs flowed at 30 cfs. A water balance for Town Lake based on flow data from 1980 to 1989 shows an average excess of 29 cfs that could be attributed to unmeasured springflow entering Town Lake, or leakage around the Tom Miller Dam (City of Austin, 1992). A temperature survey of Town Lake and Lake Austin (see Appendix C) failed to identify any additional springs, although water depth may mask temperature differences between lake and aquifer water. Appendix D correlates flow measurements of Cold Springs to recorded flow at Barton Springs. Over a 10-year period of record, the average daily flow loss between the USGS Loop 360 and Lost Creek stations on Barton Creek was 14 cfs. This flow loss, in addition to much smaller unmeasured losses from other sources, can be attributed as recharge to Cold Springs and other springs on the south bank of the Colorado River.

About one-half mile downstream of Cold Springs near the mouth of a steep-walled unnamed tributary is a minor spring that discharges from a bluehole or plunge pool. The overflow from the sink is partially visible as it flows through alluvium on the bottom of the channel. Its rate is visually estimated to be only about 0.02 to 0.06 cfs (10 to 30 gallons per minute [gpm]). For identification purposes and due to lack of historical reference, this spring will be referred to as "Rollingwood Springs."

Bee Springs includes a number of small springs that discharge below the Mount Bonnell Fault crossing of Bee Creek, a tributary to the Colorado River that enters Lake Austin about 2.8 miles upstream of the mouth of Barton Creek (Figure 1.4). It has been measured to flow at least 0.2 cfs in September 1972, although a portion of the discharge below the water surface generally cannot be readily measured (Brune, 1981). During the draining of Lake Austin on January 27, 1999, BS/EACD staff measured a flow of 0.6 cfs at the mouth of Bee Creek that was attributed to the combined Bee Springs.

Backdoor Springs discharges into Barton Creek about 6 miles upstream of Barton Springs pool. These permanent springs flow from at least two outlets at rates of about 0.02 cfs (10 gpm). During low groundwater-flow conditions in 1996, one of the spring outlets temporarily ceased flowing. Other minor seeps and springs discharge within a few hundred feet upstream of Backdoor Springs. Combined flow from the seeps and springs near Backdoor Springs sustains a large pool of water in Barton Creek even during drought periods. Backdoor Springs may to represent the discharge of a shallow Edwards Aquifer water table, but may alternatively originate from perched waters above the water table. The Edwards Aquifer is relatively thin beneath Backdoor Springs but thickens considerably due to down faulting a short distance to the east (see Figure 1.8).

The San Marcos Springs are located within Spring Lake in the City of San Marcos (Figures 1.1 and 1.5). They consists of at least ten known springs including Weismuller, Diversion (also known as Installation or Pipe Spring), Deep Hole, Crater Bottom, Salt and Pepper (I and II), Cabomba, Cream of Wheat, Catfish Hotel, and Rio Grande Springs. San Marcos Springs averaged 67 cfs from 1956 to 2001, with a minimum reported flow of 46 cfs on August 15, 1956 and a maximum of 452 cfs on March 12, 1992 (USGS daily average flows).

Fern Bank Springs (also known as Little Arkansas or Krueger Springs) is a major spring discharging from the south bank of the Blanco River about 9 miles east of Wimberley in Hays County (Figure 1.1). The spring discharges near the Hidden Valley Fault crossing of the Blanco River. The flow of Fern Bank was reported to be 4.9 cfs on May 31, 1975 and 0.32 cfs on May 1, 1978 (Brune, 1981). On June 20, 2000, BS/EACD measured springflow to be at least 0.29 cfs. Based on the local geology, the spring probably drains from the base of the Edwards Aquifer with flow focused along the Hidden Valley Fault. Although the source of the spring's water is most likely to the south, this spring was monitored during Phase VI to determine if it receives partial flow from tracer injection sites on Onion Creek to the north.

Figure 1.5 Location of San Marcos Springs in San Marcos, Hays County

The geologic framework of the study area strongly influences groundwater flow (Slade, Dorsey, and Stewart, 1986). Recent mapping of the Barton Springs segment has delineated geologic faults and the surface exposure of several informal hydrostratigraphic members within the Edwards Group, each having distinctive hydrogeologic characteristics (Small, Hanson, and Hauwert 1996; BS/EACD 2003a). In the Barton Springs segment, the Edwards Group consists of the generally less permeable Basal Nodular Member (Walnut Formation equivalent), the moderately permeable Dolomitic Member, the highly permeable Kirschberg Member, the erosion-resistant Grainstone Member, the less permeable Regional Dense Member, and the highly permeable Leached and Collapsed Members. The Marine member of the Edwards Group is almost entirely restricted to Hays County portion of the Barton Springs segment and appears to have a high permeability comparable to the underlying Leached and Collapsed Members. The groundwater of the Edwards Aquifer overlies the less permeable upper member of the Glen Rose Formation in the Trinity Group, and in some places over the Basal Nodular Member . The Georgetown Formation overlies the Edwards Group and is considered a part of the Edwards Aquifer. The outcrop of the geological units within the study area is shown in Figure 1.6. Geological cross sections interpret the subsurface extent and configuration of the hydrostratigraphic units along lines shown in Figure 1.7. The cross sections are based on surface geology, geophysical well logs, and measured sections. Cross Section A is located along Barton Creek and is extended subparallel to Highway 71 (Figure 1.8). Cross Section B is located along Slaughter Creek (Figure 1.9), and Cross Section C is located along Bear Creek (Figure 1.10).

Water enters the aquifer primarily through sinkholes and solution-enlarged fractures in six major creek channels of Barton, Williamson, Slaughter, Bear, Little Bear, and Onion Creeks, as well as minor creeks such as Eanes Creek that cross the outcrop of the Edwards Aquifer (*Recharge Zone*, Figure 1.1*)*. The Recharge Zone also includes a fringe of overlying units exposed to the east which drain back to the outcrop area of the Edwards Group. The Recharge Zone of the Barton Springs segment is 98 square miles in size (Smith and Hunt, 2002). On the western edge of the Recharge Zone, groundwater within the Edwards Aquifer may be seasonally absent in some places or limited to groundwater perched on less permeable beds within the Edwards Aquifer (BS/EACD, 1997a).

Figure 1.6 Geological Map of the Study Area

Figure 1.7 Locations of Geological Cross Sections

Figure 1.8 Geological Cross Section Along Barton Creek Watershed

Figure 1.9 Geological Cross Section Along Slaughter Creek Watershed

Figure 1.10 Geological Cross Section Along Bear Creek Watershed

The majority of the water that recharges the Barton Springs segment originates as rainfall runoff in the *Contributing Zone* west of the outcrop of the Edwards Aquifer (Slade, Ruiz, and Slagle, 1985; Barrett and Charbeneau, 1996). The Glen Rose Formation of the Trinity Group is generally exposed throughout the Contributing Zone. The Contributing Zone is 254 square miles in size (Slade, Dorsey, and Stewart, 1986).

In the *Artesian Zone* to the east of the Recharge Zone, the Edwards Aquifer is overlain by the less permeable Del Rio Clay and other limestone and clay units, which serve to protect the aquifer from surface contamination derived from overlying land-use. The eastern side of the potable portion of the Artesian Zone contains significant increases in sulfate, strontium, and fluoride, probably due to lateral leakage from the Glen Rose along major fault offsets (Senger and Kreitler, 1984). The Artesian Zone consists of only the potable portion of the confined Edwards Aquifer.

East of the Barton Springs segment is the *Saline Water or Bad Water Zone, a* nonpotable confined portion of groundwater within the Edwards Group generally located east of IH 35. It is characterized by sharp increases in sodium, chloride, and other mineral constituents that raise the total dissolved solids to greater than 1,000 mg/l (Flores, 1990). The position of the Saline Water Zone may be in part due to fault barriers (Senger and Kreitler, 1984) and restrictions of overlying confining units east of Barton Springs that block natural discharge to the Colorado River. In the northernmost portion of the Barton Springs segment, the Saline Water Zone is found just east of Barton Springs.

The aerial extent of the Barton Springs segment is defined by groundwater divides and boundaries, which are in some cases leaky or not well delineated. The northern divide is assumed to be the Colorado River since it is the regional base level. Extrapolated potentiometric surface elevations seem to be at the elevation of the Colorado River or above it. The sharp increase in dissolved constituents and decrease in transmissivity at the Saline Water Zone boundary marks a leaky boundary on the eastern edge of the Barton Springs segment (Flores, 1990; BS/EACD, 1997a). The western boundary of the Recharge Zone is probably a leaky boundary due to subsurface flow from the Trinity Aquifer of the Contributing Zone. Evidence for this leakage is based on increases in sulfate and fluoride and similarities in the water levels from Edwards and Glen Rose source wells within the western edge of the Barton Springs segment. Recent groundwater models for the Trinity Aquifer required significant lateral groundwater leakage into the Edwards Aquifer in order to simulate observed hydrogeologic conditions (Mace, 2000). The groundwater divide between the Barton Springs segment and San Marcos Springs source area of the San Antonio segment has been estimated in various locations between the Blanco River and Highway 967 at Buda based on potentiometric-surface elevations (Slade and others, 1986; Stein, 1995; Petitt and George, 1956; Garza, 1962; Guyton, 1958; Maclay, 1980). The groundwater divide may move based on groundwater-flow conditions and pumpage (DeCook, 1963; Stein, 1995). The divides defined solely by potentiometric-surface mapping should be considered tentative until verified by positive groundwater tracer recoveries under varying flow conditions.

The study area lies in the Balcones Fault Zone, which is composed of normal faults generally oriented northeast to southwest. The majority of these faults are downthrown to the southeast. The total vertical offset from west to east across the study area totals about 1,100 feet. Some of the major faults in the study area include: the Mount Bonnell Fault, which has an offset of about 400 feet near Barton Creek; the Mountain City Fault, which has an estimated offset of about 110 feet; and the Barton Springs Fault, which is believed to have an offset of at least 40 feet at Barton Springs.

Because faults are associated with crushed material, voids, and fractures, they represent planes of weakness along which groundwater flow may be focused, facilitating the dissolution and erosion of the host carbonate rock into more integrated conduits parallel to the general direction of faulting. Solution cavities also develop preferentially along more soluble or softer bedding planes as a result of chemically undersaturated or rapidly moving groundwater. Through the processes of dissolution and to a lesser extent, erosion, a positive feedback loop is formed and these solution cavities tend to become larger and better integrated over time. A *karst* aquifer develops within relatively soluble rock where appreciable groundwater flow occurs through the dissolved openings (Maksimovich, 1962; Aley, 2000b; Field, 2002a). Karst areas or landscapes are underlain by karst aquifers and commonly contain sinkholes, losing streams, caves, and springs. As limestone areas develop into more mature karst terrains, these conduits can be expected to enlarge and more effectively connect recharge areas with discharge areas. Along these areas where the subsurface "plumbing" is well connected, single recharge points in creek bottoms can introduce large volumes of creekflow into the aquifer. In fact, entire creek sections can be pirated underground. For example, Barton Creek is believed to have originally been a tributary to Williamson Creek, but was pirated by subsurface flow toward an early Barton Springs (Woodruff, 1984b). The subsurface-flow route eventually dissolved and eroded into the steep-walled stream channel that exists today. Incision and lowering of the base level of the Colorado River led to the lowering of active spring locations as well as the active conduits that fed them (Veni, 1991). It is the localization of flow that creates *preferential groundwater-flow paths* that are single well-connected master conduits, or a series of subparallel master conduits that serve to rapidly carry groundwater from recharge to discharge areas. Airman's Cave, located in the vadose zone above and parallel to an active preferential groundwater-flow path through Sunset Valley, provides an observable model of an abandoned conduit of a past preferential groundwater-flow path that fed an earlier Barton Springs (Russell, 1975). Airman's Cave is strongly associated with the Barton Springs Fault, and its entire length is perched above the less permeable Regional Dense Member hydrostratigraphic unit, illustrating the influence of structural and stratigraphic elements on cave development (Hauwert and Russell, 1996). Studies of flow systems developed in the limestone areas of Kentucky suggest that the groundwater-flow paths in that area resemble branching networks, where smaller branches connect to larger trunk conduits downgradient (Thrailkill, 1985; Quinlan, 1990). The fact that almost all of the natural discharge of the Barton Springs segment occurs at only two locations (Barton and Cold Springs), supports the concept that much of the groundwater flow within the aquifer is highly localized.

These preferential flow paths can be potentially located by detailed groundwater-level measurements, cave mapping, and groundwater tracing (Thrailkill, 1985; Quinlan, 1990). The preferential groundwater-flow paths generally correspond to water-level troughs in sufficiently detailed potentiometric-surface maps because groundwater is transmitted to discharge areas faster than recharge is supplied from source areas. These troughs may be indiscernible for short periods after rain events, as the rapid influx of recharging water may cause a flattening or even mounding of the potentiometric surface (Raymond Slade, USGS, personal communication, 1998). Drawdown resulting from large aquifer discharges can be expected to be greatest along the trend of the flow path. During low groundwater-flow conditions, the draining of Barton Springs pool has been observed to result in water-level declines in wells up to three miles away along the trend of the Barton Springs Fault (Senger and Kreitler, 1984).

The occurrence of groundwater within the Barton Springs segment is not limited to these preferential groundwater-flow paths. Varying quantities of groundwater can generally be encountered in wells in the Artesian Zone due to hydraulic connection along permeable beds, fractures, smaller conduits, and open bedding planes. Karst aquifers such as the Barton Springs segment can be described as dual or triple porosity systems, since groundwater flow will be influenced by matrix, fracture, and conduit flow (Ford and Williams, 1992; ASTM, 1995, Quinlan and others, 1996). Groundwater tracing using the injection of an introduced substance has been recognized as an effective means to better understand complex karst flow systems. It is one of the few direct measurements of groundwater travel time and flow paths. Prior to the beginning of this tracer study in 1996, no successful long-distance groundwater traces had been reported within the Barton Springs segment. A small amount of tracer was injected by the USGS in well 58-42-903 and was detected about 200 feet northeast at the Main Barton Springs outlet. The tracer initially appeared about 10 minutes after injection and peaked about an hour after injection (Slade, Dorsey, and Stewart, 1986).

Groundwater tracers were successfully detected several miles from their injection points by the Edwards Aquifer Research and Data Center (EARDC) during the early 1980s within the San Marcos Springs area of the adjacent San Antonio segment of the Edwards Aquifer (Ogden, Quick, Rothermel, and Lunsford, 1986). Three successful traces were performed by EARDC. On April 1, 1983, 1 pound of a fluorescein dye mixture was injected into a deep lake within Ezell's Cave, located about 4 miles southwest of San Marcos Springs during a period of relatively high flow conditions. The tracer was detected only in the Deep and Catfish Hotel outlets of San Marcos Springs 11 days later (a travel rate of about 0.4 miles/day).

On August 30, 1984, 3 ounces of a fluorescein mixture and 5 pounds of a Tinopal CBS-X mixture were injected in Rattlesnake Cave under low groundwater-flow conditions and was detected 4,000 feet to the southwest at all of the monitored San Marcos Springs outlets within 40 days. The third trace, injected on May 8, 1983 under high groundwater flow conditions, demonstrated a possible connection between Tarbutton's Showerbath Cave on the Blanco River near Kyle, and San Marcos Springs about 7 miles to the south. This cave is also referred to as injection Site Q in this report. The tracer may have arrived at San Marcos Springs a year later (a travel rate of about 0.02 miles/day), as the injected tracer was detected in all of the San Marcos Springs outlets for a month and a half. This possible tracer arrival at San Marcos Springs occurred under drought conditions, and the second half of the traced year was associated with lower than average flow conditions. The report on this trace did not reference monitoring at sites north of the Blanco River to determine if the tracer also moved towards Barton Springs (Ogden, Quick, Rothermel, and Lunsford, 1986). This study was very significant in that it demonstrated that groundwater tracers could be successfully recovered from the Edwards Aquifer and helped define the source areas for San Marcos Springs. However, the possible hydrogeologic connections of the Blanco River to San Marcos Springs and/or Barton Springs have not been definitively established and require further investigation under various flow conditions.

This study conducted by the BS/EACD and COA uses groundwater tracing, water-level measurements, and other data to measure the groundwater-flow paths, delineate any preferential groundwater-flow paths, measure the initial travel times for selected tracer substances, characterize the arrival (or breakthrough) of the tracer at monitored sites, and delineate groundwater divides. The results of initial long-distance groundwater traces injected within the Barton and Williamson Creek watersheds of the Barton Springs segment were described in an initial report by Hauwert, Johns, and Aley (1998). Those results are repeated and expanded in greater detail within this report. An attached addendum report (Smith and others, 2004) briefly describes the results of additional traces of Onion Creek conducted in 2002. Additional analysis of these results are included in Hauwert and others, 2004.

## 2.0 METHODS

Groundwater tracing was performed in this study to delineate the groundwater-flow paths and measure the travel time of groundwater flow. Groundwater tracing involves the introduction of non-toxic materials (*tracers*) into surface drainages or the subsurface (*injection points*) and monitoring the movement of these materials at wells and springs (*receptor sites*). The general methodology of tracing and an evaluation of various tracers are described by Aley (1999) and Smart and Laidlaw (1977). A Quality Assurance Project Plan (QAPP) was prepared by BS/EACD and approved by BS/EACD, Ozark Underground Laboratory (OUL), Texas Commission on Environmental Quality (TCEQ, formerly Texas Natural Resource Conservation Commission), and the Environmental Protection Agency (EPA) in 1999 that described the methodology used in the study for Phases III, IV, and V. Phases I and II were completed prior to the approval of the QAPP, but followed the same methodology described in the plan.

### 2.1 Groundwater Tracers Used

For the purposes of this study, the tracers used were evaluated and selected according to the following criteria**:**

1) is non-toxic to humans and aquatic life;
2) can be detected and readily quantified at low concentrations;
3) has been extensively tested with documented histories;
4) only low or non-detectable background levels are present in the aquifer;
5) has low dispersion so that the speed of groundwater movement can be measured (in some cases, a substance with a higher dispersivity may be desired, such as a sediment tracer);
6) has low adherence to clays and other fine-grained materials;
7) has small particle size (in some cases a larger diameter may be desirable for a sediment tracer); and
8) can be acquired and detected economically.

The tracers used in this study are traditional, well-documented organic dyes. The common names for the tracers used in this study are eosine, fluorescein, rhodamine WT, sulforhodamine B, and pyranine; these names are used throughout the report. Dye quantities identified in the report represent the dye mixture used; none of the dye mixtures contained 100% dye.

Eosine is Acid Red 87 and its Color Index Number is 45380. The eosine mixtures used contained approximately 75% dye equivalent and 25% diluent. The dye mixture was purchased as a powder.

Fluorescein is Acid Yellow 73 and its Color Index Number is 45350. It is also known as sodium fluorescein and uranine. The fluorescein mixtures used contained approximately 75% dye equivalent and 25% diluent. The dye mixture was purchased as a powder.

Rhodamine WT is Acid Red 388 and it does not have an assigned Color Index Number. The rhodamine WT mixtures used contained approximately 20% dye equivalent and 80% diluent. The dye mixture was purchased as a liquid.

Sulforhodamine B is Acid Red 52 and its Color Index Number is 45100. The sulforhodamine B mixture used contained approximately 75% dye equivalent and 25% diluent. The dye mixture was purchased as a powder.

Pyranine was purchased as Drug and Cosmetic Green 8. Its Color Index Number is 59040. The pyranine mixture used contained 77% dye equivalent and 23% diluent. The dye mixture was purchased as a powder.

In preparation for the traces, background levels of the primary tracers considered for this study were measured at Barton Springs for several months in late 1994. At least 2 weeks of background monitoring was conducted at each regular monitoring spring or well in 1996 and 1997. The results of the background measurements indicated that the organic dyes referenced were appropriate for use in this study. The tracers selected are not necessarily rare substances but may be present in some quantity in stormwater runoff, automotive coolants, sewage, hydraulic fluids, cooling tower emissions, fluorescent stationary, and other sources (Aley, 1999).

The actual groundwater flow rates and/or recoveries from recharge features will likely always be greater than those indicated by tracers due to the properties of the tracers, interactions between the tracers and aquifer matrix, the limited mass of tracer used, the *tortuosity* (or circuitous pathway compared to a direct path estimated on a map), as well as other factors. Information on the properties of the tracers and their safety is discussed in Section 3.0.

### 2.2 Injection Site Selection

Sites were selected based on a set of criteria that would be expected to provide the greatest amount of information for multiple objectives. Some of the criteria used to select potential injection sites are listed below:

1) Initially, injection sites were selected near major discharge points (Barton and Cold Springs). The traces were initiated in the northernmost watersheds in order to insure that the tracers could be detected and to estimate the locations of necessary receptor sites and monitoring frequency before tracing from more remote watersheds.

2) Injection sites were selected to provide the greatest information about the nature of the aquifer in order to best protect the resource for multiple uses. Sites suspected to be up-gradient of active pumping wells were selected to provide information necessary for source-water protection. Some sites were selected to delineate groundwater divides.

3) Injection sites were selected near suspected preferential groundwater-flow paths and at major recharge points. Locations of large-volume creek losses, major recharge points, or caves with flowing water were preferred due to their probable connection to preferential groundwater-flow paths. Injection was performed at some of these sites to confirm and delineate groundwater-flow paths. The recharge features selected are not necessarily

unique or the most transmissive features in the study area. Recharge features are common in both the creekbeds and uplands throughout the Recharge Zone of the study area.

4) Some injection sites were located near potential sources of contamination. The measurement of groundwater-flow direction and travel velocities from potential sources of contamination was determined from a few sites. Proximity to sites such as dumpsites, petroleum pipelines, major transportation route crossings, and large tributaries that drain these types of sites were considered. There are many more sites that contain potential sources of contamination that need to be evaluated in a separate study. The injection sites used in the study are shown in Figure 2.1.

**2.3 Receptor Site Selection**

In order to monitor the movement of the tracers, charcoal receptors were placed into springs, creek and river sites, and many accessible wells. Monitored wells with active pumps were fitted with receptors at a point prior to any water treatment systems. These *active well sites* were either allowed to flow continuously at a low rate, or pumped for a period of time each day (Appendix E1). For active well systems, a small seep or drip of flow from a periodically pumping well was diverted through a standard garden hose and into specially constructed polyvinyl chloride (pvc) holders containing charcoal receptors. These pvc receptor holders were designed by OUL and constructed by BS/EACD. The receptor holders were often placed in pairs to allow for duplicate samples, although it was difficult to insure both receptor holders received the same quantity of flow. Open wells without anchoring a receptor at a depth where flow was believed to enter the well bore monitored pumps. The optimal monitoring depths within these *passive well sites* were estimated from downhole camera observations of void intervals within the well or from available caliper logs of the well bore. Any springs that represented likely discharge points for the injection sites were monitored (Appendix E2). Since springs might exist within the channel of the Colorado River, which are not obvious, receptors were placed in the Colorado River at numerous locations. Creeks were monitored downstream of the injection point where necessary to determine if creek flow subsequent to injection could move the tracers along surface flow routes to other recharge points. As the study progressed, a few monitoring sites were added and some were dropped due to monitoring needs and accessibility. Continued and regular access was one of the most limiting factors to selecting or sustaining a monitoring site. The monitoring sites used in the study are shown in Figure 2.1.

Figure 2.1 Locations of Injection Sites

## 2.4 Data-Collection Procedures

Receptor sites were monitored using a combination of adsorbent activated charcoal packets (*receptors*) and grab samples. Receptor sites were monitored for 2 weeks prior to tracer injection to detect any background presence of tracers. Several receptors were placed at each receptor site and collected at intervals ranging from several hours to three weeks. Short-term receptors, those collected over hours or days, were generally overlapped by a long-term receptor. The long-term receptor was analyzed initially and if a tracer was detected, then the short-term receptors were analyzed for that interval. This procedure reduced analytical costs and allowed refinement of the arrival times for tracers. Breakthrough curves were prepared from the laboratory results, from which the initial travel time, duration, and peak concentrations were calculated. To allow comparison of results from receptors placed over varying periods of time, the cumulative concentration of the results were divided by the number of days in that time period. Because of this mathematical adjustment of the cumulative concentrations, some receptors may show an average daily concentration below the cumulative concentration detection limit.

Water samples, known as *grab samples,* were collected in plastic bottles at the time the receptors were replaced and provided information on the instantaneous tracer concentrations in the water. Because the concentration of tracers measured in the charcoal receptors is cumulative, higher concentrations of tracer can be expected to be present in an adsorbent receptor than are measured in instantaneous grab water samples from the same site. Consequently, the tracers are more easily detected in receptors than in grab samples. Grab samples also served to verify positive detections measured on corresponding receptors.

The tracer recovery is the mass of tracer that is estimated or calculated to discharge from the aquifer system. Tracer recoveries were calculated using measured concentrations at wells and springs and calculated springflows and pumping rates at each receptor site where the tracer was detected to estimate the mass of discharging tracer (Glenrose Engineering, 2000). The percent recovery is the ratio of recovered tracer mass to the mass of tracer injected. The tracer masses described in this report refer to pure dye masses and not dye mixture amounts. Because there is no direct comparison between receptor and water-sample results, only the grab-sample results (and not the charcoal receptor results) were used to calculate tracer recoveries. Consequently, the calculated recoveries may be underestimated, since many of the traces showed detectable tracer concentrations on receptors for months after the grab-sample concentrations declined below detection limit (also see Section 3.1). Sampling frequency will also affect tracer recovery. Daily and weekly water samples will tend to miss the peak of the tracer arrival, when most of the tracer will typically discharge. Therefore, less frequent sampling will generally result in the underestimation the actual tracer recovery. Hourly sampling for tracers was only conducted in one trace of this study (Trace E, the shortest trace) because for most of the other traces, the projected discharge site and/or week of arrival was not known. Calculation of percent recoveries can also be affected positively or negatively by errors in the estimation of springflow at each outlet. Although the combined springflows of Main, Eliza, and Old Mill Springs are accurately measured, the individual flow of the Main, Eliza, Old Mill, and Upper Barton Springs outlets or the Cold Springs outlet has not been sufficiently measured to most accurately assess their individual flows. Calculation of percent recovery is valuable to estimate hydraulic parameters, transport of constituents and effects of a volume of water entering the aquifer, either naturally or through recharge enhancement or Aquifer Storage and Recovery (ASR). Recovery data is also important for modeling groundwater constituent transport, to insure monitoring sites are properly located on downstream preferential groundwater flow paths, and to insure that all major discharge sites from the aquifer were monitored (Field, 2002b). Jones (1976) listed several factors that can account for failure to recover a tracer at its discharge site including: (1) the discharge site(s) were not monitored, (2) an insufficient amount of tracer was used, (3) complete sorption losses occurred due to fine-grained sediment or organic matter, (4) very slow, diffuse groundwater flow causing the tracer to arrive below the detection limit, (5) the duration or frequency of sampling was insufficient, (6) high background concentrations obscured the tracer arrival, (7) the receptors were coated or saturated, (8) the tracer concentration was reduced by photo-decay or other degradation, (9) the tracer was diluted due to flooding, and (10) an inadequate amount of time was provided to allow purging of the same tracer from previous tests.

Water-level measurements were collected from well and spring sites during the course of the study so that potentiometric maps could be prepared. A *potentiometric surface* represents the elevation that water could rise in a well screened within the aquifer of interest. The potentiometric-surface elevation is distinguished from a water table, because within the Artesian Zone, the water level in an Edwards Aquifer well will rise above the top of the Edwards Aquifer. This map served to estimate the groundwater-flow paths between injection sites and monitored sites where the tracer was detected. The depth to water within a well was measured using an electric water-level meter read to the nearest 1/100 of a foot from the top of casing or other reference point. Some potential errors in mapping the potentiometric-surface elevation include inaccurate measurement of the elevation of the reference point; changes in the potentiometric surface over time; short-term, localized changes in water level due to pumpage; mixing of separate aquifer-producing units due to well construction; and extrapolation of the potentiometric elevation between measured sites. Water-level measurements were collected prior to the injection of tracer for each phase. The water-level meter was decontaminated between sites with a 50% Clorox solution in order to prevent cross contamination of monitored sites.

The top of casing or spring surface elevation of about 80% of the sites from which water-level measurements were taken were measured by a Trimble Pathfinder XRS Global Positioning Unit (GPS). A comparison of ten elevation measurements collected at a first order benchmark on different days by this GPS unit indicated an average accuracy of $\pm$2.47 feet in elevation measurements with a maximum error of 4.17 feet. For other sites, the elevation of the reference point was either estimated from a 7.5 minute, 10- to 20- foot contour interval USGS topographic map, surveyed relative to sea level to within 1/100 of a foot, measured with a digital altimeter, or estimated from City of Austin 1- to 2-foot contour interval topographic surveys or other site-survey maps. The surface elevation of a flowing spring was used as the potentiometric-surface elevation if the spring likely represents discharge of the water table from the Edwards Aquifer.

The span of time over which the water-level data were collected for a potentiometric map ranged from two days for a local area to several months for the complete map. Continuous water-level measurements were generally available from nine to 15 water-level monitor wells maintained throughout the Barton Springs segment of the Edwards Aquifer by the BS/EACD and USGS. The water-level data from wells not screened within the Edwards Aquifer were not used for the potentiometric-surface maps. However, on the western side of the study area, wells commonly appear to be screened in both the Edwards and upper Trinity Aquifers to the extent that these cannot be fully evaluated without further information. In addition, wells on the eastern side of the study area commonly do not fully penetrate the Edwards Aquifer, and it is possible that different water levels could be measured from fully-penetrating wells if the upper and lower portions of the Edwards Aquifer are not well connected hydraulically. In some areas, water-level data may be sparse over the period represented by the potentiometric map. In these cases, potentiometric elevations are estimated, sometimes from historical data, tracer response, geology, and other data. Therefore, the potentiometric-surface maps presented should be considered as interpretations.

**2.5 General Preparations**

A Quality Assurance Project Plan (QAPP), approved by BS/EACD, TCEQ, EPA, and OUL, was developed for the groundwater tracing study. The Rules and Bylaws of the BS/EACD requires the submittal of an operations plan and subsequent authorization from the BS/EACD prior to any groundwater trace in the Barton Springs segment of the Edwards Aquifer where materials are introduced into surface or groundwaters (BS/EACD, 1997b). This rule was enacted so the BS/EACD could track tracer studies within the Barton Springs segment, avoid interference between groundwater traces, and to evaluate the proposed injection materials for possible detrimental affects. Approval was received from the TCEQ prior to any land disturbance associated with hand excavation of any injection points or to the injection of tracers into a well, to comply with the Edwards Rules (Chapter 213 TAC) and injection well regulations. Access for all sites was obtained in advance from the site owner or authorized representatives. Identified well users in close proximity to the injection points were notified in advance of the test to prepare for possible visible levels of the tracers. Note that many unidentified wells exist that were undocumented by records of the BS/EACD, consequently the owners of these wells may not have been notified directly. Well owners within the BS/EACD boundaries are encouraged to register their wells with the BS/EACD, so that direct and immediate notification can be given in the event of an accidental spill of hazardous materials or other emergency.

A committee of representatives from other agencies, including the City of Austin (COA), Texas Water Development Board (TWDB), TCEQ, Texas Parks and Wildlife Department (TPWD), U.S. Fish and Wildlife Service (USFWS), the Edwards Aquifer Authority (EAA), and the San Antonio Water Systems (SAWS), was created by the BS/EACD in early 1996 to advise and facilitate the study. In addition to the authors of this report, this committee consisted of John Ashworth, geologist formerly of the TWDB; Dianne Pavlicek and Margaret Hart, geologists for TCEQ Central Office; Patti Reeh Stone, Jerry Salgado, and Pat Hudson of the TCEQ Region 11 office; Dr. David Bowles, biologist of the TPW; Lisa O'Donnell, biologist of the USFWS; Jim O'Connor, water-quality specialist of the SAWS; and John Waugh, geologist formerly with the EAA currently with the SAWS; and Geary Schindel of the EAA. Regrettably, former TCEQ geologist Margaret Hart passed away as the study was progressing. This committee reviewed work plans developed for Phases I and II of the study and assisted in locating support necessary to continue the study.

The BSEACD and City of Austin partnered for the entirety of the study, both supplying funds for expenditures and in-kind labor. For Phase II, the City of Sunset Valley participated in the study and participated by providing notification and information to local residents, locating potential monitoring sites, arranging access, and acting as liaison for residents in their city. Following public notification, a public meeting regarding the tracer study was held in Sunset Valley to provide information, answer questions, and address concerns by local residents using well water. In Phase III, only a few wells were identified and monitored in the vicinity of the injection sites, and the owners of these wells were notified in person. In Phase IV, many identified and undocumented wells existed near the injection sites. Well owners were notified in person and asked to cooperate in the monitoring for the tracers. Prior to injection, press releases were sent out to TCEQ, City of Austin Spill Response staff, the Manchaca Volunteer Fire Department, the EARDC in Hays County, as well as a number of local newspapers and TV stations including the Hays County Free Press, the Austin American-Statesman, and In-Fact newsletter. A front-page article on the tracing study was printed in the Austin American-Statesman on the day following the Phase IV injections.

Additional notification was performed in Phase V, notifying the TCEQ spill response divisions of the Field Office and Central Office, the Hays County Health Department, the City of Austin spill response staff, and door-to-door notification of known wells in the vicinity of injection sites. Press releases were sent out to the same newspapers and TV stations. A full-page advertisement was purchased in the Hays County Free Press. At 7:00 am, the next day following the Phase V injections, one well owner about a mile away encountered visible levels of tracer in his water, who contacted the BS/EACD later that day. For Phase VI, additional door-to-door notification was performed in the vicinity of Onion Creek, but no cases of visible tracer were reported.

## 2.6 Quality Control

The quality control and assurance procedures utilized in this study incorporated trip blanks, field duplicates, laboratory-spiked standards, and the testing of a portion of the sample containers for possible contaminants. Trip blanks, consisting of charcoal packets handled by field personnel during the course of sampling, were submitted to the lab from each team recovering receptors in order to periodically test for cross contamination between sites or contamination from other materials the teams were exposed to. Over twelve percent of the total charcoal samples submitted to the OUL for analysis included a field duplicate sample in order to allow two independent measurements of the same sample for comparison. A portion of the duplicates and blanks submitted to the laboratory were blind, so that the lab did not know their purpose. OUL tested standard solutions of the tracers daily as described in its procedures and quality control document. Laboratory blank samples were analyzed on each twentieth sample. OUL tested one percent (1%) of the unused sample containers to assure that tracer contaminants were not present. Grab samples were collected to verify the results of the receptors, and to measure the concentration of tracers at one point in time.

The procedures and criteria of the laboratory analysis for the tracer were described in detail by Aley (2000a). The criteria for determining a positive detection of a tracer are as follows:

1) The peak must lie within the normal emission wavelength for the specific tracer, as determined by the analytical laboratory.

2) The tracer concentration should be at least three times the detection limit, which ranges from 0.010 to 0.325 ppb for charcoal receptors and ranges from 0.0005 to 0.007 ppb in water samples (Table 2.1).

3) The tracer concentration must be at least ten times greater than background concentrations.

4) The shape of the peak must be typical of the specific tracer, as determined by the analytical laboratory.

5) The tracer measured in a receptor will also be measured in the water samples associated with both the placement and collection of the receptor, provided these water samples were collected and analyzed. Where duplicate receptors were placed and analyzed, the duplicate should verify the results of the original receptor. This criterion is not valid if the associated receptor did not duplicate the conditions of the original, such as if flow was not evenly distributed through both receptors, or if there was no associated receptor.

6) There must be no factors, which suggest that the fluorescence peak may not have resulted from the tracer introduction.

More detail on the quality assurance procedures used in this study is described in the Quality Assurance Project Plan, available for review at the BS/EACD office.

**Table 2.1 Tracer Precision and Accuracy**

**A) 1996 through 1999**

| Tracer | Normal Acceptable Emission Wavelength Range (nanometers) | Detection Limit (parts per billion) | Practical Quantity Limits (PQL) (ppb) | Precision Limits (RPD) (%) |
|---|---|---|---|---|
| **Elutant Extractions from Charcoal Receptors** | | | | |
| Fluorescein | 510.7 to 515.0 | 0.01 | 0.03 | 26-34 |
| Eosine | 533.0 to 539.6 | 0.02 | 0.06 | 29-36 |
| Rhodamine WT | 561.7 to 568.9 | 0.155 | 0.465 | 37-49 |
| Sulforhodamine B | 567.5 to 577.5 | 0.08 | 0.45 | 35-46 |
| | | | | |
| **Water Samples** | | | | |
| Fluorescein | 505.6 to 510.5 | 0.0005 | 0.0015 | 1.7-2.7 |
| Eosine | 529.6 to 538.4 | 0.001 | 0.003 | 3-4.5 |
| Rhodamine WT | 569.4 to 574.8 | 0.007 | 0.021 | 4.5-6 |
| Sulforhodamine B | 576.2 to 579.7 | 0.02 | 0.12 | 4.2-5.5 |

**B) 2000 through 2001**

| Tracer | Normal Acceptable Emission Wavelength Range (nanometers) | Detection Limit (parts per billion) | Practical Quantity Limits (PQL) (ppb) | Precision Limits (RPD) (%) |
|---|---|---|---|---|
| **Elutant Extractions from Charcoal Receptors** | | | | |
| Fluorescein | 510.7 to 515.0 | 0.01 | 0.03 | 26-34 |
| Eosine | 533.0 to 539.6 | 0.035 | 0.0105 | 29-36 |
| Rhodamine WT | 561.7 to 568.9 | 0.275 | 0.825 | 37-49 |
| Sulforhodamine B | 567.5 to 577.5 | 0.15 | 0.45 | 35-46 |
| Pyranine | 499.1 to 503.9 | 0.055 | 0.165 | ** |
| | | | | |
| **Water Samples** | | | | |
| Fluorescein | 505.6 to 510.5 | 0.0005 | 0.0015 | 1.7-2.7 |
| Eosine | 529.6 to 538.4 | 0.008 | 0.024 | 3-4.5 |
| Rhodamine WT | 569.4 to 574.8 | 0.05 | 0.15 | 4.5-6 |
| Sulforhodamine B | 576.2 to 579.7 | 0.04 | 0.12 | 4.2-5.5 |
| Pyranine* | 501.2 to 505.2 | 0.03 | 0.09 | ** |

* pH adjusted water with pH of 9.5 or greater.

** insufficient data for generalizaton.

## 3.0 TRACER PROPERTIES

This section discusses the hydraulic characteristics and health properties of several introduced fluorescent dyes, including sodium fluorescein (fluorescein), rhodamine WT, eosine, sulforhodamine B, and pyranine, and evaluates factors that may affect their use within the Barton Springs segment. Their sorptive characteristics influence how well the tracer is recovered at monitored discharge sites. Also, each tracer has different responses to factors such as sunlight, temperature, acidity, and chlorine. This type of comparison is important to help distinguish when limitations due to the type of tracer used will limit recoveries. The tracers selected for the study have been well tested to determine their low toxicity for drinking water sources and aquatic life.

### 3.1 Transport and Recovery of the Tracers

In one reported groundwater trace of another area, two organic tracers were used simultaneously from the same location. One of the tracers, fluorescein, was detected in 18 domestic wells, while the rhodamine WT tracer was only detected in two of the 18 wells (Aley, 1999). In a separate study, Brown and Ford (1971) discovered three different breakthrough curves using rhodamine WT, fluorescein, and rhodamine B tracers from the same site in a karst area of Canada. In this 1.3 mile trace, 98% of the rhodamine WT was recovered and none of the fluorescein was detected. Furthermore, the rhodamine B took twice as long as the rhodamine WT for its initial arrival. Obviously, different properties of the tracers themselves will influence the result of any tracer test. When interpreting the results of tracer studies, it is important to understand the hydraulic properties of the tracers and how they may influence the recovery and travel time measured as well as the shape of the breakthrough curve. No direct comparison of the tracers' performance within the Barton Springs segment was conducted as part of this study. However, some information on tracer properties is available in the literature.

#### Sorption

*Sorption* includes both absorption and adsorption. *Absorption* is the assimilation of dissolved constituents of a solution (solute) inside a solid matrix. *Adsorption* is the attraction of a solute to a solid surface by weak electrical attraction or stronger chemical bonds. The amount of a solute that is adsorbed onto a solid depends on the characteristics of the solute, the nature of the solid, and the concentration of the solute (Helfferich, 1962, Mercer and Faust, 1981). As a result of adsorption, organic tracers move slower than water and slower than ionic or radioactive tracers (Davis and others, 1985). *Conservative* tracers have low sorptive properties and are preferred for estimating groundwater-flow rates. Organic tracers adsorb to varying degrees on sediments and clay.

Based on experimental data of fluorescence changes with a suspended kaolinite mixture, Smart and Laidlaw (1977) found that at a 20g/l suspended clay concentration, 51% of sulforhodamine B, 67% of rhodamine WT, 93% of fluorescein, and 95% of pyranine remained dissolved in solution. Suspended sediment not only adsorbs the organic tracers, but to a lesser degree also raises the background fluorescence and reduces the tracer fluorescence by light absorption and scattering. Suspended sediment is usually not a significant problem when sediment concentrations are less than 1,000 mg/l, the sediment is not composed of extremely fine particles or organic matter, and the suspended sediment is allowed to settle and separate prior to analysis.

Some studies show that rhodamine WT is strongly sorbed in sediment-laden water and organic sediments (Smart and Laidlaw, 1977; Aley, 1999), but otherwise appears to be relatively conservative as a tracer (Wilson, 1971; Smart and Laidlaw, 1977; Aley, 1999, Aulenbach and others, 1978; Brown and Ford, 1971). The inconsistent sorptive nature of rhodamine WT may be due in part to its molecular structure. Rhodamine WT typically shows a two-peak breakthrough curve in chromatograms (Rochat, 1975; Hofstraat, 1991) as well as in column tests (Sabatini and Austin, 1991). This two step breakthrough curve is attributed to two isomers of rhodamine WT, one which is relatively conservative, and the other which has relatively high sorption (Shiau, Sabatini, and Harwell, 1992). Rhodamine WT breakthrough curves may show spreading due to this nonequilibrium sorption. For this reason, relatively higher masses of rhodamine WT are necessary to obtain a recovery comparable to fluorescein.

The ionic tendency of the tracer and the type of aquifer medium will affect the amount of sorption that may occur. Rhodamine WT and sulforhodamine B have both cationic and anionic groups that will tend to sorb on most surfaces, although they sorb less on anionic surfaces, such as kaolinite sediment (Smart and Laidlaw, 1977) and sand or sandstone aquifers (Sabatini, 2000). Fluorescein and eosine are anionic and tend to sorb most strongly onto positively charged surfaces such as limestone (Sabatini, 2000). If significant, this factor may allow fluorescein to pass with greater ease through fine-grained sediment at recharge feature entrances, but cause a reduction in fluorescein as it passes through the aquifer. During this tracer study, fluorescein was never recovered at levels greater than 5% although eosine experienced the highest consistent recovery of all the tracers used, with eosine recoveries as high as 77%.

Greater losses occur in soil than with cave sediment or cave stream pebbles possibly due to greater sorption and biological decomposition (Aley, 1999). Fluorescein and rhodamine WT are also most strongly sorbed onto organic materials. Sorption of the tracers within shallow, fine-grained sediment covering the opening of injection sites probably accounts for a significant loss of the tracer mass. Most of the injection sites (A, B, C, E, G, K, P, M, N, and O) were filled with an undetermined thickness of sediments near the surface that acted to reduce the recovered tracer mass. For traces F, H, J, D, I, L, M’, Q, and R, the tracer was poured directly into conduit openings.

Due to partial or complete saturation of the sorption media, the percent recovery of the organic tracers increases significantly with larger injection tracer mass. Low injection masses of tracer are a significant cause for error in qualitative calculations of percent recovery because of arrival of tracers below the detection limit and the greater significance of possible errors in discharge estimations (Smart and Laidlaw, 1977). Consequently, percent recoveries of a small mass of tracer injected cannot be accurately used to calculate the results of a larger injection mass, and estimates of percent recovery for a larger injection mass will invariably be underestimated.

**Hydrogen Ion Concentration (pH)**

Smart and Laidlaw (1977) examined the effect of pH on the organic tracers. Two reasons for degradation due to pH were suggested: changes in ionization and chemical structure. Each of the organic dyes discussed here have a net negative charge (anionic) at pH over 7, and reverse charges or become positively charged at some lower pH, depending on its general chemical group. This charge reversal appears to result in a loss of fluorescence. Rhodamine WT experiences a decline in fluorescence below 5 pH. Variations in pH have little effect on the fluorescence of sulforhodamine B (a sulphonate acid group). The second explanation for tracer degradation at lower pH may be due to other chemical structure changes. For example, fluorescein abruptly changes from a fluorescent quinoid structure to a colorless leuco compound below 6 pH. Pyranine experiences a sharp shift in the absorption spectrum causing an elimination of fluorescence below 6.5 pH. Even below 9.5 pH, pyranine shows a substantial decrease in fluorescence (Aley, 1999). The pH of natural waters within the Barton Springs segment generally range from 6.8 to about 7.5 (Hauwert and Vickers, 1994), so that the effects of pH are likely only a consideration for pyranine traces.

**Chlorine**

Of the tracers examined in the literature, only rhodamine WT was tested for its response to chlorine (Deaner, 1973). In this test, strong declines in fluorescence were observed at high concentrations of chlorine and for high periods of exposure to the chlorine. For example, when 0.01 mg/l of rhodamine WT is exposed to a 20 mg/l chlorine residual for 20 hours, a 23% reduction in the original concentration can be expected. In the Barton Springs segment tracing study, chlorinated water was occasionally used to flush the tracer. Based on a 1 mg/l chlorine residual and 20-hour exposure duration, only about a 2% reduction in the original concentration of rhodamine WT can be expected.

**Salinity**

Laboratory tests by Feuerstein and Selleck (1963) found fluorescein strongly effected by high levels of chloride up to 18,000 mg/l, and that sulforhodamine B showed only slight degradation. Additional laboratory tests by Smart and Laidlaw (1977) found very different results of sodium chloride degradation of organic tracers. Using chloride concentrations of up to 17,800 mg/l, rhodamine WT and sulforhodamine B fluorescences declined eight and four percent, respectively. No fluorescence degradation was measured in either fluorescein or pyranine. Within the Barton Springs segment, chloride concentrations generally ranged from about 5 to 20 mg/l in 20 wells and springs sampled in the freshwater portion over two sampling events (Hauwert and Vickers, 1994). Chloride concentrations from one Saline Water Zone sample location ranged from 273 mg/l to 388 mg/l over two sampling events. Old Mill Springs shows elevated levels of chloride attributed to mixing of the fresh water and Saline Water Zones. Some minor reduction in fluorescence due to chloride is possible in tracer concentrations measured at Old Mill Springs.

**Temperature**

Temperature variations at the time of analysis can be significant for sulforhodamine B and rhodamine WT, but less significant for fluorescein and pyranine (Smart and Laidlaw, 1977). For the Barton Springs segment tracing study, all analytical results were corrected for temperature by OUL.

**Photodecay**

Exposure to light causes fluorescent tracers to absorb light, increasing molecular vibration, and raising the energy state (Smart and Laidlaw, 1977). The higher energy state leads to greater chemical reactivity and greater decomposition through oxidation. Fluorescein, eosine, and pyranine show strong photodecay, causing nearly complete loss of a 1,000 ppb tracer concentration within 3 hours (Aley, 1999). A similar test of rhodamine WT revealed only a 17% reduction in a 1,000 ppb sample after 5 hours, but a 68% reduction in the concentration of a 100 ppb sample, and resulted in an emission wavelength shift that resembled eosine. Sulforhodamine B samples of 1,000 and 100 ppb concentration showed losses of 5% and 40%, respectively, over 5 hours of exposure. Photodecay is not a major source for tracer degradation in the traces where the entire trace occurred underground. However, photodecay may be a major factor for tracer degradation in traces A, A', B, E, and N, where a portion of the tracer may have been exposed at the surface for several hours, or was only detected in a river downstream of the spring discharge point.

**Detection Limits**

As indicated in Table 2.1, the detection limits vary for the tracers used. The detection limit for rhodamine WT is an order of magnitude higher than that of fluorescein. Some mass of a tracer may arrive at the discharge spring below the detection limit, as discussed in Section 2.4. Table 3.1 shows that the mass of tracer that can be expected to discharge at the detection limit under average flow over a 24-hour period at Barton and Cold Springs is relatively small.

**Table 3.1 Calculated Tracer Recoveries At Their Detection Limits**

| Tracer | Total Theorectical Mass of Tracer Discharging over 24 hours at Pre-2000 Detection Limit | |
|---|---|---|
| | Barton Springs (lbs/day at 53 cfs flow) | Cold Springs (lbs/day at 14 cfs flow) |
| Fluorescein | 0.00014 | 0.00004 |
| Rhodamine WT | 0.00200 | 0.00053 |
| Eosine | 0.00143 | 0.00038 |
| Sulforhodamine B | 0.00572 | 0.00151 |

In general, the tracers used in this study have been rated in order of decreasing recovery as follows: fluorescein, pyranine, eosine, rhodamine WT, and sulforhodamine B (Behrens, 1986; Aley, 1999). Pyranine, however, shows the poorest ability to adsorb on charcoal receptors and then release the tracer to an elutant for analysis. Based on about 1,000 traces reported in the literature, Aley (1997 and 2000a) found that recoveries typically ranged from 20% to 50%.

## 3.2 Safety of the Tracers

In designing this study, the potential adverse effects were considered for human health and safety as well as other uses of the aquifer resources. The tracers were selected based on their well-documented history and non-toxicity as discussed in this section. Wherever possible, the mass of injected tracers was kept low to avoid nuisance effects of visible tracer levels to downgradient and recreational users. Where visible levels of tracers persisted, activated charcoal filter systems were installed for the well owner at no cost. Furthermore, amounts of tracer injected were targeted to be sufficiently low to avoid potential impacts on aquatic life that inhabit the system, such as the Barton Springs salamander.

The potential adverse properties of the tracers used were discussed in two reports (Smart, 1984 and Field, Wilhelm, Quinlan, and Aley, 1995) that examined the existing toxicological research. No acute problems were identified as a result of the high short-term concentrations associated with injections of the tracers. Smart (1984) recommended that persistent tracer concentrations not exceed 100 ug/l (about 100 ppb). Field and others (1995) also found that none of the dyes referenced in this report presented significant concern for the health considerations of humans and aquatic biota, but recommended that concentrations at points where water was withdrawn for use should not exceed two mg/l (2,000 ppb) for durations in excess of 24 hours. This assessment was based on a specialized chemical evaluation, utilizing structure activity relationships (SARs) developed by the EPA.

During the course of the study, bottled water was offered to well owners identified as likely to encounter visible levels of tracers. In 1996 and 1997, visible levels of tracers were observed by the investigators on two occasions discharging from Cold Springs as discussed in Section 4. In four instances during Phases IV and V, well owners as far as one mile from the injection site reported visible levels of tracer in their well water. In one case where the well (58-57-3DB) was immediately adjacent to the injection site, levels of the tracer became non-visible after a few days and required only continued monitoring. In the three other cases (wells 58-57-3DO, 58-57-3FH, and 58-58-424), activated charcoal filter systems were provided to the well owners to remove the tracer prior to consumption.

## 4.0 RESULTS

Twenty tracer injections were performed for this study from 1996 through 2000 (Table 4.1). Only three of the 20 tracer dye introductions were not detected at any site (Traces I, R, and Q). Four of the traces (Traces B, K, M, and M′) performed under low aquifer-flow conditions were only detected in wells or in the Colorado River downstream of its discharge spring and not detected at the point of its natural discharge from the aquifer. One site was traced under both low and high groundwater-flow conditions (Traces A and A’). Hydrologic conditions were highly variable, with a near record drought in 1996 and near record high water-level conditions in 1997. Figure 1.3 illustrates these conditions with daily discharge measurements of Barton Springs during the period of these traces. Most of the injection phases were conducted under low to moderate flow conditions that could result in slower than average travel times and poorer hydraulic connection. The velocity of water flow through a conduit or aquifer is directly proportional to the slope of the potentiometric surface or hydraulic head. Also, upper-level flow paths may dry, masking interconnections that are present during higher flow conditions. Portions of the main creek flow of Barton, Williamson, Slaughter, Bear, and Onion Creeks were observed in reconnaissance surveys to determine points of significant flow loss. Stream flow was measured on several occasions upstream and downstream of some of the identified infiltration locations in order to estimate their recharge contribution. Table 4.2 characterizes the arrival, duration, and persistence of the traces. A separate report by Glenrose Engineering (2000) describes the methodology and calculations used to estimate percent recovery of the tracers that are presented in Table 4.1.

Breakthrough curves were prepared based on the final laboratory results that illustrate the change in tracer concentration at specific monitored sites (Appendix A). The breakthrough curves were then analyzed to characterize the tracer response at each groundwater-monitoring site where tracers were detected. The length of time following injection when the tracer first arrived at a monitored site (or the *initial arrival time*) indicated the relative downgradient hydraulic connection of a site to the injection site. The *peak recovery time* represents the period of time after injection that the maximum concentration arrived at a monitored site, where sufficient tracer data is available. The *duration of the tracer pulse* (or persistence) was determined as the length of time over which the tracer was measured at a monitor site. The breakthrough curves were also analyzed to estimate how much time was required for the tracer to decline from its peak concentration by one and two orders of magnitude.

**Table 4.1 Summary of the Injections**

| Site # | Site Name | Watershed | Latitude | Longitude | Injection Date | Injection Time | Barton Sp. Flow (cfs) | Tracer | Tracer Volume | Mass Recovery |
|---|---|---|---|---|---|---|---|---|---|---|
| | **PHASE I** | | | | | | | | | |
| A | Mopac Bridge | Barton Creek | 30-14-30 | 97-48-39 | 8/13/1996 | 9:00 | 18 | RWT | 10 lbs | 59% |
| B | Mt Bonnell Fault | Barton Creek | 30-15-58 | 97-49-24 | 8/13/1996 | 12:00 | 18 | Fl | 10 lbs | --- |
| | **PHASE II** | | | | | | | | | |
| A' | Mopac Bridge | Barton Creek | 30-14-30 | 97-48-39 | 8/5/1997 | 15:20 | 107 | Eosine | 5 lbs | 77% |
| C | Dry Fork Sink | Williamson Creek | 30-12-53 | 97-49-35 | 6/17/1997 | 9:00 | 101 | Fl | 3 lbs | 4.2% |
| F | Brush Country | Williamson Creek | 30-15-27 | 97-49-20 | 6/24/1997 | 9:20 | 110 | RWT | 10 lbs | --- |
| | **PHASE III** | | | | | | | | | |
| H | Brodie Sink | Slaughter Creek | 30-10-42 | 97-50-57 | 4/27/1999 | 11:00 | 83 | Eosine | 7 lbs | 7.4% |
| J | Midnight Cave | Slaughter Creek | 30-12-01 | 97-53-16 | 4/27/1999 | 14:00 | 83 | RWT | 5 lbs | 16.6% |
| D | Whirlpool Cave | Williamson Creek | 30-12-59 | 97-50-47 | 6/16/1999 | 15:35 | 68 | Eosine | 5 lbs | 0.07% |
| E | Westhill Drive | Barton Creek | 30-14-29 | 97-47-31 | 6/16/1999 | 19:00 | 68 | SRB | 2 lbs | 7% |
| | **PHASE IV** | | | | | | | | | |
| I | Hobbit Hole | Bear Creek | 30-09-58 | 97-54-52 | 9/28/1999 | 16:40 | 37 | Fl | 5 lbs | 0% |
| K | Spillar Ranch | Bear Creek | 30-09-18 | 97-53-57 | 9/28/1999 | 14:10 | 37 | RWT | 10 lbs | 0.0002% |
| L | Dahlstrom Cave | Little Bear Creek | 30-06-50 | 97-54-40 | 9/28/1999 | 10:45 | 37 | Eosine | 10 lbs | 0.7% |
| | **PHASE V** | | | | | | | | | |
| M | Antioch Cave | Onion Creek | 30-04-35 | 97-51-52 | 3/28/2000 | 10:35 | 26 | RWT | 20 lbs | <0.0001% |
| N | Barber Falls | Onion Creek | 30-04-11 | 97-52-58 | 3/29/2000 | 9:00 | 26 | Fl | 10 lbs | 0.04% |
| P | Marbridge Sink | Bear Creek | 30-08-27 | 97-51-17 | 3/28/2000 | 12:30 | 26 | Eosine | 20 lbs | <0.001% |
| | **PHASE VI** | | | | | | | | | |
| G | Loop 360 | Barton Creek | 30-14-36 | 97-48-05 | 6/23/2000 | 10:00 | 61 | Pyranine | 5 lbs | 1.1% |
| Q | Tarbutton Cave | Blanco River | 29-58-22 | 97-55-02 | 8/3/2000 | 13:30 | 29 | Fl | 2.5 lbs | 0% |
| Q | Tarbutton Cave | Blanco River | 29-58-22 | 97-55-02 | 8/4/2000 | 14:15 | 29 | Fl | 4.5 lbs | 0% |
| Q | Tarbutton Cave | Blanco River | 29-58-22 | 97-55-02 | 8/5/2000 | 11:30 | 29 | Fl | 8 lbs | 0% |
| O | Crooked Oak | Onion Creek | 30-03-02 | 97-56-33 | 8/12/2000 | 9:55 | 28 | Eosine | 25 lbs | 13% |
| R | Recharge Sink | Slaughter Creek | 30-11-14 | 97-52-24 | 10/6/2000 | 14:30 | 24 | SRB | 12 lbs | 0% |
| M' | Antioch Cave | Onion Creek | 30-04-35 | 97-51-52 | 11/21/2000 | 11:30 | 81 | RWT | 24 lbs | <0.001% |

Average Recovery 16%

Median Recovery 4.20%

## Table 4.2 Summary of the Tracing Results

| Trace | Stations where Tracer was Recovered | Injection Date (day/ mo/yr) | Straight Distance from Injection Point (miles) | Min. Estm. Actual Flow Path (miles)* | Initial Recovery Time (days) | Velocity of Initial Arrival Pulse (miles/ day) | Peak Recovery Time After Arrival (days) | Duration of Tracer Pulse (days) | Time Required for Concentration Decline One order magnitude (days after peak) | Two orders magnitude (days after peak) |
|---|---|---|---|---|---|---|---|---|---|---|
| A | Cold Springs | 8/13/1996 | 3.2 | 3.4 | 5 | 0.7 | <1 | < 62 | 1 | 2 |
| B | Colorado River | 8/13/1996 | 2.7 | 2.7 | 6 | 0.7 | ? | ? | ? | ? |
| C | Upper Barton Spr. | 6/17/1997 | 4.5 | 4.8 | <1.25 | > 4 | 1 | > 104 | 1 | 2 |
| C | Main Barton Spr. | 6/17/1997 | 4.5 | 4.8 | <1.25 | > 4 | 1 | 4 - 8 | 1 | 2 |
| C | Well 58-50-207 | 6/17/1997 | 0.3 | 0.3 | 3 - 5 | 0.1 | 0 - 2 | 12 - 19 | 3 - 5 | 7 |
| C | Well 58-50-2JR | 6/17/1997 | 0.6 | 0.6 | 9 - 15 | 0.1 | 13 - 20 | 20 - 27 | < 7 | 7 - 15 |
| C | Well 58-50-221 | 6/17/1997 | 1.5 | 1.5 | 9 - 15 | 0.1 - 0.2 | 1 - 14 | 42 - 46 | 19 - 27 | 32 - 40 |
| C | Well 58-50-2CW | 6/17/1997 | 1.3 | 1.3 | 9 - 15 | 0.1 - 0.2 | 15 - 29 | 42 - 47 | >41 | 34 - 41 |
| F | Cold Springs | 6/24/1997 | 5.2 | 5.3 | < 8 | >0.7 | 1 | < 15 | < 7 | ? |
| F | Well 58-50-211 | 6/24/1997 | 1.5 | 1.5 | 6 - 13 | 0.1 - 0.3 | 28 - 37 | > 78 | 27 - 37 | 28 - 42 |
| A' | Cold Springs | 8/5/1997 | 3.2 | 3.4 | 0.79 | 4.3 | 2 | < 22 | 1 | 1 |
| H | Main Barton Spr. | 4/27/1999 | 7.5 | 8.6 | 1 - 2 | 4.3 - 8.6 | 0 - 1 | >50 | 1 - 2 | 3 - 4 |
| H | Eliza Springs | 4/27/1999 | 7.6 | 8.6 | 1 - 2 | 4.3 - 8.6 | 0 - 1 | 26 - 34 | <1 | 3 - 4 |
| H | Old Mill Springs | 4/27/1999 | 7.6 | 8.6 | 1 - 2 | 4.3 - 8.6 | 0 - 1 | 26 - 34 | 1 | 2 |
| H | Well 58-50-4MC | 4/27/1999 | 0.04 | 0.04 | 9 - 11 | 0.004 | 43 - 62 | >75 | >13 | ? |
| J | Main Barton Spr. | 4/27/1999 | 8.3 | 11.0 | 7 - 8 | 1.5 | 0 - 1 | 10 - 13 | 1 | 4 - 5 |
| J | Eliza Springs | 4/27/1999 | 8.3 | 11.0 | 7 - 8 | 1.5 | 0 - 1 | 6 | 1 - 2 | 4 - 5 |
| J | Old Mill Springs | 4/27/1999 | 8.4 | 11.0 | 7 - 8 | 1.5 | 0 - 1 | 9 - 13 | 1 | 3 |
| D | Main Barton Spr. | 6/16/1999 | 5.5 | 5.7 | Main Spring arrival obscured by background tracer | | | | | |
| D | Upper Barton Spr. | 6/16/1999 | 5.5 | 5.6 | 3 - 4 | 1.4 - 1.9 | 0 - 1 / 2 - 3 | >25 | 1 / 7 - 13** | 2 / 28** |
| E | Main Barton Spr. | 6/16/1999 | 1.8 | 2.0 | 0.37-0.42 | 5.0 | 0.25 | 7 - 14 | 0.667 | 1 |
| E | Eliza Springs | 6/16/1999 | 1.8 | 2.0 | 0-1 | 1-5 | <1 | 3 - 6 | 1 | 2 - 4 |
| E | Old Mill Springs | 6/16/1999 | 1.8 | 2.0 | 1 - 2 | 1 - 2 | 1 | 14 | 1 | 6 - 13 |
| K | Well 58-50-742 | 9/28/1999 | 1.3 | 1.3 | 22 - 28 | 0.1 | 0 - 6 | 36 - 55 | 15 - 21 | 36 - 55 |
| L | Main Barton Spr. | 9/28/1999 | 13.3 | 14.9 | 14 - 21 | 0.7 - 1.1 | 1 - 7 | 80 - 107 | <7 | <7 |
| L | Eliza Springs | 9/28/1999 | 13.4 | 14.9 | 21 | 0.7 | 0 - 7 | 36 - 58 | 0 - 7 | > 36 |
| L | Old Mill Springs | 9/28/1999 | 13.4 | 14.9 | 21 - 29 | 0.5 - 0.7 | 0 - 7 | <43 | 7 - 14 | >43 |
| L | Well 58-57-3DB | 9/28/1999 | 0.02 | 0.02 | < 0.5 | <0.04 | 1 days | > 118 | 22 - 29 | 77 - 98 |
| L | Well 58-57-3FH | 9/28/1999 | 0.09 | 0.09 | 42 | 0.002 | < 7 | > 118 | 50 - 63 | > 118 |
| L | Well 58-57-3DO | 9/28/1999 | 0.1 | 0.1 | 14 | 0.0057 | < 7 | > 118 | 50 - 63 | > 118 |
| L | Well 58-50-733 | 9/28/1999 | 4.0 | 4.0 | 0 - 8 | 0.5 - 1 | 0 - 8 | 13 - 29 | >29 | > 29 |
| L | Well 58-50-7TH | 9/28/1999 | 4.2 | 4.1 | Detected during bkgrnd sampling for Phase V | | | | | |
| L | Well 58-50-7PL | 9/28/1999 | 4.4 | 4.4 | 22 - 29 | 0.2 | 14 - 21 | 48 - 75 | 27 - 43 | > 43 |
| L | Well 58-50-7DF | 9/28/1999 | 4.6 | 4.6 | Detected During Background Sampling For Phase V | | | | | |
| L | Well 58-50-742 | 9/28/1999 | 5.1 | 5.1 | 22 - 28 | 0.2 | 22 - 42 | >118 | 13 - 47 | >70 |
| M | Well 58-58-128 | 3/28/2000 | 1.0 | 1.0 | 8 - 22 | 0.04 - .2 | 0 - 14 | < 14 | --- | --- |
| M | Well 58-57-903 | 3/28/2000 | 3.3 | 3.3 | 98 - 119 | 0.03 | 0 - 21 | <21 | --- | --- |
| N | Main Barton Spr. | 3/29/2000 | 14.9 | 15.7 | 14 - 16 | 1 - 1.1 | 4 - 6 | 47 - 56 | 42 - 52 | 52 - 59 |
| N | Eliza Springs | 3/29/2000 | 14.9 | 15.7 | 16 - 18 | 0.9- 1 | 0 - 2 | 10 - 19 | 17 - 26 | > 26 |
| N | Well 58-58-424 | 3/29/2000 | 0.9 | 0.9 | 0.92 | 1.0 | 1 | >84 | 1 - 2 | 1 - 2 |
| N | Well 58-58-4W | 3/29/2000 | 1.0 | 1.0 | < 5 | >0.2 | < 5 | 49 - 68 | 1 - 7 | <7, 35 - 49** |
| N | Well 58-58-4JP | 3/29/2000 | 1.1 | 1.1 | 41 - 51 | 0.02 | 14 - 28 | >42 | > 42 | > 42 |
| N | Well 58-58-121 | 3/29/2000 | 2.7 | 3.0 | 5 - 13 | 0.2 - 0.6 | 13 - 19** | >78 | 19 - 26 | > 78 |

**Table 4.2 Summary of the Tracing Results (Continued)**

| Trace | Stations where Tracer was Recovered | Injection Date (day/ mo/yr) | Straight Distance from Injection Point (miles) | Min. Estm. Path of Flow To Spring Discharge (miles)* | Initial Recovery Time (days) | Velocity of Initial Arrival Pulse (miles/ day) | Peak Recovery Time After Arrival (days) | Duration of Tracer Pulse (days) | Time Required for Concentration Decline: One order magnitude (days after peak) | Time Required for Concentration Decline: Two orders magnitude (days after peak) |
|---|---|---|---|---|---|---|---|---|---|---|
| P | Main Barton Spr. | 3/28/2000 | 9.8 | 11.0 | 36 - 43 | 0.3 | 36 - 43 | >15** | 1 - 7 | 1 - 7 |
| P | Well 58-50-7TH | 3/28/2000 | 0.4 | 0.4 | Background Interference | | | | | |
| P | Well 58-50-7PL | 3/28/2000 | 0.6 | 0.6 | 69 - 83 | 0.007 - 0.009 | 14 - 28 | > 49 | <14 | <35 |
| P | Well 58-50-7DF | 3/28/2000 | 0.8 | 0.8 | Background Interference | | | | | |
| P | Well 58-50-742 | 3/28/2000 | 1.2 | 1.2 | Possible Background Interference | | | | | |
| G | Cold Springs | 6/23/2000 | 2.8 | 3.3 | < 2 | >1.7 | < 2 | <5 | <3 | >3 |
| O | Main Barton Spr. | 8/12/2000 | 18.0 | 18.6 | 23 | 0.8 | 3 | 139 | 30 | 57 |
| O | Eliza Springs | 8/12/2000 | 18.0 | 18.6 | <24 | 0.77 - 0.8 | >2 | 66 - 84 | 35 - 42 | 64 - 82 |
| O | Old Mill Springs | 8/12/2000 | 18.1 | 18.6 | 30 - 32 | 0.6 | 7 - 16 | 59 - 77 | 21 - 44 | 59 - 87 |
| O | 58-50-703 | 8/12/2000 | 8.0 | 8.0 | 24 - 45? | 0.2 - 0.3 | --- | --- | --- | --- |
| O | 58-50-718 | 8/12/2000 | 8.3 | 8.3 | 65 - 86 | 0.09 - 0.13 | 86 - 107 | >42 | --- | --- |
| O | 58-50-742 | 8/12/2000 | 10.1 | 10.1 | <2 | >5 | 2 - 24 | 63 - 86 | 24 - 45 | 65 - 86 |
| O | 58-50-511 | 8/12/2000 | Unverified possible slight detection on receptor placed 2-24 days after injection. | | | | | | | |
| O | 58-57-3ES | 8/12/2000 | Two continuous slight detections on receptors placed 67-107 days after injection[2]. | | | | | | | |
| Q | None | 8/3 - 5/00 | No Detection of Fluorescein Tracer though June 2003 | | | | | | | |
| R | None | 10/6/2000 | No Detection of SRB Tracer at any Monitored Site | | | | | | | |
| M' | 58-58-121 | 11/21/2000 | 2.0 | 2.0 | <5 | >0.4 | <28 | 42 - 48 | 42 - 48 | 42 - 48 |
| M' | 58-58-128 | 11/21/2000 | 1.0 | 1.0 | < 6 | >0.16 | < 6 | --- | < 6 | < 6 |
| M' | 58-58-1JK | 11/21/2000 | 0.9 | 0.9 | < 8 | >0.1 | < 8 | --- | < 8 | < 8 |
| M' | 58-58-1KM | 11/21/2000 | 1.7 | 1.7 | 6 - 28 | 0.06 - 0.28 | 6 - 28 | 15 | --- | --- |
| M' | 58-58-1PL | 11/21/2000 | 0.85 | 0.9 | < 8 | >0.1 | < 8 | > 40 | 8 - 28 | --- |

[2] Monitoring did not commence until 10/5/00, which was 54 days after injection.

### 4.1 Phase I Barton Creek

Phase I injections were conducted in August 1996. The Phase I injections occurred during a near record drought when Barton Springs discharge was below 20 cfs (Figure 1.3). During August 1996, three wells having a long period of water-level records showed the lowest water levels since the drought of the 1950's (BS/EACD, 1997a). At the time of the Phase I injections in August 1996, the Contributing Zone baseflow on Barton Creek completely ceased near the edge of the Recharge Zone. Phase I included two injection sites on Barton Creek (A and B), both within the City of Austin Barton Creek Greenbelt (Figure 4.1). During this initial phase, City of Austin staff and BS/EACD staff conducted monitoring of Barton Springs, Cold Springs, the Colorado River, and well sites jointly.

Figure 4.1 Phase I (July-August 1996) Map of Monitored Sites and Recoveries

4.1.1 Trace A Mopac Bridge

The first injection point, Site A, is located downstream of the Mopac bridge over Barton Creek and upstream of the confluence with Gaines Creek. A well-defined sinkhole is present in the channel of Barton Creek with a bedrock escarpment bounding the upstream side and a large gravel bar complex on the downstream side. This sinkhole is located a few hundred feet downstream of a visible fault crossing Barton Creek (see Figure 1.6) and appears to be developed at the top of the Kirschberg Member within the Edwards Group. Site A is in an area where major construction projects have discharged sediment-laden runoff to Barton Creek (Johns, 1991). Being near a major highway, this sinkhole is located where hazardous materials could spill from accidents on the nearby Mopac Expressway. Following rains, streamflow from Gaines Creek has been observed to flow back upstream to the sinkhole on days where there is no baseflow in Barton Creek. This site has been observed to infiltrate large volumes during some visits and none during periods of sustained creek flow. Flow measurements taken upstream and downstream of Site A by Don Rauschuber and Associates and BS/EACD on January 16, 1995, indicated a surface-flow loss of about 9 cfs.

Prior to tracer introduction, this sinkhole was hand excavated to a depth of 5 feet. The Environmental Corps volunteers, Austin Parks and Recreation staff, and Nico Hauwert of BS/EACD performed this excavation. No open cavities were visible in the sinkhole, which appears to be filled with thick deposits of mud to gravel-sized sediment. Tanker and fire trucks provided by the Austin Fire Department were used to supply water to flush the tracer into the subsurface. Water for the flushing of Tracer A was pumped into tank trucks from Lake Austin. Fire hose was laid to the upstream edge of the sinkhole and water was discharged to saturate surface soils and establish flow into the main part of the sinkhole.

At Injection Site A, 10 pounds of rhodamine WT mixture (Tracer A) was injected on August 13, 1996 at 9:00 am. Tracer A was poured into flowing water and allowed to flow into the sinkhole where it infiltrated through the sediment (Appendix E5). Approximately

8,000 gallons of Colorado River water were used to saturate the sinkhole and flush the tracer. Observations made 24 hours later confirmed that the flush water completely infiltrated into the sinkhole.

Tracer A traveled 3.2 miles northeast and arrived at Cold Springs about 5 days following injection (Figure 4.1). The breakthrough curve for the arrival at Cold Springs is shown in Appendix A.I.1. The resurgence of the tracer was strongly visible on August 18, 1996, 5 days after the injection. The tracer resurgence was barely visible on the following day (August 19). Tracer A was not detected in any wells monitored between Injection Site A and Cold Springs.

The estimated recovery of the rhodamine WT injected for Trace A was 59%, based on an estimated flow of Cold Springs at 4.1 cfs. A high relative recovery was verified by the strong visual appearance of the tracer at Cold Springs (Appendix E5). The actual tracer recovery may differ from the estimated recovery due to over-representation of the tracer peak due to coincidental sampling near the peak discharge of tracers or alternatively by errors in estimating the springflow of Cold Springs. Traces discharging from Cold Springs (A, A', and G) tended to show strong, generally visible recoveries, suggesting that the water source contributing to it has much less dilution than the aquifer segment contributing to Barton Springs.

#### 4.1.2 Trace B Mount Bonnell Sink

Site B is at the western, or upstream edge of the Recharge Zone in Barton Creek, a few hundred feet downstream of the Mount Bonnell Fault. It is developed within the Dolomitic Member of the Edwards Group. The feature is a sediment-filled sinkhole in the creek channel first reported by William Russell of the Texas Speleological Survey (personal communication, 1993). The feature was hand excavated to a depth of 4 feet by David Johns of the City of Austin to reduce absorption of the tracer by sediment (Appendix E6). This site has been observed to take significant infiltration as indicated by flow measurements; it typically absorbs the entire discharge of Barton Creek during low flow conditions, and appears to be the first significant recharge feature below the

Contributing Zone in Barton Creek. The infiltration capacity of Site B seems to vary over time. On May 29, 1980, the USGS measured a flow loss of about 1 cfs in the vicinity of Site B (Slade, Dorsey, and Stewart, 1986). On January 24, 1997, the City of Austin measured a 5 cfs loss at Site B. The City of Austin found no measurable loss at Site B on February 14, 1997. Zahm (1998) measured relatively consistent flow losses on five occasions across this site ranging from 2.8 to 4.9 cfs.

Ten pounds of a fluorescein mixture (Tracer B) were injected at injection site B on August 13, 1996 at 12:00 noon. On this day, base flow in Barton Creek completely infiltrated within a shallow pool about 300 feet upstream from the injection point. A portable pump supplied by the Austin Fire Department was used to pump water from the upstream pool to the injection site. The pump ran approximately 10 minutes to saturate sediment in the feature. The tracer was poured directly into the feature and flushed with approximately 7,500 to 9,000 gallons of creek water.

Five to six days following injection, Tracer B was detected at two nearby locations in the Colorado River 2.7 miles northeast of the injection site and about 200 feet downstream of Cold Springs (Appendix A.I.2). None of the receptors placed at Bee Springs, Cold Springs, or upstream of Cold Springs in the Colorado River tested positive for Tracer B during the monitoring period for Phase I. It appears that the tracer discharged from an unidentified and unmonitored spring outlet in the vicinity of Cold Springs. The flow route of Tracer B is not precisely defined since its specific discharge point could not be identified and was not monitored. The poor recovery of this tracer may be due largely to heavy dilution by the Colorado River and photodegradation of the tracer in sunlight following its discharge from an unidentified spring outlet.

### 4.2 Phase II Williamson Creek and Reinjection at Barton Creek

Phase II of the study included injections on Williamson Creek (C and F) during the summer of 1997, when groundwater-flow conditions were high. At the time of the two Williamson Creek injections in June 1997, Barton Springs discharge was over 100 cfs (see Figure 1.3) and Barton Creek flow was over 500 cfs at Loop 360. Water levels in the aquifer rose significantly between the summers of 1996 and 1997 (see potentiometric-surface contours in Figures 4.1 and 4.2). Flow was sustained in the upper stretches of Williamson Creek on the Recharge Zone for several weeks during the time of injections of Phase II. Phase II also included a re-injection at one of the original sites (Site A) on Barton Creek. During this phase, the City of Austin staff largely monitoring of Barton Springs, while BS/EACD staff primarily monitored Cold Springs, the Colorado River, and most well sites.

### 4.2.1 Trace C Dry Fork Sink

Injection Site C is a natural sinkhole in the Kitcheon Branch (also known as Kincheon, Kenchion, and Dry Branch) of Williamson Creek near William Cannon Drive and Brodie Lane in Sunset Valley (Figure 4.2). William Russell of the Texas Speleological Survey (TSS) initially reported this sinkhole to be a major recharge feature known as Dry Fork Sink (personal communication, 1993). This feature was observed by the TSS and BS/EACD staff to absorb the entire flow of the tributary following some rain events (Appendix E7). This site is adjacent to and upgradient of the community of Sunset Valley, which relies solely on water from the Edwards Aquifer for drinking water supplies. The site lies near the extension of a deep trough in the potentiometric surface (Figure 4.3) and a line of faulting toward Barton Springs (Figure 1.6). Major roadways and active gasoline dispensing sites are located near Injection Point C, where harmful materials spills are possible. At this site, stormwater drains from an adjacent subdivision discharge into the creek a short distance upgradient of the sinkhole. Dry Fork Sink is developed within the Leached and Collapsed Members, probably near the contact with the underlying Regional Dense Member.

Three pounds of a fluorescein mixture (Tracer C) were injected on June 17, 1997 at 9:00 am. Members of the Environmental Corps and BS/EACD had previously partially excavated the sinkhole to clear out accumulated sediment and trash, which included aluminum cans, bottles, and a tire. Approximately 750 feet of fire hose, provided by Austin Fire Department, directed chlorinated water from a fire hydrant to the injection

Figure 4.2 Phase II (July-September 1997) Map of Monitored Sites and Recoveries

Figure 4.3 Potentiometric Surface Trough Near Sunset Valley (July 1993) feature. Water was run into the sinkhole prior to injection for approximately 20 minutes. Tracer C was poured into flowing water entering the feature. Approximately 3,000 gallons of water were used to saturate the sediments and flush the tracer.

Following injection, the initial pulse of Tracer C traveled 4.5 miles northeast to Barton Springs in less than 30 hours (Figure 4.2). The first arrival of Tracer C at the Upper Barton Springs corresponded with a high concentration pulse that discharged within six days after injection (Appendix A.II.1). For the next three months, low instantaneous tracer concentrations of about 0.01 to 0.05 ppb persisted at Upper Barton Springs. Tracer C also arrived at the Main Barton Springs, where grab sample concentrations declined below detectable levels within about three days (Appendix A.II.2). Tracer C was not detected at Eliza or Old Mill Springs during Phase II. Following its arrival at Barton Springs, Tracer C appeared days later at receptors placed in a number of wells along the way (Appendix A.II.3-6). The tracer arrived at the nearest monitored well to the injection site, located about 1,000 feet north, between 3 to 5 days after injection.

The flow path of the tracer between wells in Sunset Valley to Main and Upper Barton Springs was estimated using detailed potentiometric surface mapping performed in 1993. A July 1993 water-level surface map of a portion of the study area near Sunset Valley showed a 40-foot deep trough corresponding to a probable preferential groundwater-flow path to Barton Springs (Hauwert and Vickers, 1994, Figure 4.3). Many of the key wells used in the July 1993 potentiometric surface map have been plugged and were not available for either water-level measurements or tracer monitoring in 1997. The water levels from the key wells (58-50-2N1, 58-50-2N2, 58-50-2N3, 58-50-2N4) were estimated from correlations with well 58-50-301 for times when 58-50-301 had potentiometric surface elevations less than 521 feet (Appendix F).

Recovery of Tracer C from grab samples collected at Barton Springs was estimated to be 4.2%. Factors contributing to this relatively low recovery are: the greater sorption expected due to smaller injection masses of tracer, the tendency of fluorescein to sorb onto limestone rock, and sorptive effects of sediment fill at the sinkhole entrance.

Insufficiently frequent grab sampling around the time of peak recovery may have been a major factor in reducing the percent recovery. The arrival of tracer at Barton Springs below the detection limit for water samples may account for less than 1% loss in measured recovery, since the tracer was detected in charcoal receptors for months after the tracer concentration declined below the detection limit for grab samples. The chlorine degradation of fluorescein from the flush water used may have resulted in a net decline of the recovered tracer by only one to two percent.

### 4.2.2 Trace F Brush Country

Site F is a monitoring well owned by the City of Austin in the Williamson Creek channel near Brush Country Road (Figure 4.2). The U.S. Geological Survey drilled this well and described its lithology from core cuttings. Water-level measurements and the core logs suggested a direct connection to the regional aquifer water table of the Edwards Aquifer.

The injection at Site F was performed on June 24, 1997 at 9:20 am. At Site F, ten pounds of a liquid rhodamine WT mixture (Tracer F) were poured directly into the well and flushed with water diverted from the creek (Appendix E8). Natural creekwater was flowing around and beyond Site F during the injection. Approximately 200 gallons of water were used to flush the tracer into the aquifer. The tracer injected at Site F reached Cold Springs, 5.2 miles northeast, in less than eight days (Appendix A.II.7). Because high flow along the Colorado River resulted in flooding, dangerous currents, and poor-quality water, receptors at Cold Springs could not be changed more frequently within the first week following injection to provide a more definitive travel time and recovery (Appendix E8). The tracer was also detected in one monitored well (58-50-211) located about 2.5 miles from the injection point (Appendix A.II.8). Tracer F required from 6 to 13 days to reach this well.

#### 4.2.3 Trace A’ Mopac Bridge Reinjection

For Trace A’, an additional injection was conducted at Site A on Barton Creek in order to replicate the Phase I trace under high aquifer conditions. The second injection at Site A was performed on August 5, 1997 at 3:20 pm. Injection occurred as flow in Barton Creek was retreating upstream. Flooding had scoured out much sediment and gravel in the sinkhole since Phase I, partially revealing a rock rim. The sinkhole contained approximately 25,000 gallons of residual water at the time of injection. No water was flowing into or out of the feature during injection and the water level in the sinkhole was dropping approximately 1 inch per hour. Five pounds of eosine mixture (Tracer A’) were thoroughly mixed with creek water onsite, allowed to dissolve in buckets for several hours, and poured directly into the sinkhole and where it infiltrated at the base of the sinkhole (Appendix E9). The sinkhole was completely dry when visited the next day.

Following injection, the tracer traveled to Cold Springs, this time requiring less than 19 hours to travel the 3.2 miles (as opposed to 5 days during drought conditions). Appendix A.II.9 shows the breakthrough curve for the arrival of Tracer A’ at Cold Springs. The resurgence of tracer was visually observed on August 6, 1997 (Appendix E9). This was the only one of the 20 injection points that was traced during both high and low aquifer conditions.

A high recovery of about 77% was estimated for Trace A’ based on an estimated flow of about 7.3 cfs. This high recovery may be attributed to the relatively lower dilution within the Cold Springs subsegment than in the groundwater feeding Barton Springs, resulting in more concentration of tracer arriving above the detection limit. The relatively higher recovery estimation for this trace is supported by the visual observation of the eosine tracer (Appendix E9).

### 4.3 Phase III Slaughter Creek Watershed with Reinjections on Barton and Williamson Creeks

Phase III was conducted under higher than average groundwater-flow conditions, from late April until late July 1999 (Figure 1.3). The recharge features where tracers were injected during this phase included two sites on Slaughter Creek: Site H (Brodie Sink) and Site J (Midnight Cave), Site D (Whirlpool Cave) on the Kitcheon Branch of Williamson Creek, and Site E (Westhill Drive) on Barton Creek (Figure 4.4). Due to the recent listing of the Barton Springs salamander by U.S. Fish and Wildlife as an endangered species and subsequent protection measures that were implemented, access and monitoring of Barton Springs was conducted by City of Austin staff. The City has been issued a permit by the U.S. Fish and Wildlife Service to access these sites. Cold Springs was also largely monitored by City of Austin staff. BS/EACD staff monitored nearly all of the well sites during this phase.

4.3.1 Trace H Brodie Sink

Brodie Sink is a prominent sinkhole and cave located in a tributary to Slaughter Creek (Figure 4.5). Its entrance is formed in the Leached and Collapsed Members of the Edwards Group. According to staff observations, as well as reports by local residents, cave explorers, and videotape coverages, this cave absorbs the entire flow of the tributary under most runoff conditions.

Seven pounds of an eosine tracer mixture were injected inside the cave on April 27, 1999 beginning at 11:00 am (Appendix E10). Water from a nearby fire hydrant was used to flush the tracer. Two monitored wells were located several hundred feet east of the sink. No visible levels of tracer were observed in either well, however essentially no tracer was detected in water samples and/or charcoal receptors collected from either of the wells (Appendix A.III.7 and A.III.8). The eosine tracer traveled at least 7.5 miles to arrive at Main Barton Springs, Eliza Springs, and Old Mill Springs only 24 to 48 hours after injection (Figure 4.4, Appendices A.III.1, A.III.2, and A.III.3). The tracer was not detected at Upper Barton Springs, even though it was flowing during this phase (Appendix A.III.4). About a month after injection, several days of rainfall, each totaling about 0.5 to one inch, occurred in the study area. Following the rain, levels of tracer near the detection limit were measured in well 58-50-417 over one mile north of the injection site (Appendix A.III.9).

Figure 4.4 Phase III (March-June 1999) Map of Monitored Sites and Recoveries

Figure 4.5 Map of Estimated Flow Paths Near Site H

Tracer detections at monitored sites, potentiometric surface maps, and information from a local cave were used to estimate the flow path from the injection site to Barton Springs (Figure 4.5). The entrance to Blowing Sink Cave is located about one-half mile north of injection site H. A south to southeast flowing stream passage, known as *Eileen's River*, is encountered in the cave at a depth of 240 feet, estimated to be at an elevation of 540 feet (Appendices B.1 and E11; Russell, 1996). A circular, 10-foot diameter passage trends northeast from this stream passage (Appendix E11). Known as the *Dark Side of the Moon* passage, this dry passage dips about 40 feet over its 800 foot mapped extent before encountering a water-filled siphon. The water level in this siphon has been surveyed at a depth of about 255 feet below the entrance (about 525 feet relative to sea level). The water level elevation in nearby well 58-50-411 remains surprisingly constant at about 542 feet above mean sea level (msl), except after heavy storms when the water level can rise up 15 feet (Appendix F). The constant water level appears to be the result of the well-integrated cave system and limited source area such that the cave conduit is rarely able to completely fill, except for short periods after heavy storms. It is hypothesized that Eileen's River represents groundwater flowing under average to low flow conditions to the south, connecting to an eastward trending groundwater-flow path, eventually connecting with a wide potentiometric-surface trough subparallel to the east side of Manchaca Road. Heavy rain may result in flooding of the lower level passage and cause water to cross a groundwater divide between the Upper/Main Barton Springs source area and Old Mill/Eliza/Main Springs source areas as water enters the Dark Side of the Moon passage and flows northeast. Well 58-50-417 showed persistent low-level detections of eosine after a storm period. This well is hypothesized to be across the groundwater divide from the normal flow route. This hypothesis is supported by the fact that none of the monitored wells in the Sunset Valley area, nor Upper Barton Springs, showed detections of the tracer, perhaps indicating that an insufficient amount of tracer flowed across the divide after the storms.

The estimated recovery of this trace was 10%, based on grab sample results. As shown in Appendix A.III.7, eosine concentrations measured from water samples in a well near the injection site remained about 1 to 6 ppb through the entire 3 months of monitoring. This tendency for eosine to linger within the aquifer system, seen also in Traces D, P, L and O, may suggest a greater sorption for this tracer than anticipated. An estimated 1% of the tracer mass may have arrived below the grab sample detection limit over the time tracer was detected in corresponding receptors.

Charcoal receptors collected on March 28 through 29 suggested that higher concentrations had passed through the Main and Eliza outlets of Barton Springs, and that the peak concentration had been missed by grab samples. Sampling frequency, therefore, may have played a significant role in underestimating recovery.

#### 4.3.2 Trace J Midnight Cave

Midnight Cave is located on the western edge of the Recharge Zone within the 100-year floodplain of Slaughter Creek (Figure 4.4). The cave consists of a 65-foot pit that extends from the entrance through the upper portion of the Dolomitic Member of the Edwards Group. A pool of water is nearly always present at a depth of about 80 feet below the surface, fed in part by a constantly flowing travertine waterfall (Appendix E12). The pool of water may represent the actual water table in this area. During higher than average flow conditions, such as those experienced during this phase of the study, the pool of water overflows into a north-trending 2-foot diameter conduit (Appendix E12). It appears that this conduit serves to keep the pool at a nearly constant level, although debris perched on higher ledges suggest that the cave fills after severe floods or high water-level conditions. The cave had been utilized as a trash dumpsite during the 1950's to possibly as late as the 1980's. Cave cleanups of the trash began in 1993 by the City of Austin Parks and Recreation Department, and have nearly restored the cave to natural conditions. Austin Nature Preserves of the City of Austin Parks and Recreation Department provided access and other assistance for this site.

On April 27, 1999, five pounds of rhodamine WT mixture was poured into the overflow conduit at the bottom of Midnight Cave. A small amount of flow was running through the conduit from the pool at the time of injection. Water from a nearby fire hydrant was used to flush the tracer through the conduit and further into the aquifer. The tracer was not detected in any of the monitored well sites, but was detected at the Main Barton Springs (Appendix A.III.15), at Eliza Springs (Appendix A.III.16), and at Old Mill Springs (Appendix A.III.17) within 7 to 8 days after injection. Because this tracer was not detected in monitored wells in the Sunset Valley area and was not detected in Upper Barton Springs, it is hypothesized that the tracer moved east toward a wide potentiometric-surface trough that is subparallel to the east side of Manchaca Road. This northeast-trending potentiometric trough is suspected to represent a preferential groundwater-flow path that has been previously hypothesized and named the Manchaca Flow Route (Hauwert and Vickers, 1994).

The recovery of rhodamine WT from Trace J was 16.6%, even higher than Trace H which required much less time to arrive at Barton Springs. It may be that rhodamine WT shows less sorption within this aquifer system than the eosine used nearly simultaneously at Site H. As noted in Section 3.1, rhodamine WT tends to separate into two isomers, one of which is conservative and the other with poor sorptive properties. However, due to its chemical properties, rhodamine tends to show less sorption onto limestone than to sediment.

#### 4.3.3 Trace D Whirlpool Cave

Site D, Whirlpool Cave, was selected for injection in the middle of Phase III in order to further delineate the groundwater divide between Cold Springs and Barton Springs. It is located within the 100-year floodplain of the Kitcheon Branch of Williamson Creek, about 8 to 10 feet above the creek bottom (Figure 4.4). Whirlpool Cave was named for the whirlpool reported over the entrance during flooding conditions (Appendix E13). The entrance of the cave was raised a few feet and gated by local cave conservation association who persuaded the landowner to donate the cave property in order to utilize it as a preserve. The cave property serves as part of the Balcones Canyonland Conservation Preserve and houses rare invertebrate cave “species of concern” including the beetle *Rhadine austinica* and the millipede *Speodesmus sp.* The cave is still observed to flood on occasion, although most, if not all, of the water that pours into the entrance appears to be absorbed by drains in rooms below the entrance room, and does not appear to follow the horizontal extent of the cave. This observation is based on the lack of flood debris further into the cave and in the soft but uneroded floor of passages leading away from the entrance area.

The Texas Speleological Survey lists this cave as the third longest cave in Travis County. The explored depth of the cave, however, has been extended only to about 40 feet below the surface. Whirlpool Cave begins with generally tight passages in the Grainstone Member of the Edwards Group, but expands as the passages encounter the upper Kirschberg Member. Most of the cave is developed along a single 4-foot thick dolomitic pulverulite layer.

The Texas Cave Management Association provided access permission for Whirlpool Cave. A floor drain, two levels below the entrance room, was selected for the direct injection of the tracer. On June 16, 1999, 5 pounds of an eosine dye mixture were injected at 3:35 pm. Eleven thousand gallons of water from a nearby fire hydrant were directed into the drain using a fire hose. The selected drain was capable of completely absorbing 200 gpm, the maximum discharge rate from the fire hose.

The eosine tracer was detected at Upper Barton Springs between 3 and 4 days after injection, 5.5 miles to the northeast (Appendix A.III.4). Because of residual eosine tracer in the aquifer from Tracer H, it could not be determined if the tracer also arrived at Main, Eliza, and Old Mill Springs (Appendices A.III.1, A.III.2, and A.III.3). The eosine tracer was not detected at Cold Springs, nor at any monitored well site following injection. Because of its appearance at Upper Barton Springs, it is hypothesized that the eosine tracer moved northeast to converge with the same preferential groundwater-flow path as Trace C (Figure 4.4).

A recovery of only 0.07% was estimated from water sample results for the eosine used in Trace D. As noted for Trace H, eosine may show a higher than expected sorption within this aquifer system that may account for the poor recovery of this trace.

4.3.4 Trace E Westhill Drive

Site E is a point of significant infiltration on Barton Creek downstream of a drainage extending to nearby Westhill Drive (Figure 4.4). Located in the eastern-most bend of Barton Creek within the City of Austin Barton Creek Greenbelt, Site E is about 200 feet east of the Barton Springs Fault that has been mapped to extend to Barton Springs (see Figure 1.6). No solution-enlarged openings are visible at this site since gravel and alluvial deposits cover the underlying Leached and Collapsed Members of the Edwards Group.

The injection was performed on June 16, 1999 at 7:00 pm. At the time, the residual flow of Barton Creek completely infiltrated at Site E, although creek flow was present downstream from springs between Campbell’s Hole and Upper Barton Springs. Two pounds of sulforhodamine B mixture were injected at site E, and were flushed only with the flowing creek water (Appendix E14).

Tracer E traveled about 2 miles to the northeast and arrived at Barton Springs between 9 and 10 hours after injection (between 4:00 and 5:00 am). The tracer arrived only at the Main, Eliza, and Old Mill outlets of Barton Springs, and was not detected at Upper Barton Springs (A.III.10, A.III.12, and A.III.13). Hourly water samples collected at Barton Springs showed the breakthrough curve of the tracer arrival at the Main Barton Springs (Appendix A.III.11).

A recovery of 7% was estimated for Trace E, based on the results from water samples. Sorption of sulforhodamine B through the unknown depth of sediment at the injection site likely played a significant role in reducing the recovery masses.

## 4.4 Phase IV Bear and Little Bear Creek Watersheds

Phase IV focused entirely on recharge features within the Bear and Little Bear Creek watersheds. It was conducted under low groundwater-flow conditions of September 1999 through March 2000, where Barton Springs flow began at 40 cfs and declined to 23 cfs. The Upper Barton Springs outlet was dry during this phase. All three injection sites were located on the western side of the Recharge Zone, Site I (Hobbit Hole), Site K (Spillar Ranch Sink) and Site L (Dahlstrom Cave, Figure 4.6). Phase IV demonstrated the slowest travel times and poorest recoveries of any of the phases. For this reason, this phase was extended beyond the typical 3-month period of monitoring. For this phase, COA staff monitored Barton Springs, while BS/EACD staff monitored nearly all of the well sites. Due to time-consuming access and the small likelihood of tracer recovery, neither Cold Springs nor Colorado River sites were monitored during this phase.

Each of the three injection sites utilized three water trucks provided by Austin Parks and Recreation and one fire truck provided by the Manchaca Volunteer Fire Department. All three injections of this phase were conducted on September 28, 1999. Because of the poor recoveries from Sites I and K, and the lingering of tracer in wells near Site L, 10,000 gallons of water was reinjected into each site on December 29, 1999. The reflushing did not appear to increase recoveries of the tracers.

Access to two of the three sites (Sites I and K) and other assistance for the Spillar Ranch injections was provided by Mr. Gary Bradley of Bradley Development and local ranch owner, Cal Varner.

#### 4.4.1 Trace I Hobbit Hole

Site I is a solution feature known as Hobbit Hole near a hilltop north of Bear Creek. It is about 1.5 feet wide and extends at least 4 feet down a narrow shaft to a horizontal bedding plane. The entrance of Hobbit Hole is formed within the Dolomitic Member. Five pounds of fluorescein dye mixture were injected into Hobbit Hole beginning at 4:40 pm on September 28, 1999 (Appendix E15). During injection, the flow rate of flush water from the water trucks had to be reduced due to the limited capacity of the solution feature.

The fluorescein mixture injected into Hobbit Hole was not detected at any of the monitored sites from September until March 2000, when fluorescein was reused in Phase V (Figure 4.6). It is believed that, under the low groundwater-flow conditions of this phase, no regular water table exists below the site with hydraulic connection to Barton Springs or any other monitored site. Local wells in this area do not typically encounter water within the Edwards Aquifer, and any water present here may be restricted to discrete cave or conduit streams. Such a conduit can be observed to supply Spillar Ranch Spring, which discharges from the contact of the Basal Nodular Member near the south side of Bear Creek at a rate of about 30 gpm. Another spring discharges from the lower portion of the Basal Nodular Member on the north bank of Bear Creek about a half mile southeast of Hobbit Hole. This spring was dry during Phase IV and could not be monitored. However, it is possible that with a greater mass of tracer, more flush water, and a greater monitoring time, recoveries could be made. Furthermore, it is possible that that tracer recoveries could be made with injections into local recharge features under higher groundwater-flow conditions. It is also conceivable that the discharge point(s) for Hobbit Hole were not identified and monitored. Trace I remains one of the few injection sites of the study where tracer was not detected at any of the monitored sites.

### 4.4.2 Trace K Spillar Ranch Sink

Site K is a well-defined sinkhole that forms the bottom of a minor tributary to Bear Creek (Figure 4.6). The sinkhole, known as Spillar Ranch Sink, contains several conduits at its base. The extent of cavernous passage below Spillar Ranch Sink is unknown but likely large, considering the loss of material within the bowl of the sinkhole due to dissolution and possible collapse that has occurred in the past. Spillar Ranch Sink is developed within the Kirschberg Member of the Edwards Group.

Ten pounds of rhodamine WT mixture were injected on September 28, 1999 beginning at 2:10 pm (Appendix E16). One conduit at the base of the sinkhole easily absorbed the entire 10,000 gallons of flush water from the water trucks. The water was delivered at a maximum rate of about 200 gpm.

Over the Phase IV monitoring period, rhodamine WT was only detected at one well, 58-50-742, located about three miles directly east of Spillar Ranch Sink (Appendix A.IV.1). No detections of rhodamine WT were made from any other site during this phase. The

Figure 4.6 Phase IV (Sept. 1999-Jan. 2000) Map of Monitored Sites and Recoveries lack of recovery may be due to relatively poor hydraulic connection or slow travel times from Site K during the low aquifer conditions of the trace. Because other traces (P and L) reaching the same well (58-50-742) were also detected at Barton Springs, it is assumed that Tracer K eventually reached Barton Springs below detection limits of the grab and receptor samples.

#### 4.4.3 Trace L Dahlstrom Cave

Dahlstrom Cave includes a well defined sinkhole entrance at the termination of a minor surface drainage cut off from nearby Little Bear Creek (Figure 4.6). Owner William Russell, a noted local cave explorer, provided access to the cave for tracer injection. The cave is located within the Hays Country Oaks subdivision, whose sole water supply relies on private domestic wells. The sinkhole is surrounded in all directions by these private water wells. The saturated thickness of the aquifer in the local area was estimated to be only about 50 feet under the drought conditions of August 1996 (BS/EACD, 1997a). The thin saturated thickness of the aquifer in this area is demonstrated by the tendency of some nearby wells to dry up after less than an hour of pumping during periods of drought. The geology of the cave was not examined for this study, although geological mapping within the area places the cave entrance within the Kirschberg Member of the Edwards Group. A cave map is provided in Appendix B-5.

On September 28, 1999, beginning at 10:45 am, 10 pounds of eosine dye mixture were poured into the cave at a depth of about 20 to 30 feet below the surface (Appendix E17). Later that evening, the tracer was observed in the closest well (58-57-3DB), located about 200 feet to the west. Levels were reported to have diminished within 3 days after injection, although the tracer was detected in charcoal and grab samples for the 4 months of monitoring (Appendix A.IV.5). Two weeks after injection, the tracer was observed in well 58-57-3DO, located about 400 feet directly east of the Dahlstrom Cave entrance (Appendix A.IV.6). The tracer remained visible for at least 7 months and was measured in grab samples from the well for at least a year after injection. The persistence of the tracer necessitated the installation of an activated charcoal filter system on the well to remove the tracer from the residents' water supply. Six weeks after injection, the tracer was obseved in well 58-57-3FH, located about 450 feet east of the entrance to Dahlstrom Cave (Appendix A.IV.7a). The pink color of the tracer remained visible in the well water for at least 6 months after injection (about 4.5 months after initial recovery in the well), and continued to be detected in grab samples for over a year after injection (Appendix A.IV.7b).

Sometime prior to 6 days after injection, the eosine tracer was detected in public water supply well 58-50-733, located in San Leanna about 4 miles to the northeast of Dahlstrom Cave (Appendix A.IV.8). About a half-mile north of this well, eosine made its appearance at well 58-50-7PL between 22 and 29 days after injection and remained detectable in charcoal samples until 77 to 97 days after injection (Appendix A.IV.9).

Eosine was measured in the initial background samples collected at wells 58-50-7DF and 58-50-7TH in late March 2000, prior to the reinjection of eosine for Site P in Phase V (Appendices A.V.10 and A.V.12). This interference of eosine is believed to be residual from the Site L injection at Dahlstrom Cave. About 5 miles northeast of Dahlstrom Cave, eosine was consistently measured at well 58-57-742 from its initial appearance 22 to 28 days after injection until at least June 19, 2000 or about 8 months after injection (Appendix A.IV.10).

The eosine tracer was not detected in any additional wells north of the line of wells where it was detected between Dahlstrom Cave and the San Leanna area. The eosine tracer did arrive at the Main, Old Mill, and Eliza outlets of Barton Springs sometime between 14 to 21 days after injection (Appendices A.IV.2, A.IV.3, and A.IV.4). The tracer was detected only in one weekly grab sample at the Main Springs (0.007 ppb) and at one weekly grab sample collected at Eliza Springs (0.011 ppb), although the eosine was detected on multiple weekly charcoal receptors from the three spring outlets. A recovery of only 0.7% was estimated from water samples of this trace. It is estimated that 1.5% of the tracer mass may have discharged from Barton Springs below the detection limit, and was not measured for the recovery estimate. The results from this trace validate the need for charcoal receptors in addition to grab samples to help define the arrival of tracers. It also demonstrates the difficulty in selecting an injection mass of tracer that will not overwhelm nearby water-supply wells and other aquifer uses, yet allow sufficient detection at a distant discharge point. The persistence of eosine near Site L may also be due, in part, to the sorptive characteristics of this tracer within the Barton Springs segment as seen in Traces H, D, P, and O. The low-groundwater flow conditions of this trace likely was a major factor in the relatively slow initial arrival and recovery observed in this trace.

### 4.5 Phase V Onion Creek Watershed and Reinjection in Bear Creek

In January and February 2000, two rain events of an inch or two in magnitude raised the flow of Barton Springs from about 23 cfs to about 40 cfs. Phase V mirrored Phase IV as it commenced with springflow discharging at about 40 cfs and declined into low groundwater-flow conditions later in the phase. Upper Barton Springs was dry during this phase. Phase V focused on the downstream Recharge Zone stretches of Onion Creek at Sites M (Antioch Cave) and N (Barber Falls), and included a sinkhole on Bear Creek (site P, Marbridge Sink) in order to examine this creek near the eastern edge of the Recharge Zone (Figure 4.7). During this phase, two identified alternative injection sites on upstream Onion Creek near the western edge of the Recharge Zone could not be accessed, one for lack of permission and the other due to poor access for water trucks needed to flush the tracer. Permission was later obtained for the former site that allowed injection in the upstream Onion Creek Site O in Phase VI. Phase V extended from the injections on March 28 and 29, 2000, through June 2000.

During Phase V, monitoring at Barton Springs continued to be conducted by City of Austin staff. Cold Springs was not monitored during this phase due to its difficult access and the improbability that it would receive tracers from the three sites. San Marcos Springs was monitored during this phase, directly at the most prominent five of the 10 spring outlets (Weismuller, Crater, Salt and Pepper I, Caromba, and Deep Spring) and also at the convergence of Spring Lake water near Aquarena Springs Road. Charcoal receptors placed at spring outlets and grab samples were collected by divers provided by

Figure 4.7 Phase V (June-July 2000) Map of Monitored Sites and Recoveries the Aquarena Center, which manages these springs. The potentiometric surface map and traced flow paths are shown in Figure 4.7.

### 4.5.1 Trace M Antioch Cave

Site M, Antioch Cave, is located in the creek bottom of Onion Creek about 200 feet upstream of the Mountain City Fault that defines the eastern edge of the Recharge Zone (Figure 4.7). The entrance of Antioch Cave is formed along a fissure in the Georgetown Formation of the Washita Group. The fissure joins a 15- to 20-foot wide, 30-foot deep shaft that plunges into the Marine Member of the Edwards Group. Extensive horizontal passages extend to the north and south near the bottom of the entrance shaft and about 10 feet below the top of the Marine Member (Appendix B4). A sediment-filled conduit continues downward for an unknown depth from the bottom of the entrance shaft. Prior to injection, a portion of the sediment from the pit was excavated so that the tracer and flush water could be directed downward. The cave property is owned by BS/EACD.

A concrete structure was built around the entrance of Antioch Cave by BS/EACD in 1997 to reduce the load of sediment and debris entering the cave. This structure contains a valve that allows the creek flow to be regulated as it enters the cave. Since the early 1990's, a whirlpool can typically be observed over the cave entrance during flowing creek conditions (Appendix E18). Following the construction of the concrete structure around Antioch Cave, a whirlpool often develops when water flows into the opened valve. Using water depths and pipe dimensions, the infiltrating flow was estimated to average 47 cfs over 104 days in 1998, with a maximum flow of 95 cfs (Fieseler, 1998). An infiltration rate of 26 cfs was calculated at Antioch Cave on April 13, 1998, based on the difference of actual creek flow measured upstream and downstream.

The injection at Antioch Cave began at 10:35 am on March 28, 2000, as 20 pounds of rhodamine WT dye mixture were poured into the sediment-filled pit at the bottom of the shaft. Onion Creek was essentially dry except for (1) about 30,000 gallons of flush water from a well which had been previously poured into the creek around Antioch Cave by Centex Materials Company and (2) the flow of a minor upstream spring. The flush water was insufficient to force water along the horizontal passages to the north and south, but instead drained through the sediment-filled conduit at the bottom of the entrance shaft. The rhodamine WT tracer was only weakly detected or possibly detected in wells near the injection site. Between 5 and 12 days after injection, rhodamine WT may have been detected near the detection limit in a receptor placed at a nearby monitored well, 58-58-424. No later receptor samples or grab samples verified this detection. Over two months after injection, a two-inch rain event resulted in increases from low to moderate groundwater-flow conditions (Figure 1.3). In receptors placed from June 5 to June 19 at well 58-58-128, located about a half mile northeast of Antioch Cave, rhodamine WT was measured at a cumulative receptor concentration of 95.8 ppb (Appendix A.V.7). Again, no repeat detections were made at this well site. Slight levels (0.986 ppb over 21 days) of rhodamine WT was measured in a single receptor placed from July 3 through July 24, 2000 in well 58-57-903 at Mountain City, 3.3 miles southwest of Site M. The rhodamine WT associated with this injection was never directly measured at any spring discharge point. The Blanco River was dry at the start of the trace near Kyle, and therefore could not be monitored for possible resurgence of the tracers in Phase V.

The few tracer recoveries in wells of different directions from the injection point suggest that groundwater flow moves in at least three directions from Antioch Cave under the tested conditions. This trifurcation of flow, particularly under low groundwater flow conditions, could result in greater adsorption of the tracer, greater diffusion and multiple advective flow rates, greater dilution of the tracer if portions of the injected mass went to multiple springs, and could contribute to the non-detection of tracer at distant spring resurgences. It is possible that the fine-grained sediment at the entrance room drain of Antioch Cave may have absorbed an appreciable amount of the tracer. However, as described in Section 2.3, there are other possible explanations for the poor recovery of the tracer injected at Antioch Cave. Under flowing creek conditions, the BS/EACD reinjected 24 pounds of rhodamine WT on November 21, 2000 to allow the tracer to flow through the primary open passages to the north and south. The results of this reinjection are discussed in Section 4.6.5.

4.5.2 Trace N Barber Falls

Barber Falls is a large sinkhole in the bottom of Onion Creek about a half mile upstream of the FM 1626 bridge crossing (Figure 4.7 and Appendix E19). It has a rim diameter of about 200 feet and a depth of about 80 feet. The sinkhole is bowl-shaped and has accumulated large volumes of sediment and large rocks that may reduce its infiltration capacity. Barber Falls is developed within the Marine Member of the Edwards Group, although the underlying Leached Member may also be exposed within the sinkhole. A fault can be traced through a nearby quarry pit to the south and through the middle of Barber Falls. Stream flow measurements taken upstream and downstream of Barber Falls by the BS/EACD, COA, and Don G. Rauschuber and Associates staff on January 13, 1999 suggested an infiltration rate of about 4.5 cfs within the sinkhole.

At the time of injection, Onion Creek had not flowed through Barber Falls for some time. Centex Materials Inc provided about 30,000 gallons of flush water. The flush water was pumped through fire hoses to the bottom of the sinkhole on the day of injection, March 29, 2000. From 9:00 am until 11:00 am, 10 pounds of fluorescein tracer were poured into the water at the bottom of the sinkhole (Appendix E19). The water level in the sinkhole continued to rise as more water was added during the morning of March 29, and infiltration was not readily obvious during the injection. The sinkhole was revisited a week later on April 7 and still contained pools of flush water colored with the tracer.

At about 7:00 am on the morning following the injection of fluorescein at Barber Falls, a nearby well owner first observed a yellowish tint in his water that soon became a strong green color. This well, 58-58-424, is located about a mile northeast of Barber Falls. Bottled water was brought out to the family depending on this well on the afternoon of March 30. On the day after the tracer's appearance, an activated charcoal filtration system was installed on the well that effectively removed the tracer from the drinking water supply. Analysis of the samples collected from this well verified the appearance of the tracer at well 58-58-424, although the levels of tracer declined to near non-detection levels within 15 days (Appendix A.V.3). Levels of the tracer reappeared about 2 months after injection, apparently associated with a rain event that caused creek flow to recharge at Barber Falls for about 2 days.

The fluorescein tracer was detected in receptors and water samples from three other wells within 3 miles of the injection site. Wells 58-58-4JP and 58-58-4WP, both located near well 58-58-424 where the tracer was observed, showed detections of the fluorescein tracer after injection (Appendices A.V.4 and A.V.5). A public water supply well for the Leisurewoods subdivision (58-58-121) received the first arrival of the tracer within 5 to 13 days after injection (Appendix A.V.6).

The fluorescein tracer was initially detected at the Main Barton Springs within 14 to 16 days after injection and at Eliza Springs within 16 to 18 days after injection (Appendix A.V.1 and A.V.2). The fluorescein tracer was not detected at the Old Mill Springs or Upper Barton Springs outlets of Barton Springs. The tracer was not detected in wells such as 58-50-742 where tracers were detected from multiple traces in the Bear and Little Bear Creek watersheds. Therefore, it is assumed that the tracer from Barber Falls in Onion Creek followed a separate branch of the flow path that converges somewhere north of San Leanna. The tracer was assumed to follow the potentiometric trough along the east side of Manchaca Road (the Manchaca Flow Route) towards Barton Springs.

A mass recovery of 0.04% was estimated from water samples. Fluorescein is expected to be the most conservative of the tracers used in this study. Although fluorescein was measured consistently in charcoal samples at Main Barton Springs for 56 days after its initial arrival, the tracer was never detected in the water samples. The arrival of tracer at Barton Springs below the grab-sample detection limit was estimated to account for less than 0.01% of the original tracer mass.

### 4.5.3. Trace P Marbridge Sink

Marbridge Sink is a well-defined sinkhole in the center of Bear Creek, west of FM 1626. The sinkhole has a rim about 50 feet in diameter and forms a waterfall on its upstream end that plunges about 25 feet. The sinkhole is primarily formed within the Leached

Member of the Edwards Group, although a 5-foot thick bed of Marine Member is exposed on the bank above the sinkhole, just below the contact with the overlying Georgetown Formation. A major fault that has an estimated throw of about 110 feet crosses Bear Creek about 200 feet downstream of Marbridge Sink. Marbridge Sink is positioned near the downstream edge of the Recharge Zone. On April 7, 1998, the sink was observed to absorb the entire upstream flow of 3.7 cfs. On November 10, 1998, a flow rate of about 2.4 cfs infiltrated into Marbridge Sink, based on upstream and downstream flow measurements. The sink has an unknown thickness of gravel and alluvium at its base that obscures any conduit that may be present and limits its infiltration capacity. Marbridge Farms provided access to the property and the water supply for the flush water. The sinkhole and portions of its upstream contributing area has since been acquired by the City of Austin through Proposition 2 water-quality protection land purchase.

On March 28, 2000, 20 pounds of eosine dye mixture was poured into a shallow overhang at the bottom of the sinkhole (Appendix E20). At the time of injection, Bear Creek had been dry for several months. The tracer was flushed with about 10,000 gallons of water from a nearby water well, and was transported by tanker trucks provided by the City of Austin Watershed Protection Division and Associated Drilling Company. The gravel and alluvium at the base of the sinkhole easily absorbed the flush water at a rate of about 200 gpm.

Residual eosine tracer, injected on September 28, 1999 at Site L, was detected at relatively high levels in background samples in late March 2000 from several wells (58-50-7DF, 58-50-7TH, 58-50-7PL, and 58-50-742) monitored near Site P. For this reason, it was difficult to distinguish the possible arrival of eosine tracer from Site P at these wells. A pulse of eosine from Site P arrived at the Main Barton Springs 36 to 43 days after injection. Tracer P was not measured at either Eliza or Old Mill Springs. Following a 2-inch rain event in early June, eosine tracer briefly appeared in wells 58-50-703 and 58-50-7WC near the injection site.

## 4.6 Phase VI Follow-up Traces on Barton Creek at Loop 360, the Blanco River, and Upstream Onion Creek

Additional sites were traced near the end of the study; primarily to help define uncertain groundwater divides under the low aquifer conditions of this phase. These sites included Site G, Barton Creek upstream of Loop 360, Site Q, Tarbutton's Showerbath Cave on the Blanco River, and Site O, Crooked Oak Cave on upstream Onion Creek, and Site R, Recharge Sink at the Lady Bird Johnson Wildflower Center. Phase VI began in late June 2000 and was monitored through November 2000. Figure 4.8 shows the potentiometric surface elevations measured in June and July 2000, as well as the traced flow paths.

### 4.6.1 Trace G Loop 360

A fourth site on Barton Creek was traced to further delineate the recharge divide between Barton and Cold Springs. A significant infiltration point was identified about 800 feet upstream of Loop 360 where complete flow loss had been observed on one occasion. Because of the difficulty in getting tanker trucks or a fire hydrant source near this site, the tracer was injected at a time when natural creek flow ceased flowing past Loop 360. On June 23, 2000, beginning at 10:00 am, 5 pounds of pyranine dye mixture were poured into a rock-bottomed ripple above the gravel filled recharge point (Appendix E21). At the time of injection, the flow to the infiltration point was measured to be 0.95 cfs.

Within 2 days of injections, the pyranine tracer was measured at Cold Springs about 2 miles north (Appendix A.VI.1). Within 5 days after injection, no further pyranine was measured at Cold Springs. Pyranine was not detected at Barton Springs within the period of 1 month for which pyranine samples were analyzed.

### 4.6.2 Site Q Tarbutton's Showerbath Cave

Tarbutton's Showerbath Cave is located on the south bank of the Blanco River (Figure 4.8). It has a well-defined sinkhole entrance with a rim diameter of about 25 feet. On the north side, the sinkhole rim is only about 5 to 10 feet higher than the bottom of the

Figure 4.8 Phase VI (July-October 2000) Map of Monitored Sites and Recoveries

Blanco River. On the south side of the sinkhole, the rim drops steeply about 40 feet into the bottom of an entrance room (Appendix E22). From the entrance room, the passage trends north beneath the Blanco River. Under flowing river conditions, a shower of water enters the roof of the passage and flows down the passage at a rate estimated to be 20 to 40 gpm. Access to Tarbutton's Showerbath Cave was provided by Mr. Emmett McCoy of Blanco River Investments and with the assistance of ranch foreman David Allen. The entrance sinkhole of Tarbutton's Showerbath Cave is developed within the Georgetown Formation of the Washita Group. The entrance room and north trending passage is developed within the Marine Member of the Edwards Group.

Over a 3-day period from August 3 through August 5, 15 pounds of fluorescein dye mixture were poured into Tarbutton's Showerbath Cave. Technical problems were experienced with injecting the tracer that prevented a more instantaneous injection. Rains in June 2000 caused the Blanco River to flow in the vicinity of Tarbutton's Showerbath Cave until it stopped flowing around July 1. At the time scheduled for injection on August 3, 2000, a water truck provided by the City of Austin Watershed Protection Department was used to inject about 1,500 gallons of flush water. However, due to an uneven surface, the tank had begun shifting off the truck, effectively stopping the completion of the injection. Only 2.5 pounds of fluorescein dye mixture were injected on August 3, beginning at 1:30 pm. On August 4, continuation of the injection was attempted using a pump provided by the Austin Fire Department to direct water from a nearby 2-foot deep standing pool in the Blanco River. After injecting 4.5 pounds of fluorescein, beginning at 2:15 pm and flushing about 500 gallons of water from the standing pool, the pump stopped and could not be restarted. Arrangements were made to have three water trucks from the COA Watershed Protection Department flush about 8,000 gallons of water into the sinkhole on August 5. The final 8 pounds of fluorescein dye mixture were injected on August 5, beginning at 11:30 am. No fluorescein has been detected at San Marcos Springs or Barton Springs after this injection in samples submitted to OUL through October 2001. Additional analysis for most receptors collected from San Marcos Springs and Barton Springs through June 2002 and analyzed by the Edwards Aquifer Authority did not reveal the presence of this tracer. As described in Section 1 of this report, a tracer previously injected at Site Q as part of an earlier study may have discharged from San Marcos Springs a year later. Wells 58-58-4W and 58-58-4LO on the north side of Onion Creek show a pulse of fluorescein tracer arriving two to three months after the injection of Tracer Q (Appendix A). However, other nearby wells, 58-58-4JP and 58-58-121 also show residual fluorescein from previous Tracer N, so the movement of tracer north of Onion Creek from the site Q is not clear from this trace. Unfortunately, the August 2000 trace of Tarbutton's Cave was unsuccessful in providing new information on groundwater flow from the Blanco River.

#### 4.6.3 Trace O Crooked Oak Cave

Site O is a cave in the bottom of Onion Creek about 1 mile downstream of faults that mark the western edge of the Recharge Zone (Figure 4.8 and Appendix E23). Heather Beatty, a geologist for TCEQ who was inspecting the site in advance of a proposed housing development known as Sky Ranch, discovered the cave in November 1999. The cave is developed within the Kirschberg Member of the Edwards Group, which is generally the most permeable hydrostratigraphic unit (Small and others, 1995). The cave entrance drops 13 feet and leads to an adjacent room that measures 8-feet high and 8-feet wide. Flow measurements collected by the USGS in 1981 and BS/EACD and COA in 1999 suggest that between 15 and 36 cfs, or about one third of the entire creek-flow loss for Onion Creek, occurs on the 2-mile stretch of creek located on the property containing Crooked Oak Cave. In June 2000, measurements by COA and BS/EACD staff indicated flow loss of 25 cfs through this reach of Onion Creek. Visual observations of creek flow to the cave in June 2000 by COA and BS/EACD staff, indicated that the cave did recharge, but its inner orifices were not large enough to develop a whirlpool such as those observed at Antioch Cave and other similar recharge features on Onion Creek. Access permission to inject groundwater tracers in Crooked Oak Cave during Phase V was not granted by the property owner. However, in July 2000, the City of Austin acquired the entire property under Proposition 2 bonds and facilitated the tracing from Crooked Oak Cave for Phase VI.

On August 12, 2000, from 9:55 am until 12:00 noon, 25 pounds of eosine dye mixture were injected into the room within the cave. Water trucks provided by City of Austin Parks and Recreation Department provided about 12,000 gallons of flush water for the tracer. The flush water and tracer could be seen flowing primarily into sediment-covered conduits on the floor of the inner room and entrance pit. The eosine tracer arrived at the Main Barton Springs 22 days after injection. The tracer arrived at Eliza Springs 24 days after injection and at Old Mill Springs 30 to 32 days after injection. Upper Barton Springs was dry during the first month after injection, but began flowing around October 16, 2000. Eosine was detected at relatively consistent concentrations at Upper Barton Springs from November 9, 2000 through March 22, 2001 (Appendix A.VI.12). During a previous interval of flow at Upper Barton Springs during June and July of 2000, eosine had been measured at comparable levels from June 14 through 28, but was not detected in three consecutive receptors thereafter, up to July 26, 2000. Previous traces within the Onion (Trace N), Little Bear (Trace L), Bear (Trace P), and Slaughter (H and J) were detected only at the Main, Eliza, and Old Mill outlets of Barton Springs and not at Upper Barton Springs. Therefore, it is believed that the eosine detected in Upper Barton Springs beginning in November of 2000 was not from injection Site O, but rather reactivated tracer from an earlier trace in the Sunset Valley groundwater basin or from another unknown source. Although unlikely, it is also possible that eosine traveled from Site O, and if so then under certain conditions groundwater must cross a divide previously observed between the Upper/Main Barton (Sunset Valley) groundwater basin and Eliza/Old Mill/Main Barton Springs (Manchaca) groundwater basin. As indicated in Figure 1.3, Barton Spring flow did not exceed average flow rates for long periods from August 1999 through October 2000.

Eosine may have been weakly detected for the first time at wells 58-50-511 and 58-57-3ES, both of which lie near the projected groundwater-flow path.

### 4.6.4 Trace R Recharge Sink

Recharge Sink is a sinkhole on the bottom of a tributary to Slaughter Creek at the Lady Bird Johnson Wildflower Center (Figure 4.8). On one occasion in 1994, the recharge feature was observed to absorb the entire flow of the creek through a whirlpool following a rain event. At the same time, foam from recently placed emulsion on upstream Mopac Expressway could be seen floating on the recharging water. This observation demonstrated the sensitivity of this feature to roadway runoff and potential hazardous material spills from Mopac Expressway. Recharge Sink is positioned within the top of the Kirschberg Member, about 10 feet below its overlying contact with the Grainstone Member.

On October 6, 2000, from 2:30 to 2:50 pm, 12 pounds of sulforhodamine B were poured into Recharge Sink and flushed with about 10,000 gallons of chlorinated water from a nearby fire hydrant (Appendix E24). Laboratory results for samples from receptor locations collected prior to May 2001 showed no detections of this tracer. Sulforhodamine B is believed to be the least conservative of the five tracers and the tracer may not perform well over long distances. Furthermore, the trace was conducted under relatively low groundwater-flow conditions.

#### 4.6.5 Trace M′ Antioch Cave

A reinjection at Antioch Cave was desired since the overlying creek was dry and the flush water was insufficient to carry the rhodamine WT tracer into higher open conduits within the cave on the previous trace of March 28, 2000 (see Section 4.5.1). The entrance drain of Antioch Cave is filled with silt and mud sized sediment that could have retained the tracer used in the previous trace, since that tracer was not detected at Barton Springs. On November 21, 2000, following several weeks of flow in Onion Creek, 24 pounds of rhodamine WT tracer were reinjected in Antioch Cave under flowing creek conditions. Once again, the rhodamine WT tracer was only detected in wells within two miles of Antioch Cave, and apparently arrived below detection limit at Barton Springs.

Water-level measurements taken in June and July of 2000, indicate a potentiometric-surface ridge extending northeast from Antioch Cave on Onion Creek (Figure 4.8). Rhodamine WT traveled almost 2 miles north to well 58-58-121 within 5 days after injection (Appendix A.VI.7). During Phase V of this study, this well also showed the presence of Tracer N injected on Onion Creek at Barber Falls Sink (see Section 4.5.2), suggesting the well is situated near a preferential flow path draining the lower 2-mile Recharge Zone portion of Onion Creek. Rhodamine WT appeared in wells 58-58-128 and 58-58-1JK, located about 1 mile northeast of Antioch Cave, in less than 6 and 8 days of injection, respectively (Appendices A.VI.8 and A.VI.9). A slight presence of rhodamine WT was detected in well 58-58-1KM between 6 to 28 days after injection. This well is located over 1 mile from Antioch Cave to the northeast and the presence of tracer here may suggest a bifurcated flow path since it is in a widely separate direction from well 58-58-121. Since well 58-58-121 has been traced to Barton Springs in Trace N, it is assumed that a portion of Tracer M′ arrived at Barton Springs below the detection limit. The flow path from well 58-58-121 to Barton Springs was estimated based on potentiometric-surface elevations, general fault trends, and wells where the tracer was not detected. In the previous trace of this site, low levels of tracer were also recovered to the south of Onion Creek in a well of the Mountain City area. A recovery of less than 0.001% may be attributed to effects of multiple flow paths from the same injection point, the tendency of a large portion of the rhodamine WT to sorb (see Section 3.0) or heavy dilution from the actively recharging creeks.

## 5.0 DISCUSSION

The actual travel time and percent recovery of the tracers varied with several factors, including groundwater-flow conditions, aquifer storage, and the hydraulic connection between the recharge site and discharge point, and the hydraulic gradient of the groundwater. The hydraulic connection between the recharge and discharge sites is influenced by the saturated thickness of the underlying aquifer, the slope of the water-table surface, the conduit size, interconnectivity of water-saturated conduits, and blockage caused by sediment filling the recharge opening.

As explained in Section 3, the groundwater travel times and recoveries reported in this study may underestimate actual groundwater values, due to the tracer properties, tortuosity, the low groundwater-flow conditions experienced during much of the study, the relatively small amount of tracer used, and sampling frequency.  The variation in sorption for the tracers could be an important factor, although an insufficient amount of information from the traces is available to determine its significance.  Most of the recharge sites (A, B, C, E, G, K, P, M, N, O) were filled with an undetermined thickness of sediment near the surface that could have potentially retarded or adsorbed the tracer. Higher recoveries can be expected using a greater injection mass of the same tracer. In several of the traces, tracers were measured in charcoal receptors at the outlet springs for several months after arrival, but were below the detection limit for grab sample concentrations used to calculate recoveries.  However, the net loss of tracer is relatively small for the long recession period after the majority of the pulse has discharged from the spring, generally accounting for less than 1% of the injected tracer.

The frequency of sampling can significantly affect the amount of tracer recovered in grab samples.  Longer sampling intervals tend to underestimate the mass of recovered tracer, since maximum breakthrough peak of short duration will almost invariably be missed.  It is less likely but possible to overestimate recovery as a result of widely spaced sampling. Errors in the estimation or measurement of individual springflow can positively or negatively affect the accuracy of recovery calculations.

The measured travel rates of the tracers changed significantly between high and low groundwater-flow conditions. Under low groundwater-flow conditions (when Barton Springs flow was less than 20 cfs), tracer from injection Site A traveled about 3 miles in 5 days (about 0.6 miles per day). Under high groundwater-flow conditions (when Barton Springs flow was more than 100 cfs), Tracer A′, injected at the same injection point, arrived at the same spring in less than 19 hours (about 4 miles per day). This difference in travel rates may be due to the inaccessibility of upper level conduits under low groundwater flow conditions that in the unconfined portions of the aquifer may provide more direct flow routes under higher groundwater-flow conditions. Additionally, the slope of the hydraulic gradient across the aquifer increases significantly during high groundwater-flow conditions and increases the travel rate of groundwater. Furthermore, rhodamine WT and probably other dyes used in this study may experience greater loss under low groundwater-flow conditions due to more sustained contact of the dye with adsorptive substrates (Aley, 1999). Eleven of the 20 traces were conducted under low groundwater-flow conditions.

The travel velocities using the straight-line distance will be underestimated because the actual distances traveled by the tracers will always be more circuitous than the straight-line distance between the injection and detected locations, due to tortuosity. Worthington (1991) noted that the actual distance traveled in a karst aquifer can be 1.5 times longer than the straight-line distance. In Table 4.2, the minimum actual travel distance was used to calculate groundwater velocities, rather than straight-line paths, but still likely underestimates the effects of tortuosity.

The tracers typically arrive more slowly at nearby wells than at the discharge springs. This behavior suggests that most of the monitored wells do not lie directly on the narrow conduits that transmit most of the flow from the injection site. Instead, the relatively narrow plume of tracer eventually spreads through dispersion and diffusion from the main flow conduit to the surrounding area. Advective flow from the conduits to the surrounding aquifer can be expected during periods of heavy recharge, when the potentiometric troughs associated with preferential flow paths fill and temporarily become potentiometric-surface mounds. One exception to the usual slow arrival of tracer to a monitor well was observed by the rapid arrival of Tracer N to well 58-58-424. This well located about 1 mile from the injection site, appears to be closely connected to a preferential groundwater-flow path from Site N. As seen by the many wells used for monitoring in this study, the probability that any well will directly intercept the conduit of a preferential groundwater-flow path is low. As a result, tracers were rarely visually observed in area wells following injections. The identifications of wells on or very near to preferential groundwater-flow paths is very important, both for mapping the aquifer flow systems and to provide additional protection for this wells that are more sensitive to contamination.

Three preferential groundwater-flow paths were delineated or verified in this study, the Manchaca Flow Route, the Sunset Valley Flow Route, and the Cold Springs Flow Route. The fact that nearly all of the known discharge for the Barton Springs segment occurs at two general sites, Barton and Cold Springs, supports the concept of localized flow along discrete preferential groundwater-flow paths. The convergence of flow along preferential groundwater flow paths are further indicated by repeated tracer detections at specific wells following widely spaced injections. Travel times of tracers (Sites C and H) injected during medium to high groundwater-flow conditions near preferential groundwater-flow paths were greater than 4 miles per day. The location of preferential groundwater-flow paths in the study area were located by tracer detections or non-detections at wells and springs, water-level troughs on detailed potentiometric surface maps and the general location of major fault trends that intersect the discharge spring. The actual location of the preferential groundwater-flow paths can be further verified and adjusted on maps as necessary based on positive recoveries of tracers under differing groundwater-flow conditions at key wells or possibly by examining areas of similar water-quality characteristics. Because of the discrete nature of the flow paths, the key wells must intersect on or be screened very near the major conduit(s) where flow is focused.

The results of this study suggest the presence of at least three groundwater basins, each containing at least one preferential groundwater-flow path that represent the convergence of smaller flow paths (Figure 6.1). The Manchaca groundwater basin is fed by the Recharge Zone portions of the Onion, Bear, Little Bear, and Slaughter Creek watersheds, as demonstrated by Traces J, H, K, P, L, M, N, and O. Within the Slaughter, Bear, Little Bear, and Onion Creek watersheds, groundwater initially crosses fault trends as it moves eastward towards an identified preferential flow path within the artesian zone, known as the Manchaca Flow Route, whose location is based on tracer detections and potentiometric surface troughs. The Manchaca Flow Route appears to be strongly influenced by a line of faulting that generally follows the western edge of the Artesian Zone toward Barton Springs. North of Slaughter Lane, the Manchaca Flow Route is extrapolated to continue following this general line of faulting toward Barton Springs, although well data (water level or tracer) are limited or absent in this area. The Barton Springs Fault appears to serve as a boundary between the Manchaca and Sunset Valley groundwater basins within two miles of Barton Springs. Consequently, a small portion of Barton Creek channel that lies east of the Barton Springs Fault, recharges to the Manchaca groundwater basin, as demonstrated in Trace E. The Manchaca Flow Route has at least three major branches, one fed largely by lower Recharge Zone stretch of Onion Creek watershed, one fed largely by upper Onion Creek watershed, Bear and Little Bear Creek watersheds, and one fed largely by the Slaughter Creek watershed. South of Slaughter Lane, tracer data suggests the Manchaca Flow Route bifurcates into an east and west branch. Tracers injected in widely separated recharge features (Sites L, K, O, and probably P) within the Bear and Little Bear Creek, and upper Onion Creek watersheds were detected at a single well, 58-50-742 on the west branch of the Manchaca Flow Route. Injections at Sites N and M on the lower 2 miles of the recharge portion of Onion Creek both appeared at well 58-50-121 along the east branch of the Manchaca Flow Route. The Manchaca groundwater basin discharges at the Main Barton, Eliza, and Old Mill outlets of Barton Springs. The area of the Manchaca groundwater basin is about 88 square miles in area.

The tracing results of this study provided some new information on the groundwater divide between the Barton Springs and San Antonio segments. During relatively low groundwater-flow conditions, two injection sites (N and O) on Onion Creek were traced directly to Barton Springs and were not detected in San Marcos Springs. Traces M and M' were not detected in either Barton Springs or San Marcos Springs, but were detected in wells north of Onion Creek that were traced by other injections directly to Barton Springs. Tracer M' was also detected in a well over 3 miles southwest of its injection site on Onion Creek. It is possible that under high water-level conditions Onion Creek may contribute to San Marcos Springs in the San Antonio segment, a hypothesis that may be supported by the presence of tracer so far south of Onion Creek. However, no tracer associated with this study injected in the Onion Creek watershed was ever detected at San Marcos Springs possibly because the tracer arrived slowly below the detection limits. However, even if tracers arrived at San Marcos Springs below detection limits, the amount of contributing flow from Onion Creek under the low flow conditions of Tracer O would be relatively insignificant. A maximum of only about 0.3 pounds (about 1% of the injected tracer mass) could be expected to discharge over two months at the combined flow of about 110 to 125 cfs experienced at San Marcos Springs around Tracer O injection. The amount of tracer recovered at Barton Springs within one month following Trace O injection was more than 13 times any tracer that could have potentially arrived at San Marcos Springs below the detection limit over a two-month period. Therefore, these low-groundwater flow condition traces of Onion Creek suggest that significant flow to San Marcos Springs does not occur. Subsequent tracing of Onion Creek by other tracing studies under high groundwater-flow conditions of 2002 similarly demonstrated flow bifurcation from Onion Creek, with the entire amount of recovered tracer detected at Barton Springs and no tracer detection at San Marcos Springs (BS/EACD, 2003).

The fate of bifurcated recharge that flows south from Onion Creek to the Mountain City and Kyle areas may be evident by differences in the initial arrival times and concentrations to the individual Barton Springs. If Main Barton, Eliza, and Old Mill Springs received flow from a common source, such as the Manchaca Flow route, we would expect the concentration of tracer would be well mixed and similar at all three springs and that they would arrive simultaneously. However, tracers injected into the Onion watersheds under low groundwater-flow conditions showed a noticeable delay in its arrival at Eliza and Old Mill following its initial arrival at Main Barton Springs. On

Trace O, injected in upper Onion Creek, the tracer arrived nearly simultaneously at Main Barton and Eliza Springs, but arrived at Old Mill Spring about ten days after its arrival at Main Barton Spring (Appendix A.VI.19). On Trace N injected in Onion Creek, the tracer may have arrived at Eliza Springs one to three days after its initial arrival at Main Barton Springs, but was not detected at Old Mill Springs. One explanation for this delay is that Old Mill Springs receives most of its contributing flow from a subparallel but separate and slower preferential flow route that either joins the Manchaca Flow Route upgradient of the springs or flows independently to Old Mill Springs from the east, perhaps near or adjacent to the Saline-Water Line (Smith, BS/EACD, personal communication, 2002).No such delay was observed in traces injected in the Slaughter Creek watershed under high groundwater-flow conditions (H and J, Appendix A.III.18). However, the concentration of tracer measured in grab samples at Old Mill from Trace J were about one third the concentration measured at Main Barton and Barton Springs, suggesting that Old Mill Springs receives about two thirds of its flow from a separate flow source.

DeCook (1963) produced a potentiometric-surface map for the 1950's that indicated a southeast-flowing trough near the Saline-Water Line in the Buda and Kyle area. Palmer (2002, personal communication) suggested that along the Saline-Water Line, the mixing of sulfate-enriched waters with freshly recharged groundwater could enhance the development of master conduits to create a preferred groundwater flow path. It has been suggested that the Saline-Water Line is fixed in place by faulting along the eastern side of the Barton Springs segment (Slade, Dorsey, and Stewart, 1986). The geologic cross section A-A′ interprets the potential for some lateral flow restrictions due to faulting, in addition to possible lateral restrictions due to vertical clay-rich igneous deposits (see Figure 1.8). However, the other two cross sections presented in this report (See Figures 1.9 and 1.10) do not show lateral geologic restrictions to groundwater flow near the Saline-Water Zone. Regardless of its origin and local fault location, a preferred flow path located on the eastern side of the Barton Springs segment could also serve as a relatively fixed barrier boundary to flow from the Saline Water Zone. If it exists, tracing along a preferred flow path on the eastern side of the Barton Springs segment is a difficult task since there are few wells that have not already been used for mapping potentiometric surfaces and in monitoring for tracers.

It has been suggested (Garza, 1962; Stein, 1994) that under very low groundwater-flow conditions water as far south as the Blanco River could flow north to Barton Springs, although this condition was neither supported nor discounted by the results of this study. Tracer Q was not successfully traced from the Blanco River to any of the monitored sites under low groundwater-flow conditions. An earlier groundwater trace by the EARDC connected the same Blanco River site with San Marcos Springs (see Section 1, Ogden and others, 1986). The groundwater tracing results to date support a groundwater divide separating the Barton Springs and San Antonio segments somewhere between Onion Creek and the Blanco River, such as the location of the surface-water divide (Figure 1.1) which was assumed to correspond to the groundwater divide by Slade and others (1986). Further tracing under varying groundwater-level conditions is needed to delineate this divide.

The Sunset Valley groundwater basin is fed by the Recharge Zone portion of the Barton Creek watershed downstream of Loop 360 and the lower Recharge Zone portion of the in the Williamson Creek watershed downstream of Brush Country. Under high groundwater-flow conditions or after heavy rain events, some groundwater recharging within the Slaughter Creek watershed may leak into the Sunset Valley groundwater basin, as indicated by trace H. This groundwater basin is about 11.7 square miles in size. Traces C and D demonstrated groundwater flow within this basin. The Sunset Valley Flow Route is believed to represent the convergence of flow paths within this groundwater basin. This flow path is delineated by tracer detections in wells within the Sunset Valley area, by tracer discharge at Upper and Main Barton Springs, by a deep potentiometric trough measured near Loop 360, and by the trend of the Barton Springs Fault. The Sunset Valley groundwater basin discharges primarily to Upper and Main Barton Springs during moderate and high groundwater-flow conditions, although additional discharge springs from this basin can be present in Barton Creek almost as far upstream as Loop 360. During low-groundwater flow conditions, the overflow Upper

Barton Springs dries, and discharge from the Sunset Valley groundwater basin is limited to Main Barton Springs.

The Cold Spring groundwater basin was determined by the traces performed in this study to be about 11.8 square miles in size. Previous studies suggested Cold Springs probably received some recharge from the upper part of the Recharge Zone in Barton Creek (Senger and Kreitler, 1984, Slade, Dorsey, and Stewart, 1986). Its main recharge area was previously assumed to be primarily limited to the Eanes Creek watershed. Tracers injected at Sites A, B, and G, all upstream of Loop 360 discharged from Cold Springs and not from Barton Springs under low groundwater-flow conditions. A repeat trace at Site A (Trace A′) under very high groundwater-flow conditions also discharged from Cold Springs and not from Barton Springs. This indicates that at least half of the 7 miles of Barton Creek that lies in the Recharge Zone supplies groundwater to Cold Springs. The Barton Creek watershed source area to Cold Springs encompasses 9 square miles of Recharge Zone and 107 square miles of Contributing Zone. Barton Creek flow that does not recharge upstream of Loop 360 can potentially recharge in lower Barton Creek and contribute to the flow of Barton Springs. The trace at Site F discharged from Cold Springs, indicating that the 6.7 square mile watershed area of Williamson Creek upstream of Site F contributes some recharge to Cold Springs along a 1.5 mile long section of creek bottom on the Recharge Zone. Williamson Creek flow that does not recharge upstream of Brush Country Boulevard contributes recharge to Barton Springs. Additional studies are needed to re-examine the recharge volumes previously estimated for individual watersheds (Slade, Dorsey, and Stewart, 1986; Woodruff, 1984a). Trace B did not appear to converge on the Cold Springs Flow Route, but appeared to follow an independent path to the Colorado River near Cold Springs.

The tracing results may also help evaluate the suitability of the injection sites for potential recharge enhancement or aquifer storage and recovery (ASR) projects. Recharge enhancement can serve to replenish aquifer drinking water supplies, to help maintain flow at Barton Springs during drought, and to buffer the downstream effects of flooding. Preferred sites for recharge enhancement would show a slow and well distributed tracer recovery, so that the benefits of recharge are not immediately expended at the discharge springs. Other factors to consider in the selection of recharge enhancement sites include the quality of source water, the size of the drainage basin contributing to the recharge site, the recharge capacity of the potential enhancement site, and the potential downstream surface water or downgradient groundwater benefits. It is important to note when examining tracing results for consideration of potential recharge enhancement sites, that the downgradient groundwater benefits are not limited to the narrow line of the tracer path from a recharge site. As recharge joins the water table, a pressure pulse is distributed within the aquifer to areas of lower potentiometric elevation that are hydraulically connected to the recharge site. In some areas, aquifer storage and recovery is used to pump and store injected treated water into an aquifer so that it can be recovered at a later time through the same well. As a general finding, the tracing results indicate little opportunity for the success of aquifer storage and recovery in the freshwater portion of this aquifer system, because the recharge waters generally do not remain in the same location for long periods of time where the stored water can be pumped out by the injection well. Recharge enhancement differs from ASR in that the water is stored within the whole aquifer. The tracing results suggest some portion of recharge water will discharge rapidly from the aquifer. Most of the tracer mass was never recovered due to factors such as long-term storage in the aquifer, the properties of the tracer, and sorption. Therefore, without further analysis, the results of this study may not provide much insight on how long additionally recharged water would be stored to benefit the aquifer in times of drought. The results do provide insight on the fate of recharge from specific features where tracers were injected.

The response of the tracers can be used to help predict the effects of an accidental spill of hazardous materials. Previous studies have shown that the rapid arrival of recently recharged water creates marked changes in the water quality of Barton Springs. Changes in specific conductance, turbidity, temperature, and bacteria concentrations at Barton Springs suggest an average initial arrival of a large volume of recently recharged water occurs as soon as 6 hours, but averages about 14 hours after major rain events (City of Austin, 1997). In this study, Tracers C and H showed a rapid arrival at Barton Springs, where the highest concentrations discharged within 6 days. Very low concentrations, in the part-per-trillion ranges, persisted for the remaining duration of the 3-month monitoring period (see Appendices A.II.1 and A.III.1). The relatively rapid movement of groundwater measured by the tracers under any flow conditions provides little time for mitigation efforts to reduce potential damage from a hazardous material release to groundwater supplies or spring and surface-water ecosystems. The rapid travel times also demonstrate conduit flow conditions where advective flow is relatively important compared to other non-karstic aquifer systems. The breakthrough curves for the traces also demonstrate some of the difficulties that could occur in monitoring for the release of a hazardous material. A large pulse of contaminants could move rapidly through the system, leaving a residual concentration that could be present below analytical detection limits for grab samples. The actual response of a hazardous material will depend on other factors such as the volume of material introduced and the adsorptive and dispersive characteristics of its constituents. Also, greater mass of material will tend to show a higher recovery once the buffering capacities of the soil and rock are surpassed. Furthermore, the sorbed material may act as a source of contamination if desorption occurs. As a result, contamination from a large single source may persist longer in the aquifer than would a tracer of smaller mass from the same site. As an example, beneath one above-ground storage tank release site (TCEQ LPST 104820) on the western side of the study area, gasoline contamination within the underlying groundwater has declined an order of magnitude, but is still measurable 8 years after the spill.

Of the 20 tracer injections, the percent of tracer recovered averaged 16%. The recoveries indicate that on most traces, the majority of the tracer mass is attenuated along its flow path to the springs. Figure 5.1 correlates the percent of recovered tracer to the distance between the injection point and the discharge site along the estimated flow path.
If aquifer processes acted to attenuate constituents as they are transported, it would be expected that recovery would decrease with distance from the injection site. Instead, the recovery shows a poor correlation to transport distance. One explanation for the lack of correlation between recovery and the total length of the flow path is that the observed attenuation may be limited to the fill material in the sinkhole entrance and that once

inside the aquifer, the processes that typically reduce constituent concentrations in diffuse-flow aquifers and surface-water systems, such as absorption, adsorption, dispersion, diffusion, biological update, and decay, may not be as significant within this aquifer system (Glenrose Engineering, 2000). The dispersive properties of the tracers themselves, the mass of tracers used, and sediment fill at the entrance of the injection site may represent a significant factor in tracer recovery. However it is also true that larger masses of tracer were generally used for injection sites farther away.

Figure 5.2 correlates the recovery to the ratio of effective tracer mass injected to the distance to the discharge spring. The "effective" tracer mass is the same as the injected tracer mass, except for rhodamine WT, of which only half of the injected mass is considered effective due to properties described in Section 3.1.

In general, the more mass of tracer for the same flow path length led to higher percent recoveries. The two highest recoveries were limited to traces within the Cold Springs groundwater basin.

The recovery of 12 traces was about 1% or less. These traces were largely limited by tracer design and may not be representative of aquifer recoveries under normal conditions. The inhibiting factors include:

1) The discharge spring was not identified and monitored, and instead the diluted tracer was recovered downstream (Trace B).
2) Low groundwater flow conditions may have led to poor hydrogeologic connection (Traces I, K, L, M, N, Q, P).
3) Insufficient sampling frequency may have reduced recovery of peak concentrations (possible for most traces).
4) Fine-grained sediment near the entrance may have adsorbed significant amounts of dye sites (Traces A, A", B, C, E, G, K, P, M, N, and O).
5) Under- or overestimation of discharge spring flows.

Five of the traces plot along a general trend that may represent traces relatively uninhibited by tracer design (other than injected tracer mass) and sediment blockage. Ozark Underground Laboratories reported that traces in other karst areas generally found that for each doubling of tracer injection masses, the recovery increased four times. The trend indicated by the five "uninhibited" points agree well with these OUL observations from other areas.

Figure 5.1 Comparison of Percent Recovery to Distance Traced

**FIGURE 5.2 CORRELATION OF PERCENT RECOVERY TO TRACER MASS/DISTANCE RATIO**

## 6.0 CONCLUSIONS

This study utilized the injection of five generally distinguishable organic dyes, fluorescein, rhodamine WT, eosine, sulforhodamine B, and pyranine, to directly measure groundwater flow routes, velocities, and other groundwater characteristics. The tracers were poured directly into natural caves, sinkholes, and creek swallets, as well as one well. Possible discharge sites and many wells were monitored with charcoal receptors and grab samples for the presence of the dye tracers. Twenty traces at 18 sites were conducted within the study area that includes the Barton Springs segment of the Edwards Aquifer and the Blanco River. Of these 20 traces, 17 (85%) were detected at a monitored site, which exceeds the data quality objective of 80%.

Groundwater recharging in the Barton and Williamson Creek watersheds follows general fault trends to the northeast to discharge from Barton Springs, Cold Springs, Bee Springs and possibly other springs discharging directly to the Colorado River. The Cold Springs groundwater basin of the Barton Springs segment is about 11.8 square miles and is shown in Figure 6.1. In general, groundwater flow within the Cold Springs groundwater basin converges with the Cold Springs Flow Route. Some groundwater included within this groundwater basin may also discharge at Bee Springs, Rollingwood Springs, and unidentified springs discharging to the Colorado River.

The recharge areas of the Barton and Williamson Creek watersheds that do not contribute groundwater flow to Cold Springs *generally* contribute recharge to the Upper and Main Barton Springs outlets of Barton Springs, along with other periodic spring sites further upstream of Barton Creek. This source area is defined as the Sunset Valley groundwater basin of the Barton Springs segment, and its recharge area is believed to generally include recharge areas of the Kitcheon Branch of Williamson Creek, the main branch of Williamson Creek below Mopac Expressway, and Barton Creek below Loop 360. The area of the groundwater basin that supplies Upper Barton Springs and a part of the Main Barton Springs is about 11.7 square miles in size. Water recharging in this area is believed to converge in the Sunset Valley Flow Route during high and moderate groundwater-flow conditions. As an overflow spring, Upper Barton Springs ceases to

Figure 6.1 Summary Map of Groundwater Trace Injections (1996-2000) flow during low groundwater-flow conditions, when the combined flow of Main, Eliza, and Old Mill Springs declines below 40 cfs. It appears that during low groundwater-flow conditions, groundwater from the Sunset Valley groundwater basin discharges entirely at the Main Barton Springs outlet. The Barton Springs Fault appears to both influence the transmission of rapidly-flowing groundwater along the Sunset Valley flow route and serves as a barrier separating the Sunset Valley and Manchaca groundwater basins within the vicinity of Barton Springs. Within the southern portion of the Sunset Valley groundwater basin, the divide may need further definition or may change under differing water-level conditions.

The primary source area for Main, Eliza, and Old Mill outlets for Barton Springs includes the Recharge Zone of the Slaughter, Bear, Little Bear, and Onion Creek watersheds. Within the Manchaca groundwater basin, groundwater generally flows east to converge with fault-controlled, northeast trending preferential flow paths. A number of preferential flow path tributaries converge near Slaughter Lane and Manchaca Road to form the Manchaca Flow Route, which is expressed as a potentiometric trough that parallels the east side of Manchaca Road toward Barton Springs. Observations from Blowing Sink Cave suggest that after major flooding events, groundwater may cross the divide between the Sunset Valley and Manchaca groundwater basins and flow directly toward Upper and Main Barton Springs. Water recharging Onion Creek moves northeast in the general direction of local major faults.

The tracing conducted near the southern groundwater divide under low groundwater-flow conditions did not contradict the divide location between Onion Creek and the Blanco River estimated by Slade (and others, 1986). The tracers injected at three sites (M, N, and O) on Onion Creek were detected at Barton Springs or wells north of Onion Creek that were traced to Barton Springs; however, most were conducted under moderate and low groundwater-flow conditions. These three Onion Creek traces were not detected at San Marcos Springs or at municipal wells for the City of Kyle. The southern divide for the Barton Springs segment could potentially move under different flow conditions and in response to pumping (DeCook, 1963; Stein, 1994). A tracer injected on the Blanco River during low groundwater-flow conditions was not detected at Barton or San Marcos Springs after more than a year of monitoring. A previous trace conducted by a previous study at the same site suggested that the tracer may have arrived at San Marcos Springs a year later, although this connection could not be verified in this study.

Groundwater-flow rates were determined on 14 of the traces where sufficient samples were collected. The groundwater flow velocities were more rapid near preferential groundwater-flow paths and under moderate to high groundwater-flow conditions. Some portion of recharged groundwater travels by advection along the three major groundwater flow routes at velocities over 4 miles per day during moderate to high groundwater-flow conditions and at velocities of about 1 mile per day from the western side of the Recharge Zone to the flow routes, as seen in traces A′, C, H, and J. During low groundwater flow condition, groundwater travels through the major flow routes at velocities of only about 0.6 to 1 mile per day, as seen in traces A, B, G, L, N, O, and P. Tracers K, I, M, R, and Q were all performed during low groundwater-flow conditions and were not recovered at the discharge spring, although the tracers were recovered in local wells for traces K and M. The difference in first arrival flow velocities between high and low groundwater-flow conditions was measured at Site A, where rates of 0.6 miles per day were measured under drought conditions of 1996 and five miles per day under high groundwater-flow conditions of 1997. Other portions of groundwater remain in storage within the aquifer for a longer residence period.

Calculated tracer recoveries from discharge sites varied from 0% to about 77%, with an average recovery of 16% and a median recovery of about 4%. No recovery was made from three traces (I, R, and Q), each conducted under low groundwater-flow conditions. The groundwater velocities and recoveries reported in this study will, more likely than not, underestimate the actual groundwater values due to sorption and other tracer properties, the tortuosity of the actual flow paths, the frequency of sampling, the relatively small mass of tracer used (two to 25 pounds), and the lower than average groundwater-flow conditions under which most traces were conducted. Higher recoveries can be expected in traces using higher tracer masses. This study examined the travel velocities and tracer recoveries specifically at recharge features and not from random sites in between. Recharge features, like the ones selected for tracer injections, are relatively common across the Recharge Zone, but can be expected to have faster travel times and higher recoveries than infiltration sites where conduits are poorly expressed or absent and thick soils are present.

This study provides perhaps the first direct measurements of groundwater flow within the Barton Springs segment of the Edwards Aquifer. These results will help anticipate the fate of small volume hazardous material spills on the Recharge Zone, assist in locating sites for groundwater monitoring, prioritize aquifer sensitivity, and evaluate the effects of recharge enhancement or aquifer storage and recovery. This study has examined the component of discrete flow through the aquifer and has located the major preferential groundwater flow routes.

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## 8.0 LIST OFAPPENDICES

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