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Documentation of a recharge-discharge water budget and main streambed recharge volumes, and fundamental evaluation of groundwater tracer studies for the Barton Springs segment of the Edwards Aquifer

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Abstract: Data and information reveal that the Edwards Aquifer between Lady Bird Lake (the Colorado River) in Austin, Texas and the "groundwater divide" near Kyle, Texas discharges to 2 major springs: Barton Springs and Cold and Deep Eddy Springs. The long-term mean discharges for the springs are 51 cubic feet per second and 5.5 cubic feet per second, respectively. The source for Cold and Deep Eddy Springs probably represents Dry Creek in the Rollingwood, Texas area and a small amount of recharge water from Barton Creek.

Additional springflow, which periodically discharges from the lower reach of Barton Creek immediately upstream from Barton Springs, varies from zero when Barton Springs is flowing about 50 cubic feet per second to about 5 cubic feet per second during extreme high-flow conditions at Barton Springs. Two streamflow gain-loss studies on the Colorado River document any other discharges from the Edwards Aquifer to the Colorado River to be nonexistent or minor.

A recharge-discharge water budget for a 32-month period reveals that the total discharge from Barton Springs, Cold and Deep Eddy Springs, the lower reach of Barton Creek, and groundwater pumpage is about 3% less than the surface recharge—a value within the potential error of the measurements. Additionally, for the budget period, recharge within the main channels of the 6 major streams crossing the recharge area account for a minimum of 75% of total recharge. Therefore, long-term recharge within the recharge area from overland flow or tributaries to the main channels represents a maximum of 25% of total recharge, a value equivalent to a mean depth of 2.1 inches per year over the 90-square-mile recharge area, or no more than 6.6% of the long-term mean precipitation of 32 inches per year over the recharge area.

Keywords: Edwards Aquifer, Barton Springs, water budget

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Terms used in paper

Short name or acronym	Descriptive name
BSEACD	Barton Springs/Edwards Aquifer Conservation District
TBWE	Texas Board of Water Engineers
USGS	U.S. Geological Survey

INTRODUCTION

Barton Springs discharges a relatively hydrologically distinct part of the Edwards Aquifer, commonly referred to as the Barton Springs segment of the Edwards Aquifer. The boundaries for this part of the aquifer are presented in Figure 1. The recharge area for the aquifer is composed mostly of the outcrop of rocks that form the aquifer. The western boundary for the aquifer coincides with the western boundary of the recharge area.

All of the 6 major creeks that cross the recharge area have basins that extend upstream (west) of the aquifer. Figure 1 identifies the contributing area, which covers 264 square miles—about 3 times larger than the 90-square-mile recharge area.

By 1979, streamflow gaging stations were installed and operated by the U.S. Geological Survey (USGS) near the upstream and downstream boundaries of the recharge area on 5 of the 6 streams, so that runoff and recharge volumes could be calculated. Because of the relatively small contributing area for Little Bear Creek, a streamflow station was not installed at the upstream boundary of its recharge area. Recharge volumes are calculated as explained by Slade et al. (1986). Although the recharge calculations account for total recharge within the recharge area, they cannot distinguish among the individual components of recharge that occur in each of the 3 source areas of recharge: the main channels of the 6 major streams; the channels of tributaries to the main streambeds; and the overland flow area within the recharge area. Except during extreme dry conditions, subsurface recharge and discharge to the aquifer are believed to be minimal (Slade et al. 1986).

By 1979, 12 precipitation gages were installed within the 6 basins. The distribution of precipitation measured with these gages has been used to construct a water budget that documents the fate of precipitation on the recharge and contributing areas: in other words, the amounts of recharge, runoff, and evapotranspiration (Woodruff 1984; Slade et al. 1986). The budget indicates that recharge represented 6% of precipitation; runoff represented 9% of precipitation; and evapotranspiration represented 85% of precipitation.

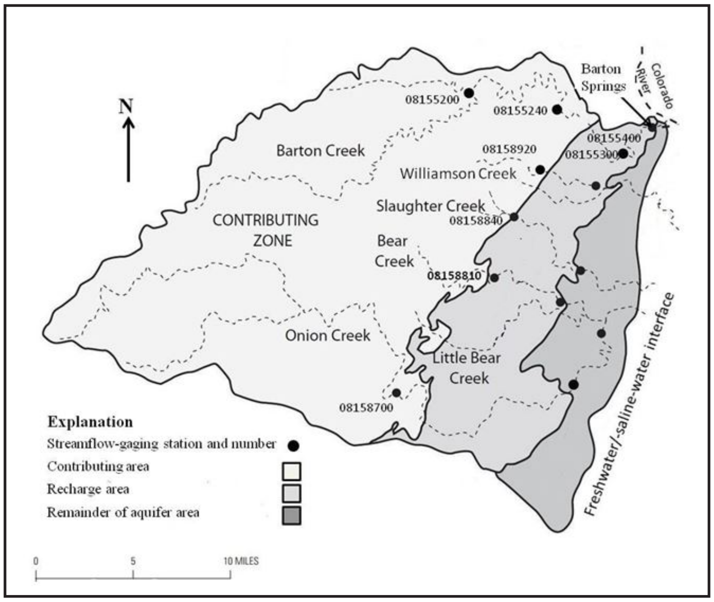

Figure 1. Boundaries for the aquifer, recharge area, and contributing area and locations of streamflow gaging stations.

PURPOSE OF REPORT

The purpose of this report is to refine the components of a recharge-discharge water budget for the Barton Spring segment of the Edwards Aquifer reported by Slade (1986) and to quantify the recharge that occurs in the main channels of the 6 major streams that cross the recharge area, as well as the recharge that occurs within the recharge area but outside the main channels. A secondary purpose is to provide a fundamental analysis of groundwater tracer studies that have been conducted in the aquifer.

LONG-TERM MEAN DISCHARGE FROM BARTON SPRINGS

The USGS has measured the discharge of Barton Springs since 1894. Beginning in 1917, more frequent measurements of springflow have been made. In 1978, a springflow gaging station was installed at the springs, providing daily-mean springflow values since then. The measurements and gaged springflow for Barton Springs include 3 major springs, 1 of which discharges into the swimming pool. The other 2 springs, locally named Concession (Eliza) Springs and Old Mill Springs, discharge into Barton Creek immediately downstream from the pool.

The monthly-mean and annual-mean discharge values for Barton Springs for 1917–1982 were estimated based on 725 discharge measurements made during 1917–1978, and daily-mean discharge gaged during 1979–1982 (Slade et al. 1986). Precipitation records for the city of Austin, published by the National Weather Service, were used to estimate springflow values for the intervals of missing measurements between 1917 and 82. Considering the reconstructed record of monthly-mean springflow during 1917–82, the mean and median values of Barton Springs discharge is 50 cubic feet per second and 46 cubic feet per second, respectively. The maximum and minimum measured discharges are 166 cubic feet per second and 10 cubic feet per second, respectively. Pumpage from the aquifer has been inventoried by the Texas Water Development Board and the Barton Springs/Edwards Aquifer Conservation District (BSEACD). For the 1917–1982 period, the mean rate of pumpage from the aquifer was about 0.8 cubic feet per second (Kent Butler, University of Texas School of Architecture, written communications 2010), thus the long-term mean discharge (springflow and pumpage) for Barton Springs is about 51 cubic feet per second. Additionally, the author and BSEACD (written communications 2013) believe that all pumpage from the aquifer represents an equal rate of reduced springflow because no evidence exists that pumpage volumes are returned to the aquifer. Additionally, other than the lowest reach of Barton Creek, the unsaturated zone of the aquifer exceeds 100 feet, and no evidence exists that reduced groundwater levels due to pumpage have caused increased recharge to the aquifer.

RECHARGE-DISCHARGE WATER BUDGET

Explanations for a 32-month recharge-discharge budget (December 1979–July 1982) were presented by Slade et al. (1986). The assumptions and qualifications for the calculation of the budget are presented on pages 43-73 in that report. Because the springflow and groundwater levels were comparable for the beginning and end of the December 1979 to July 1982 period, overall changes in aquifer storage are assumed insignificant. Whereas the budget's elements of discharge represent Barton Springs discharge, pumpage, and an estimate of the discharge for Cold and Deep Eddy Springs, recharge represents that calculated from the 6 major streams discussed above.

Of note is the fact that the water budget is characterized by 12% more surface recharge than surface discharge (Slade et al. 1986). Several explanations are presented for the discharge deficit, including the possibility that part of the recharge in Barton Creek could discharge to Cold and Deep Eddy Springs. Subsequent groundwater dye studies, explained later in this report, verify that part of the water that recharges in Barton Creek discharges from Cold and Deep Eddy Springs (Figure 2). Additionally, when groundwater levels are sufficiently high, several intermittent springs discharge from the streambed in the lower reach of Barton Creek immediately upstream from Barton Springs.

The following information and data are analyzed and used as basis for a revision in the original water budget.

Cold and Deep Eddy Springs

The location of Cold and Deep Eddy Springs is presented in Figure 2. A search of historical data for these springs reveals only 11 discharge measurements. However, part of the springflow now discharges below the level of Town Lake (now known as Lady Bird Lake), built in 1960 (Brune 1975). The measured springflow ranges from zero (during a severe drought in 1955) to a maximum of 8.2 cubic feet per second, and the mean discharge is 4.8 cubic feet per second (Table 1). The mean value is based on all but 2 measurements made before 1960, and the 1997 and 2008 measurements.

The 1914 measurement was excluded from the calculation of mean discharge because the discharge for Barton Springs was unknown for that date, and the 1955 springflow measurement of zero was excluded because it was made during a severe drought. The 1997 and 2008 measurements were included in the calculation of the mean discharge because the lake was lowered during the measurements, thus these measurements represent total springflow. It is believed that the 1972, 1979, and 1999 measurements were made when at least some of the springflow was below the lake level, thus not included in the measured discharges.

The discharge was estimated at Barton Springs for the same dates as the measurements of discharge from Cold and Deep Eddy Springs (Table 1). The mean discharge of Barton Springs for the 6 measurements used to calculate the mean discharge for Cold and Deep Eddy Springs is 45 cubic feet per second, which is 88% of Barton Springs' long-term mean springflow of 51 cubic feet per second. The assumption was made that the mean discharge for the 6 measurements of Cold and Deep Eddy Springs (4.8 cubic feet per second) also is 88% of its long-term mean discharge. Based on this assumption, the long-term mean discharge for Cold and Deep Eddy Springs is estimated to be 5.5 cubic feet per second.

Evidence that recharge in Barton Creek is conveyed to Cold and Deep Eddy Springs is presented by Slade et al. (1986). Periodically, Barton Springs pool was partially drained so that the pool walls could be cleaned. A roughly 4-foot drop

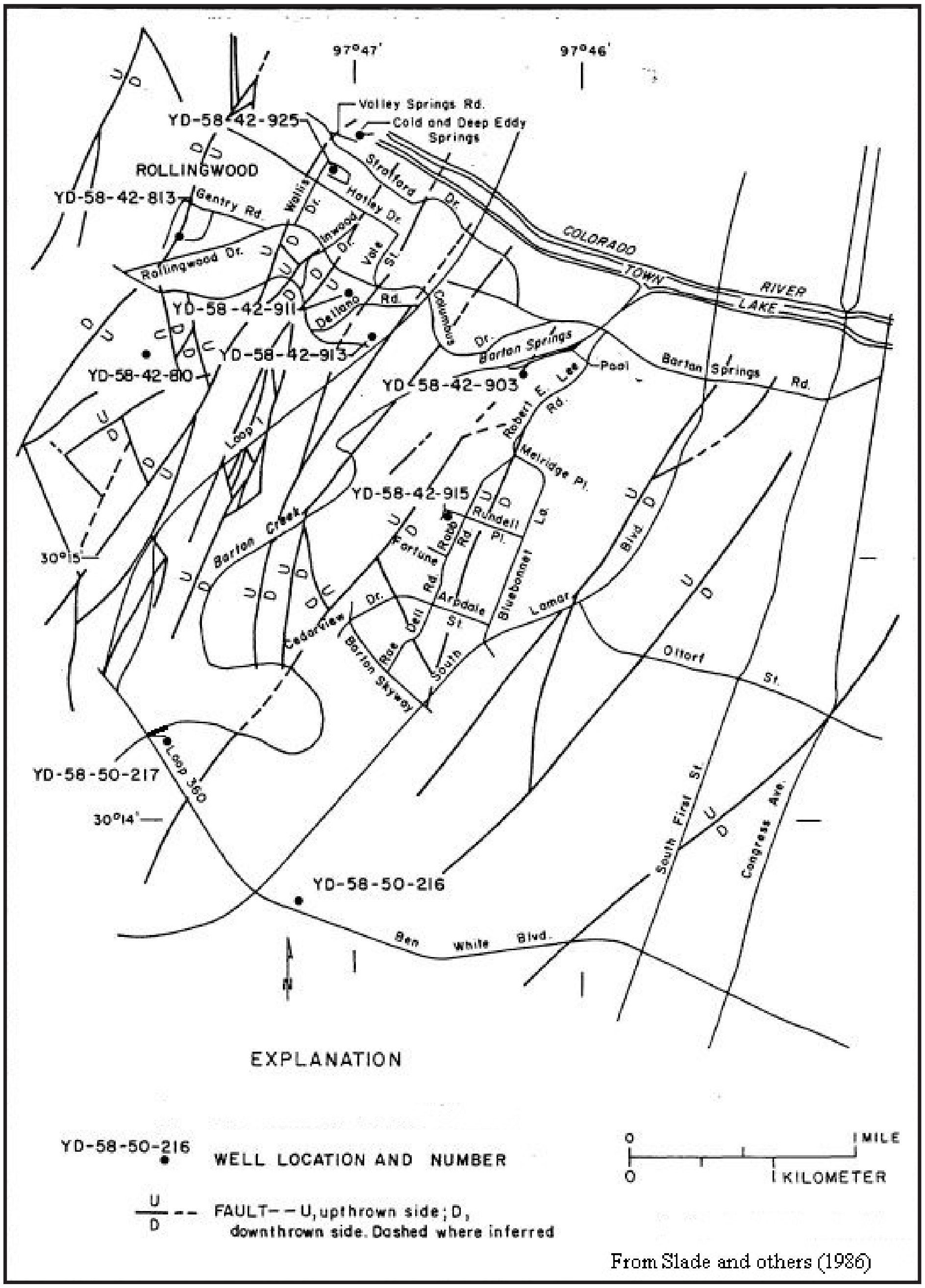

Figure 2. Mapped fault traces proximate to Barton Springs and Cold and Deep Eddy Springs.

Table 1. Discharge measurements for Cold and Deep Eddy Springs.

Date	Cold and Deep Eddy	Barton Springs
	Discharge	Discharge
	(cubic feet per second)	(cubic feet per second)
Aug. ?, 1914 [1]	4.2	unknown
Aug. ?, 1916 [2]	**3 to 4**	**31**
Aug. ?, 1917 [3]	**4.2**	**15**
Aug. 10, 1918 [4]	**3.7**	**14.3**
Feb. 8, 1941 [3,5]	**3.0**	**61**
1955 [3,6]	0	17
May ?, 1972 [3]	2.9	84
Dec. 19, 1979 [6]	2.6	46
Nov. 4, 1997 [7,8]	**6.4**	**84**
Oct. 18, 1999 [7]	4.8	33
Jan. 29, 2008 [7]	**8.2**	**66**
Mean value	**4.8**	**45**
Note: Only measurements in bold used for calculation of mean value. Part of flow for other measurements likely below lake level and thus not included in mean value.		
[1] Brune and Duffin 1983.		
[2] Source unknown		
[3] Brune 1975.		
[4] TBWE 1960.		
[5] TBWE 1959.		
[6] Mike Dorsey, U.S. Geological Survey, personal communications.		
[7] David Johns, Watershed Management Dept., City of Austin, personal communications.		
[8] 4.5 cubic feet per second directly measured and 1.9 cubic feet per second estimated.		

in the pool water level generally occurred during such times. Measurements confirm that water levels in each of the 3 wells south of the pool also decline during such times, thus indicating hydrologic communication among these wells and Barton Springs. However, none of the 4 wells west of Barton Creek (Figure 2) displayed a decline in water levels during such periods. Considering the likelihood that dissolution cavities have developed along the fault traces from Barton Creek to Cold and Deep Eddy Springs, the permeability associated with such cavities likely conveys water from Barton Creek to Cold and Deep Eddy Springs. In contrast, vertical displacement along these same faults probably create barriers to groundwater flow perpendicular to the faults: in other words, groundwater that might otherwise move to Barton Springs from areas immediately west likely is routed to Cold and Deep Eddy Springs.

The February 8, 1941 measurement of 3.0 cubic feet per second at Cold and Deep Eddy Springs (Table 1) was made during relatively high-flow conditions for Barton Creek immediately upstream from Barton Springs—probably about 100 cubic feet per second (TBWE 1959). The limited discharge from Cold and Deep Eddy Springs even during high-flow conditions for its source (Barton Creek), likely indicates that the discharge from Cold and Deep Eddy Springs is limited for most if not all flow conditions.

Groundwater dye tracing studies as indicators of flow to Cold and Deep Eddy Springs

The BSEACD and city of Austin (Hauwert et al. 2004) have conducted dye tracer studies to identify flow paths and travel times within the aquifer. A summary of the results are presented in Table 2, on pages 43-45 in the report. They report that dye was detected at Cold and Deep Eddy Springs after dye injections at Barton Creek at Loop 360 (Figure 2; Hauwert et al. 2004), and at Mopac bridge (Hauwert et al. 2004), about 2,000 feet west of the Loop 360 bridge. The same report indicates that an unknown volume of dye was detected at Cold and Deep Eddy Springs following a dye injection in a well in the Williamson Creek Basin (site F). However, during that injection Barton Springs was discharging 110 cubic feet per second (Hauwert et al. 2004), representing extreme high-flow conditions. Therefore, it is possible that the dye was routed during this injection to Cold and Deep Eddy rather than to Barton Springs because the groundwater conduits between Barton Creek and Barton Springs were at or near full capacity. Also, during this injection, groundwater levels were extremely high adjacent to Barton Springs, which might have caused the dye to move to Cold and Deep Eddy Springs rather than to Barton Springs.

Additionally, the path and travel time for off-stream sites might not be the same as the path and travel time in the streambeds where most recharge occurs. For example, Hauwert et al. (2004) report that dye injections at 2 other sites in the Williamson Creek Basin (both in streambeds) were detected at Barton Springs rather than Cold and Deep Eddy Springs (sites C and D). One of the stream channel injection sites (site D) is only about three-quarters of a mile from the well that transmitted dye to Cold and Deep Eddy Springs (Hauwert et al. 2004). Finally, review of mapped faults in the area reveal that a major fault extending south from Cold and Deep Eddy Springs passes through the area along Barton Creek between Loop 360 and Mopac bridge and is proximate to the well in the Williamson Creek Basin (Slade et al. 1986). However, the well is not a recharge source for the Williamson Creek Basin, and no evidence was found that recharge in the Williamson Creek Basin discharges to Cold and Deep Eddy Springs.

Regardless, the long-term mean discharge for Cold and Deep Eddy Springs is limited to only about 5.5 cubic feet per second, thus the source recharge area for these springs likely is confined to Dry Creek, a watershed of about 4 square miles in the Rollingwood area (Figure 2), and a limited reach of Barton Creek under at least most flow conditions.

Discharge from intermittent springs in the lower reach of Barton Creek

When groundwater levels are sufficiently high, the top of the saturated zone is at or above the bottom of the creek bed for a reach of Barton Creek immediately upstream from Barton Springs. Under such relatively high-flow conditions, the stream reach discharges water from the aquifer. These discharges are believed to be limited to the stream reach between Loop 360 and Barton Springs (Figure 2). Additionally, a streamflow gain-loss study conducted during high-flow conditions by the USGS in 1980 indicate that the upstream end of the streamflow gain-reach in Barton Creek is immediately downstream from Loop 360 (Slade et al. 1986).

The streamflow gaging station on Barton Creek at Loop 360 (station number 08155300) was installed in 1977. Beginning about October 1, 1998, a streamflow station was installed on Barton Creek immediately upstream from Barton Springs (station number 08155400) at the downstream end of the recharge reach for the creek and immediately upstream from Barton Springs (Figure 1). For selected periods, streamflow values for the upstream station were subtracted from same-date streamflow values for the downstream station, to calculate the contribution of springflow from the intervening length of streambed. The selected periods represent relatively steady-flow conditions and represent extended durations after runoff-producing precipitation. Such periods were selected with the expectation that additional inflow due to the effects of local runoff, bank storage, and perched groundwater would be nonexistent or minimal. Additionally, to minimize the potential error in the calculated springflow values, only periods representing no flow or very low flow at the Loop 360 station were used in the analyses.

The discharge from Barton Springs is highly and directly correlated with adjacent groundwater levels, especially for wells proximate to the springs (Slade et al. 1986). The data for the 628 days that were selected for analyses within the common 14-year period for the 2 stations represent many periods and long durations.

Figure 3 presents the relation between the springflow from the Barton Creek main channel for the selected dates and the same-date discharge from Barton Springs. The linear equation for the best-fit line from the graph was used to calculate, based on Barton Springs discharge, the contribution of springflow discharging from the Barton Creek main channel for each day in the 32-month water budget.

Other springflow from the aquifer

It has been reported that discharge from the aquifer might occur as springflow along the southern bank of the Colorado River. The Colorado River Valley cuts through much of the Edwards Aquifer, thus it is possible that discharge from the aquifer could discharge to the river in this area.

Such discharge would be difficult if not impossible to ascertain since 1960, when Longhorn Dam was built, which created Lady Bird Lake that inundates much of the river bank. The city of Austin reported that dye from some of its dye studies have been visible in the lake from sources other than Cold and Deep Eddy and Barton Springs, thus indicating that other springs likely discharge from the Edwards Aquifer south of the lake (David Johns, city of Austin, written communications 2013).

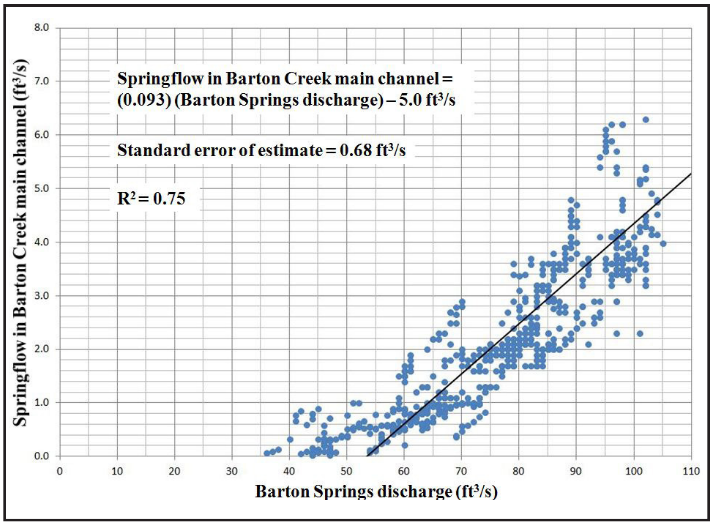

Figure 3. Relation between springflow contribution from the Barton Creek main channel and Barton Springs discharge.

However, the source and discharge for any such springs are unknown.

Prior to the construction of Longhorn Dam, a streamflow gain-loss study was conducted on August 10, 1918 along the Colorado River that included streamflow measurements made immediately upstream and downstream from the river's contact with the Edwards Aquifer. In addition to indicating that 3.7 cubic feet per second discharged from Cold and Deep Eddy Springs (Table 1) and 14.3 cubic feet per second from Barton Creek, these data indicate only 0.4 cubic feet per second of remaining streamflow gain along the reach from Tom Miller Dam (near the western contact of the river and the Edwards Aquifer) to Congress Avenue (about a mile east of the eastern contact between the river and the Edwards Aquifer (TBWE 1960). It is possible that most or all of the 0.4 cubic feet per second gain resulted from groundwater discharge through terrace deposits along the river, from groundwater discharge from the north side of the river, or from surficial runoff outside the Edwards Aquifer. It is also possible that no streamflow gain occurred due to potential error in the streamflow measurements. However, even if the entire 0.4 cubic feet per second represents discharge from the Edwards south of the river, such flow is minor compared to the known springflow discharges and, therefore, deemed too small to appreciably affect the water budget.

Additionally, the results of a streamflow gain-loss study on the Colorado River in 1925 (TBWE 1960) confirm that any other discharges from the Edwards Aquifer to the Colorado River to be nonexistent or insignificant compared to the discharge from Barton Springs and Cold and Deep Eddy Springs.

CALCULATED WATER BUDGET

The 32-month water budget (December 1979–July 1982) as published by Slade et al. (1986) indicates 144,000 acre-feet of surface recharge. During the period, Barton Springs discharged 114,000 acre-feet and pumpage was 10,100 acre-feet (based on 3,800 acre-feet per year (Slade et al. 1986). However, during this period, the mean flow from Barton Springs was 64 cubic feet per second (59 cubic feet per second from Barton Springs and 5 cubic feet per second of pumpage), which is 25% greater than its long-term mean springflow of 51 cubic feet per second. Therefore, the mean springflow from Cold and Deep Eddy (5.5 cubic feet per second) was increased by 25% to account for this springflow during the budget period. This accounts for 6.9 cubic feet per second or 13,300 acre-feet of water from Cold and Deep Eddy Springs during the 32-month period. Additionally, because the component of springflow that occurs in the Barton Creek streambed represents about 1.0 cubic feet per second (1,900 acre-feet during the 32-month period), the total discharge is 139,300 acre-feet—a value about 3.3% less than the recharge. For the budget, the potential error is about 6% for the discharge value and about 8% for the recharge value.

The percentage difference between recharge and discharge for the budget is less than the potential error for each of the 2 components, thus the discharge sources identified in the budget calculations are assumed to represent the vast majority of, if not all, stream recharge. Based on the small percentage difference by which recharge exceeds discharge, the discharge rate for any springflow sources not identified in these analyses would be minor compared to those for the identified sources.

During dry periods, a relatively small amount of subsurface recharge enters the Barton Springs segment of the Edwards Aquifer south from an area underlying the southern groundwater divide (Slade et al. 1986). Such inflow is considered insignificant for all but the driest conditions with respect to the 32-month budget period discussed above. The BSEACD has conducted several dye studies to qualify subsurface water movement into and from the Barton Springs segment of the Edwards Aquifer. Such reports can be found at http://www.bseacd.org/publications/reports#DyeTracing.

RECHARGE IN MAIN STREAMBEDS

This section presents details involved in the calculation of the total recharge that occurred in the main channel of each of the major streams crossing the recharge area. The period for this analysis is the same as that for the water budget (December 1979–July 1982).

Runoff from the contributing area can recharge in the main channels of the streams within the recharge area, or it can pass through the recharge area. However, runoff within the recharge area can pass through the recharge area, or it can become recharge within 3 source areas: overland-flow areas, tributaries to the main channels, and in the main channels. The origin of runoff measured at the downstream end of the recharge area cannot be distinguished with respect to specific source (whether from the contributing area or recharge area). Therefore, the analysis below is limited to calculation of total recharge in the main channels, regardless of source.

Streamflow is gaged on the main stream channels at the upstream and downstream ends of the recharge area. As explained later, each main channel has a maximum potential recharge rate that can be conveyed to the aquifer. For each stream, when the gaged flow at the upstream end of the recharge area is less than the maximum recharge rate for the channel, the gaged flow represents the total recharge in the main channel. However, when the gaged upstream flow exceeds the maximum recharge rate, the recharge rate in the main channel is limited to that of the maximum recharge rate.

Maximum recharge rates for main streambeds

The results of previous streamflow gain-loss studies (Slade et al. 1986) and review of daily-mean streamflow data for the streamflow gaging stations reveal that recharge to the Edwards Aquifer through each main channel is limited to a maximum rate. Based on results from these studies and data, such recharge rates were estimated by Slade et al. (1986), as presented in Table 2.

During extreme flooding conditions, instantaneous (short-term) maximum recharge rates likely exceed those indicated above by the streamflow gain-loss studies and daily-mean streamflow because higher water levels in the streams increase the wetted perimeter of the channel and likely inundate additional surface porosity associated with the faults and fractures that convey recharge to the aquifer. Also, greater water levels likely cause increased recharge due to higher water pressure over the inundated porosity. However, the maximum recharge for large floods probably cannot be documented; such discharges exist only during highly unsteady flow conditions, when stream channel flow losses are difficult or impossible to document. However, extreme floods rarely occur (perhaps a few times per year at most) and exist for only short durations, thus it is likely that any increased maximum recharge from such floods produces only a minimal increase on the recharge volumes as calculated herein.

Table 2. Maximum recharge rates for main streambeds.

Stream	Maximum recharge (cubic feet per second)
Barton	30 to about 70
Williamson	13
Slaughter	52
Bear	33
Little Bear	about 30
Onion	about 120

Table 2 indicates the extent to which maximum recharge rates vary for Barton Creek. The indicated observations are based on varying stream channel losses from streamflow gain-loss studies on the creek (Slade et al. 1986) and on varying differences between the same-date gaged streamflow at the upstream and downstream boundaries of the recharge area for Barton Creek. Additionally, a substantial part of the total recharge in Onion Creek often occurs through Antioch Cave near the downstream end of the recharge area in the Onion Creek streambed. However, the cave often becomes partially plugged with debris, thus reducing its recharge rate. Therefore, 100 cubic feet per second was used in this analysis as the maximum recharge for the Onion Creek main channel.

Maximum recharge rates for Barton Creek streambed

The maximum recharge rate for Barton Creek varies from 30 cubic feet per second to about 70 cubic feet per second depending upon the relative height of groundwater levels under the streambed. When groundwater levels are low, the saturated zone is below the altitude of the Barton Creek streambed throughout the recharge area, such that the maximum recharge that can occur is limited to a rate of about 70 cubic feet per second. When the groundwater levels are extremely high, their altitudes are comparable to or higher than the streambed for a long reach of the creek immediately upstream from Barton Springs, and thus, that reach will reject recharge. During periods of high groundwater levels, a maximum of only about 30 cubic feet per second of recharge will occur on Barton Creek.

An effort was made herein to document, for various groundwater-level conditions, the maximum recharge rate that occurs in the main Barton Creek channel. A streamflow gain-loss study, conducted by the USGS during high steady-flow conditions on May 29, 1980 (Slade et al. 1986), indicated that the upstream end of the recharge reach on Barton Creek is located near Lost Creek Boulevard (station 08155240). Beginning about October 1, 1998, a streamflow station (08155400) was installed on Barton Creek immediately upstream from Barton Springs; it is located at the downstream boundary of the recharge reach for the creek.

For selected dates representing various groundwater level conditions, streamflow values for the downstream station (08155400) were subtracted from same-date streamflow values for the upstream station (08155240) to obtain maximum recharge rates that occurred on the main channel of the creek. The selected dates represent extended periods after runoff-producing rainfall and relatively steady-flow conditions during which streamflow was occurring at the downstream station. Additionally, efforts were made to exclude extended “wet” periods—periods for which tributary flow, bank storage, and perched groundwater flow might be contributing flow to the channel reach between the gaging stations. Groundwater pumpage and return flows to the creek are believed to be minimal or nonexistent, and no major impoundments exist in the streambed between the stations. The discharge at Barton Springs is directly and highly correlated with groundwater levels in the area. Eighty-four dates met the above criteria and were identified within the 14-year common period.

Figure 4 presents the relation between the maximum recharge rates for the selected dates and the same-date discharge from Barton Springs. The equation for the best-fit line from the graph was used to calculate, based on Barton Springs discharge, the maximum recharge rates for the main Barton Creek streambed.

Calculation of recharge in main streambeds

The daily-mean recharge for the water budget period (December 1979–July 1982) was calculated and summed for the main channels of 5 of the 6 major streams. Little Bear Creek was excluded from this calculation because a streamflow station was not installed at the upstream end of its recharge area.

The recharge calculation is based on daily-mean streamflow values for the following stations near the upstream end of the recharge area: 08155200 Barton Creek at Highway 71, 08155240 Barton Creek at Lost Creek Boulevard, 08158920 Williamson Creek at Oak Hill, 08158840 Slaughter Creek at FM Road 1826, 08158810 Bear Creek below FM Road 1826,

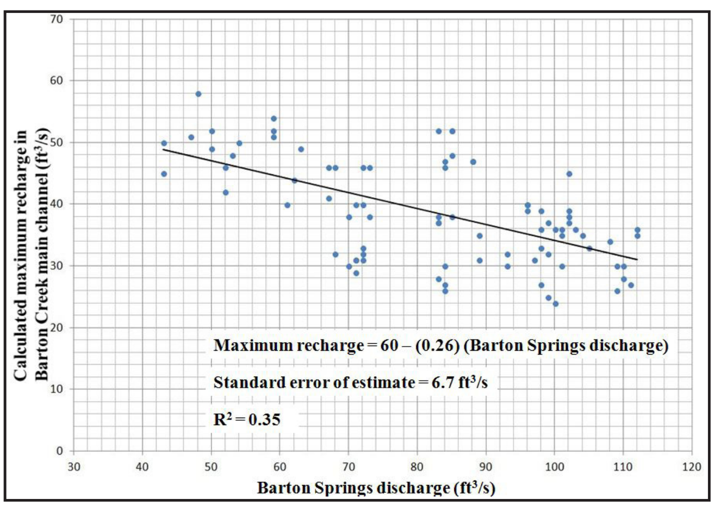

Figure 4. Relation between maximum recharge rates in Barton Creek main channel and Barton Springs discharge.

and 08158700 Onion Creek near Driftwood. The data are available from the USGS online at http://waterdata.usgs.gov/tx/nwis/dv/?referred_module=sw.

The gaging station Barton Creek at Lost Creek Boulevard was not yet in operation during the water budget period; all of the remaining stations listed above were in operation during the period. Review of the same-date streamflow for the Lost Creek Boulevard station and the upstream station Barton Creek at Highway 71 indicate that streamflow at the Lost Creek Boulevard station is 21% greater than that at the Highway 71 station. Therefore, the streamflow at the Highway 71 station was increased by 21% to represent the streamflow at the upstream end of the recharge reach for Barton Creek.

The calculation of recharge in the main streambeds is based on gaged streamflow at the upstream end of the recharge area and does not account for runoff entering the main channels from the recharge area. However, most recharge in the main channels is from the contributing area because this area is about 3 times larger than the recharge area. Additionally, unit runoff (runoff per square mile) from the recharge area to the main channels likely is slightly less than that from the contributing area because some of the runoff from the recharge area is lost as recharge within the recharge area, thus is not received in the main channels.

Nevertheless, runoff from the recharge area sometimes enters the main channels. However, because of the relatively limited size of the recharge area and its tributaries, most such runoff occurs within a few days after runoff-producing storms. During such periods, streamflow in the main channels usually is substantial and often exceeds the maximum recharge rate for the streams. The calculated main-channel recharge for such periods is based on the maximum recharge rate for the main channels, thus most of the runoff from the recharge area into the main channels does not cause increased recharge in the main channels. However, on some occasions, runoff from the recharge area enters the main channels when the main-channel streamflow is less than the maximum recharge rate. For such periods, the actual main-channel recharge would be greater than calculated by this analysis. Therefore, the main streambed recharge as calculated herein is considered to be a minimum value.

Based on the calculation, the total recharge on the main channels is 99,900 acre-feet, which represents 69% of the total recharge of 144,000 acre-feet for the period. However, Little Bear Creek was excluded from this analysis. The length of the main channel and the size of the drainage area of Little Bear Creek are comparable to those of Bear Creek, thus the assumption was made that Little Bear Creek produces an equivalent volume of main-channel recharge as does Bear Creek. Therefore, the total main-channel recharge for the 6 streams is 108,200 acre-feet—a value representing a lower limit of 75%

of total recharge. Main-streambed recharge and total-basin recharge, by basin, is presented in Table 3.

Main-channel recharge as a percentage of total recharge ranges substantially between the basins. However, as Table 3 indicates, such percentages are directly related to the relative size of the contributing area as a percentage of the total drainage area that contributes to recharge (contributing area and recharge area). Additionally, main-channel recharge as a percent of total recharge is directly related to the maximum recharge rate for the main channel. The maximum recharge rate for the main channel of Onion Creek is substantially greater than that for any of the other streams (Table 2). Therefore, most recharge in the Onion Creek Basin occurs in its main channel.

RECHARGE AS OVERLAND FLOW AND IN TRIBUTARIES TO MAIN STREAM CHANNELS

Recharge that does not occur in the main channels occurs within the recharge area as overland flow (including local karst features) or in tributaries to the main channels. Therefore, the upper limit of such recharge is 25% of total recharge.

The long-term (1917–1982) mean discharge from the aquifer is about 56 cubic feet per second (Barton Springs [50 cubic feet per second] + Cold and Deep Eddy Springs [5.5 cubic feet per second] + pumpage [0.8 cubic feet per second]). If discharge is about equal to (within a few percent of) recharge, as indicated by the 1979–1982 water budget, then the long-term mean upper limit for recharge from overland flow and tributaries is about 14 cubic feet per second (0.25 x 56 cubic feet per second). Fourteen cubic feet per second is equivalent to a recharge rate of 2.1 inches per year over the 90-square-mile recharge area, or about 6.6% of the long-term mean precipitation of 32 inches per year over the recharge area.

SUMMARY AND CONCLUSIONS

Recharge-discharge water budgets

The recharge-discharge water budget presented herein (December 1979–July 1982) contains inherent potential error. During the budget period, Barton Springs represented most of the total discharge. Springflow from Barton Springs is gaged by the USGS and has minimal potential error. Withdrawals during the budget period averaged only about 5 cubic feet per second—less than 10% of total discharge. Therefore, even though a relatively large potential error exists for much of the pumpage (which is not metered), the potential error for the total discharge is minimal.

A recharge-discharge water budget analysis for a period other than that presented in this report (December 1979–July 1982) would provide beneficial additional information regarding analyses of the volumes of surface recharge and surface discharge. However, the author is unaware of any other recharge-discharge budgets for this area.

The streamflow station at the downstream end of the recharge area for Onion Creek was discontinued in 1996, thus a budget since then would contain substantial uncertainty for recharge on that stream. Additionally, any attempts to calculate recent recharge and discharge volumes would result in large potential errors in such values due to the following:

- Groundwater withdrawals have been increasing substantially over the past many years and currently represent more than 20% of the long-term mean discharge for Barton Springs. Much of the pumpage is not metered, thus estimates of recent total pumpage and, thus total discharge would contain large potential errors.
- Urban development has increased substantially over the recharge area during the past many years. Recharge volumes due to water leakage in water distribution pipes,

Table 3. Main-channel recharge and total-basin recharge by basin, December 1979–July 1982.

Stream name	Recharge (acre-feet)		Main-channel recharge as % of total-basin recharge	Contributing drainage area as % of contributing area and recharge area
	Main channel	Total basin		
Barton	34,800	39,541	88	87
Williamson	3,400	9,248	37	33
Slaughter	5,800	17,163	34	36
Bear	8,300	14,388	58	51
Little bear	8,300[1]	14,421	58	11
Onion	47,600	49,146	97	86
Total	108,200	144,000	75	75

[1] Estimated from main-channel recharge in Bear Creek main channel.

landscape irrigation, disposal of wastewater, and leaking wastewater pipes are unknown.

- Recharge enhancement structures and strategies in Onion and Little Bear creeks have created large uncertainties in estimating recharge rates for those streams.

Recharge in main streambeds

The analysis method used herein to calculate recharge in the main streambeds contains inherent bias that probably represents most of the potential error in the calculated values. For example, as explained earlier, runoff occasionally enters the main channel from the recharge area when the maximum recharge rate for the main channel is not occurring. Such runoff is not included in the calculations of recharge on the main channels. Also, as explained within the report, during relatively large floods, recharge rates for main channels likely exceed those documented in this report. Both of these factors are the source for additional main-channel recharge not calculated herein. The total calculated main-channel recharge is qualified as representing a minimum (lower limit) value. It is unlikely that the volumes for either of the 2 sources of additional recharge could be estimated without substantial potential error in their values. The author believes that it is likely that actual main-channel recharge could represent as much as 78-80% of total recharge.

Groundwater tracer studies

Much data and information regarding the hydrology of the Barton Springs segment of the Edwards Aquifer have been collected during the past years by many entities and individuals. It is likely that groundwater tracer studies could provide the most beneficial information regarding the advancement of hydrologic knowledge of the aquifer. As discussed earlier, the BSEACD and city of Austin have conducted groundwater dye tracer studies for 18 sites in the study area (Hauwert et al. 2004). Much has been learned from such studies but additional dye studies could provide substantially more knowledge.

Because of the karstic nature of the aquifer and because most recharge occurs on the main channels of the stream, substantial porosity has developed under the stream channels and along a major path to the discharge point of Barton Springs. For example, results from groundwater models document large transmissivity values under streambeds and, in the eastern part of the aquifer, along a conduit flow path to Barton Springs (Slade et al. 1985; SRI 2009). However, one-half of the existing dye studies represent off-stream point injections (in wells and sinkholes) for which the dyes "were generally flushed into the aquifer with approximately 10,000 gallons of water to carry the dye to the water table." It is likely that the travel paths and travel times of the dye from the off-stream sites are not indicative of paths and travel times for streambed recharge.

Additionally, flow paths and travel times can vary substantially with flow conditions. For 1 of the only 2 sites with a repeated dye injection, Antioch Cave on Onion Creek, the flow path for the injections differed during the low-flow and high-flow conditions for Barton Springs (Hauwert et al. 2004). Single dye studies represent the flow path and travel time during a specific flow condition; additional injections for a range in Barton Springs flow conditions would document the range in flow paths and travel times.

All the dye studies represent point injections; no stream reaches have been tested. Needed are dye studies for which dye is injected at the upstream end of the recharge reach of each of the main streams during periods when recharge is occurring throughout or at least throughout most of the recharge reach. Additionally, such studies should be repeated for varying flow conditions at Barton Springs. The results of such dye studies would represent the time of travel of most of the recharge to the aquifer—that in the main stream channels and thus would represent actual recharge conditions.

Finally, documentation of the groundwater travel time from the streams to the springs would provide valuable information regarding spills of toxic substances into the streams or watersheds of the streams. The area is rapidly developing and it is likely that such a spill would occur in the future. Additionally, several groundwater models (Slade et al. 1985; SRI 2009) have been developed for the Barton Springs segment of the Edwards Aquifer. All such models contain substantial potential error, which could be reduced if recharge travel times from the streams to the springs were documented. Finally, a viable water quality model has not been identified for the aquifer. Information about the time of travel and dispersion characteristics from the streams to Barton Springs would be needed for such a model. In summary, tracer studies on the stream reaches would provide needed data and information for toxic spills and future groundwater models involving flow or water quality characteristics.

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