

TEXAS WATER JOURNAL

Volume 8, Number 1
2017



TEXAS WATER JOURNAL

Volume 8, Number 1

2017

ISSN 2160-5319

texaswaterjournal.org

THE TEXAS WATER JOURNAL is an online, peer-reviewed journal devoted to the timely consideration of Texas water resources management, research, and policy issues. The journal provides in-depth analysis of Texas water resources management and policies from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. It also provides updates on key state legislation and policy changes by Texas administrative agencies.

For more information on TWJ as well as TWJ policies and submission guidelines, please visit *texaswaterjournal.org*.

Editorial Board

Todd H. Votteler, Ph.D.
Editor-in-Chief
Guadalupe-Blanco River Authority

Kathy A. Alexander, Ph.D.

Robert L. Gulley, Ph.D.
Texas Comptroller of Public Accounts

Robert E. Mace, Ph.D.
Texas Water Development Board

Ken A. Rainwater, Ph.D.
Texas Tech University

Kevin L. Wagner, Ph.D.
Texas Water Resources Institute

Ralph A. Wurbs, Ph.D.
Texas A&M University

Managing Editor

Kathy Wythe
Texas Water Resources Institute
Texas A&M Natural Resources Institute

Layout Editor

Leslie Lee
Texas Water Resources Institute
Texas A&M Natural Resources Institute

Website Editor

Ross Anderson
Texas Water Resources Institute
Texas A&M Natural Resources Institute

Staff Editor

Kristina J. Trevino, Ph.D.

The Texas Water Journal is published in cooperation with the Texas Water Resources Institute, part of Texas A&M AgriLife Research, the Texas A&M AgriLife Extension Service, and the College of Agriculture and Life Sciences at Texas A&M University.


Texas Water
Resources Institute
make every drop count

A recharge-discharge water budget and evaluation of water budgets for the Edwards Aquifer associated with Barton Springs

Raymond M. Slade, Jr., PH¹*

Abstract: The Barton Springs segment of the Edwards Aquifer represents a small, relatively independent part of the aquifer. Data for the sources of recharge and especially for discharge from the aquifer are well documented. Based on a 6-year water budget of surface recharge and surface discharge, the volumes match within 5%, which is within the potential error limits of the recharge and discharge values. Recharge volumes include increased runoff due to urbanization in the recharge area. A previous water budget based on an earlier period also displayed a balance between recharge and discharge volumes. Both budgets are based on slightly “wetter” than long-term mean recharge and discharge conditions, thus subsurface recharge from south of the aquifer segment, which is documented to occur during dry conditions, was an insignificant source of recharge during the budget periods.

The recharge volumes are based on data from streamflow gaging stations operated by the U.S. Geological Survey. However, one of the stations (Bear Creek near Brodie Lane) was discontinued in 2010; this station is needed to calculate recharge volumes on Bear Creek and Little Bear Creek. Because of the discontinuance of the station, any calculations of recharge volumes after 2010 would contain substantial potential error.

Keywords: Edwards Aquifer, water budget, karst

¹Certified Professional Hydrologist and Adjunct Professor, Austin Community College

*Corresponding author: raymond643@aol.com

Citation: Slade RM, 2017. A recharge-discharge water budget and evaluation of water budgets for the Edwards Aquifer associated with Barton Springs. *Texas Water Journal*. 8(1):42-56. Available from: <https://doi.org/10.21423/twj.v8i1.7020>.

© 2017 Raymond M Slade. This work is licensed under the Creative Commons Attribution 4.0 International License. To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/> or visit the TWJ [website](#).

Terms used in paper

Acronym	Descriptive term
USGS	U.S. Geological Survey
BSEACD	Barton Springs Edwards Aquifer Conservation District
IC	Impervious cover
RC	Runoff coefficient
ET	Evapotranspiration
TWDB	Texas Water Development Board

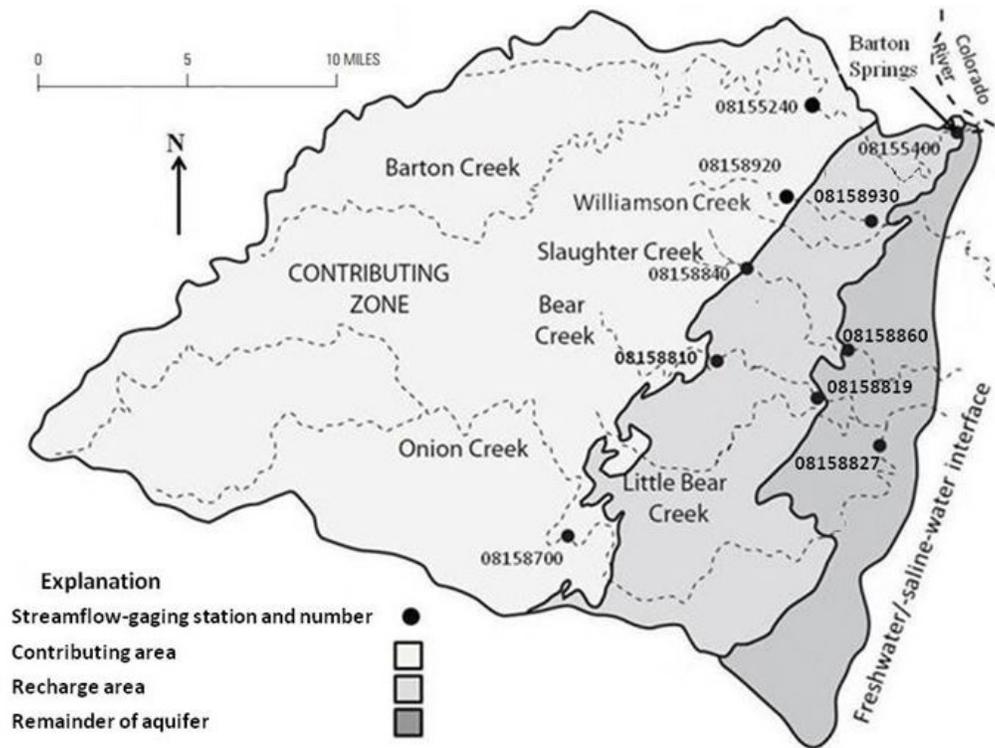


Figure 1. Boundaries for the aquifer, recharge area, and contributing area and locations of streamflow gaging stations.

INTRODUCTION

Barton Springs discharges a relatively hydrologically independent 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.

Each of the 6 major creeks that cross the recharge area has a basin that extends upstream of the aquifer. Figure 1 identifies the 264-square-mile contributing area—the surface drainage area upstream from the recharge area (Slade 1986). The contributing area is about 3 times larger than the 90-square-mile recharge area.

By 1979, with funding assistance from the city of Austin, the U.S. Geological Survey (USGS) installed and operated streamflow-gaging stations 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 (about 3.3 square miles), a streamflow station was not installed at the upstream boundary of its recharge area. Recharge volumes are

calculated as explained below. Other small streams exist in the recharge area, but their contributions to recharge are deemed minimal because their basins are much smaller than those for the 6 major streams. The basins for the 6 major stream identified in Figure 1 represent about 96% of the drainage area within the recharge area (Naismith Engineering Inc. 2005). Additionally, the USGS installed and operated 12 precipitation gages throughout the contributing and recharge areas.

Subsurface discharge is believed to be minimal compared to surface sources (Slade et al. 1986). Subsurface recharge from the adjacent and underlying Trinity Aquifer also is believed to be minimal (Slade et al. 1986). Additionally, subsurface recharge from the Edwards Aquifer south of the aquifer boundary is deemed as nonexistent or minimal except during low-flow conditions (Johnson et al. 2012 and Casteel et al. 2013).

Barton Springs represents the major discharge from the aquifer. The USGS has systematically measured its discharge since 1917 and gaged its discharge hourly since 1978. Cold Springs discharges a small part of the aquifer; its mean flow is documented based on about a dozen discharge measurements. A few other small springs represent minor discharges from the aquifer. Groundwater withdrawal volumes are mostly gaged. Therefore, the vast majority of discharge from the aquifer is gaged.

PURPOSE OF PAPER

The purpose of this paper is to present, for the Barton Springs segment of the Edwards Aquifer, a recharge-discharge water budget based on impervious cover (IC)-founded calculations of runoff and recharge volumes. An additional purpose is to present a summary and evaluation of all identified recharge-discharge water budgets conducted for the aquifer.

METHOD TO CALCULATE RECHARGE VOLUMES

The method of estimating surface recharge to the Edwards Aquifer was first introduced by Garza (1962). Recharge consists of the infiltration of streamflow plus direct infiltration of runoff in the interstream areas. The approach of estimating recharge in each stream basin is a water-balance equation, in which the recharge value within a stream basin represents the difference between gaged streamflow upstream and downstream from the recharge area, plus the estimated runoff in the intervening area. The intervening area is the drainage area within the recharge area between the 2 streamflow-gaging stations in each stream basin. Runoff from the recharge area is estimated on the basis of unit runoff from the area upstream from the recharge area. Such an assumption is deemed reasonable because the land slopes, soil and vegetation type and extent, and precipitation characteristics generally are similar in both areas. Estimates of monthly recharge during periods of high runoff probably contain the major errors (Puente 1978).

The basic equation for computing monthly recharge is as follows:

$$R = Q_u + SI - Q_d$$

where R is monthly recharge volume;

Q_u is the monthly flow volume at the upstream gaging station; SI is the estimated monthly runoff volume, including infiltration, resulting from precipitation in the intervening recharge area; and

Q_d is the monthly flow volume at the downstream gaging station.

The general equation used for estimating the total runoff derived from direct precipitation in the areas between the upstream and downstream gaging stations is expressed as follows:

$$SI = Q_u / A_u \Delta A$$

where,

Q_u is the monthly flow volume at the upstream gaging station; A_u is the drainage area for the upstream gaging station, in square miles; and

ΔA is the intervening drainage area between the upstream and downstream gaging station, in square miles.

Based on the above equations, unit runoff (runoff per square

mile) from the recharge area is assumed to represent that from the upstream contributing area. However, available precipitation records that document the distribution of rainfall for each month can be used to adjust the estimated runoff from the recharge area. The adjustment to the estimated unit runoff often is based on a precipitation depth ratio determined from the mean precipitation in the contributing and intervening areas. However, little information is available regarding the spatial focusing of recharge in particular locations. Additionally, during the past 20 to 25 years, the recharge area has experienced rapid urban development compared to that in the contributing area which is more remote from the Austin city limits. Therefore, due to greater IC density, the recharge area likely experiences greater unit runoff than that from the contributing area.

LONG-TERM MEAN DISCHARGE FROM THE EDWARDS AQUIFER

Barton Springs and withdrawals

The long-term (1917–2013) mean discharge from Barton Springs is 54 cubic feet per second. The mean discharge is based on daily-mean gaged discharges from 1978 to 2013 and on 725 instantaneous discharge measurements made from 1917 to 1978. The earlier discharge measurements were plotted on monthly hydrographs with daily resolution. Precipitation records for gages in Austin and San Marcos were used, along with known springflow recession rates from 1978 to 82, to estimate daily and monthly-mean discharges for the 1917–78 period (Slade 1986).

A limited discharge of intermittent springflow occurs in the reach of Barton Creek immediately upstream from Barton Springs. Such springflow varies from zero when groundwater levels are below the streambed, to about 5 cubic feet per second when local groundwater levels are extremely high. When Barton Springs discharges 54 cubic feet per second (its long-term mean), the springflow from the streambed is about 0.8 cubic feet per second (Slade 2014).

Monthly-mean groundwater withdrawals from 1917 to 2013 were provided by the Barton Springs Edwards Aquifer Conservation District (BSEACD). The vast majority of pumpage is metered, thus withdrawal rates are considered to have minimal potential error. Privately-owned wells are not metered but their pumpage volumes are estimated. Based on these data, the 1917–2013 mean total pumpage is 2.7 cubic feet per second. Monthly-mean pumpage ranges from 0.10 cubic feet per second in 1917 and later to 13.57 cubic feet per second in June 2008. Some of the withdrawal volumes likely are lost as leakage from transmission pipes, ineffective irrigation, or effluent discharges, but the vast majority of such losses are consid-

Table 1. Discharge measurements of Cold Springs.

Date	Cold Springs discharge (cubic feet per second)	Barton Springs discharge (cubic feet per second)
Aug ? 1914 ¹	4.2	unknown
Aug ? 1917 ²	4.2	15
Aug 1, 1918 ³	7.5	14
Aug 6, 1918 ³	4.2	14
Aug 10, 1918 ⁴	3.7	14.3
Aug 8, 1921 ³	10.7	39
Aug 13, 1930 ³	12.0	24
Feb 8, 1941 ^{2,3}	3.0	61
1955 ²	0.0	17
May ? 1972 ²	2.9	84
Dec 19, 1979 ⁵	2.6	46
Aug 18, 1996 ⁶	4.1	18
Aug 6, 1997 ⁷	7.3	107
Nov 4, 1997 ^{8,9}	6.4	84
Oct 18, 1999 ⁸	4.8	33
Jan 29, 2008 ⁸	8.2	66
Mean value	6.48	41.5
Adjusted mean value	8.4	54

Mean discharge for Cold Springs adjusted by ratio of 54/41.5 in order to estimate its mean value associated with mean flow of Barton Springs (54 cubic feet per second).

Measurements in red made by indirect method and subject to large potential error.

Measurements in blue not used for calculation of mean value. Barton Springs discharge unknown or part of spring-flow likely below lake level. 1955 measurement not used due to severe drought.

¹ Brune and Duffin 1983

² Brune 1975

³ TBWE 1959

⁴ TBWE 1960

⁵ Mike Dorsey, USGS, personal commun.

⁶ Hauwert et al. 2004

⁷ Hauwert et al. 2004

⁸ David Johns, Watershed Management Dept., City of Austin, personal commun.

⁹ 4.5 cubic feet per second measured directly and 1.9 cubic feet per second estimated.

ered to have a direct fate as evapotranspiration (ET). Therefore, only a minimal amount of pumpage is deemed to be directly lost as recharge to the Edwards Aquifer, thus gross withdrawal volumes are represented as discharge for the water budget.

Other discharges

Cold Springs is located on the southern bank of the Colorado River, about a mile northwest of Barton Springs (Slade 2014). Its recharge source probably represents Dry Creek, a small creek north of Barton Creek, and likely part of the flow in Barton

Creek. All known direct and indirect discharge measurements for Cold Springs are aggregated and presented in Table 1. Based on 11 discharge measurements, the mean discharge for Cold Springs is 6.48 cubic feet per second. Some of the spring-flow is known to discharge below the normal level of Lady Bird Lake, built in 1960; measurements made during such conditions were excluded from the calculation of the mean spring-flow value. The discharge for Barton Springs was estimated for each of the measurement dates for Cold Springs (Table 1). The mean discharge of Barton Springs for the 11 measurements is 41.5 cubic feet per second, which is 77% of its long-term

mean discharge of 54 cubic feet per second. The assumption was made that the mean measured discharge for Cold Springs (6.48 cubic feet per second) also is 77% of its long-term mean discharge. Based on this assumption, the long-term mean discharge for Cold Springs is estimated to be 8.4 cubic feet per second.

A limited amount of outflow is believed to discharge the Edwards Aquifer as seeps or springflow into Lady Bird Lake (the Colorado River) adjacent to the northern boundary of the aquifer (Figure 1). Prior to the construction of the dam forming the lake, a streamflow gain-loss study conducted on August 10, 1918, indicated an unaccounted gain of 0.4 cubic feet per second in the river reach adjacent to the Edwards Aquifer; an additional study of a similar reach in 1925 indicated a gain of 1.0 cubic feet per second. These gains could result from: groundwater discharge through terrace deposits along the river; groundwater discharge from the north side of the river; or surficial runoff outside the Edwards Aquifer. Also, it is possible that no streamflow gain occurred due to potential error in the streamflow measurements. However, even if both gains represent discharges from the Barton Springs part of the Edwards Aquifer, their discharge are minor compared to other discharges from the aquifer. For purposes of documenting such discharges from the aquifer, the assumption is made that the mean discharge from the Colorado River bank is 0.7 cubic feet per second, the mean value for the 2 streamflow gain studies. Additional information and references regarding this analysis is reported by Slade (2014). Also, additional information that documents Colorado River bank discharges to represent limited outflow from the aquifer is contained in the section "Other discharges" within the "Supplemental information" section.

Based on the 5 sources for discharge documented above, the total mean discharge from the aquifer calculates to be 67 cubic feet per second. The long-term mean recharge rate is deemed to be equivalent to this value.

A NEW RECHARGE-DISCHARGE WATER BUDGET

The first recharge-discharge water budget for the Barton Springs segment of the Edwards Aquifer was published by Slade et al. (1986) and later verified and slightly refined by Slade (2014). The budget represents the period December 1, 1979 through July 31, 1982 and is based on recharge calculations as described above and on discharges from Barton Springs and withdrawals. Based on the budget, the recharge volume exceeded the discharge volume by 3.3% (Slade 2014).

Based on the recharge calculation method described earlier, the recharge volume was calculated for a recent long-term period. Discharge values were compared to the recharge

values in order to assess the sources and values of recharge and discharge included in the budget.

Discharge and precipitation

The new water budget period represents the 6-year period from November 1, 2003 through October 31, 2009. Barton Springs discharge was 50 cubic feet per second at the beginning of the period and 51 cubic feet per second at the end. Springflow discharge is indicative of groundwater levels in the aquifer (Slade et al. 1986); therefore change in aquifer storage is deemed to be minimal during the budget period and thus an exempt component of the budget.

The mean discharge from Barton Springs during the period is 54.8 cubic feet per second. The mean withdrawal from the aquifer during the period is 7.8 cubic feet per second (BSEACD 2014, written commun.). During the period, a mean springflow of about 0.8 cubic feet per second discharged from the reach of Barton Creek immediately upstream from Barton Springs (Slade 2014). Discharge from the aquifer to Lady Bird Lake was assumed to represent 0.7 cubic feet per second during the period. Finally, the discharge from Cold Springs was assumed to represent its long-term mean value of 8.4 cubic feet per second, as documented earlier.

Therefore the total discharge for the budget period has a mean value of 72.5 cubic feet per second.

Precipitation during the period is based on 6 gages within the stream basins; 5 are operated by the Lower Colorado River Authority and 1 is operated by the National Weather Service. Based on data for the 6 gages, the mean precipitation depth during the period ranges from 163.92 inches to 191.31 inches and has a mean value of 179.20 inches, which is equivalent to 29.87 inches per year.

Recharge

Recharge volumes were calculated for the budget period, based on streamflow data for gaging stations upstream and downstream from the recharge area. Each of the stations used in the calculations are designated in Figure 1 and the data are available from an interactive map online at <http://maps.water-data.usgs.gov/mapper/index.html?state=tx>. Recharge was calculated as explained above except that, where applicable, runoff volumes for the recharge area were adjusted to account for runoff due to differences in IC densities between the contributing and recharge areas. An explanation for this adjustment follows.

A search for IC density values for the contributing and recharge areas within each major stream basin identified only one source (Naismith Engineering Inc. 2005). Table 2 presents estimated IC densities for the year 2003.

In order to calculate the runoff in the recharge area due

48 A recharge-discharge water budget for the Edwards Aquifer associated with Barton Springs

Table 2. Impervious cover densities for the contributing and recharge areas of the streams providing recharge to the Edwards Aquifer, 2003.

Watershed	Area in RZ (Ac)	Area in CZ (Ac)	Area in PR (Ac)	RZ IC (Ac)	RZ IC (%)	CZ IC (Ac)	CZ IC (%)	Total
Little Barton Creek	0	7,300	7,300	0	-	459	6.29%	6.29%
Barton Creek	4,956	64,521	69,477	1,096	22.11%	2,975	4.61%	5.86%
Bee Creek	96	1,824	1,920	15	15.37%	280	15.37%	15.38%
Little Bee Creek	397	243.2	640	80	20.04%	49	20.05%	20.08%
Eanes Creek	1,587	973	2,560	433	27.25%	265	27.25%	27.26%
Williamson Creek	5,205	5,811	11,016	1,361	26.14%	925	15.91%	20.75%
Slaughter Creek	6,743	7,256	13,999	775	11.50%	538	7.41%	9.38%
Bear Creek	4,126	11,477	15,603	179	4.33%	568	4.95%	4.78%
Little Bear Creek	11,412	1,608	13,020	337	2.95%	35	2.16%	2.86%
Onion Creek	15,739	90,986	106,725	324	2.06%	2,890	3.18%	3.01%
Total	50,262	191,999	242,260	4,598		8,982		

RZ designates the recharge zone; CA the contributing zone; and the PR the Planning Region for the report. IC designates impervious cover and AC represent acres. IC densities exceeding 10% are highlighted.

to differences in IC densities between the contributing and recharge areas, runoff volumes associated with IC densities need to be represented. The most pertinent documentation identified regarding the relations between IC densities and runoff volumes in the Austin, Texas area is presented by the

city of Austin (2009). The report includes the IC density (%), the runoff coefficient (RC), and a summary of the major land use for each basin represented by about 36 streamflow gaging sites in the Austin area. The RC represents the runoff volume expressed as a ratio of precipitation volume. Based on IC and

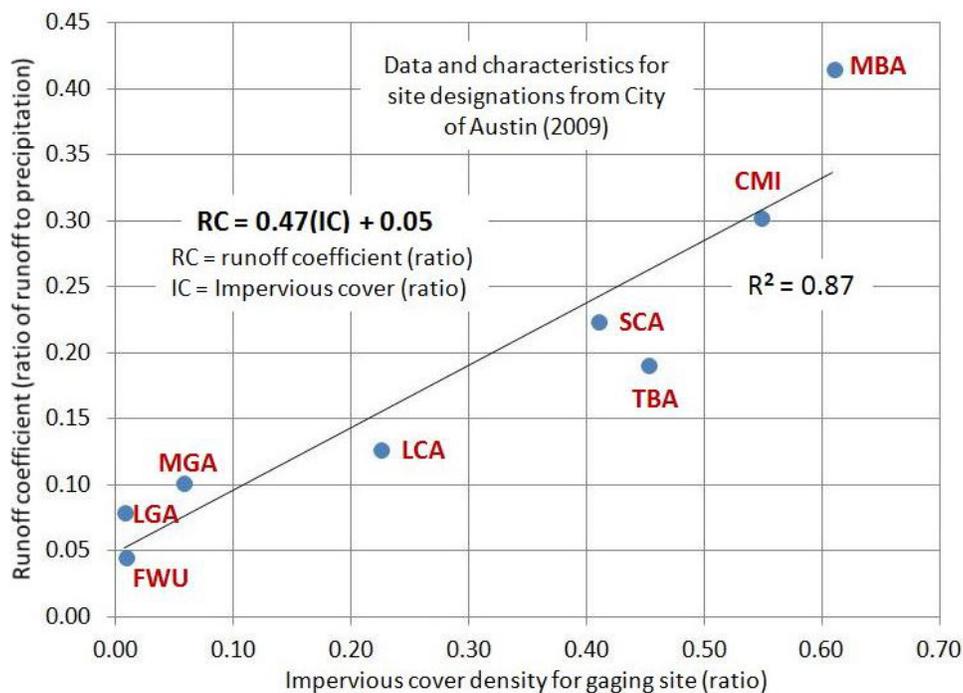


Figure 2. Relation between impervious cover densities and runoff coefficients for selected streamflow gaging sites. CMA=Central Market Influent, FWU=Windago Way Undeveloped, LCA=Lost Creek Subdivision, LGA=Lost Creek Golf Course Undeveloped, MBA=Metric Blvd., MGA=Lions Municipal Golf Course, SCA-Burnet Road @ 40th Street, TBA=Tar Branch at Carriage Parkway

RC values for selected pertinent sites, a statistical relation was developed by which to calculate runoff volumes based on IC densities (Figure 2). The approach for such calculations is presented in the “Recharge” section within the “Supplemental information” section.

Based on the recharge calculations as explained, the total mean recharge calculated to be 69.1 cubic feet per second, of which 4.2 cubic feet per second (about 6% of total recharge) is attributed to greater IC densities in the recharge area than in the contributing area. The total recharge due to IC densities exceeding zero is much greater than 6% of total recharge. The total mean recharge (69.1 cubic feet per second) calculates to be about 5% less than the total mean discharge for the period (72.5 cubic feet per second). The difference is within the range of the potential error for the calculations, thus the subsurface recharge volume is deemed to be insignificant during the period.

The mean recharge rate can be expressed as a percentage of precipitation on the contributing and recharge areas. The mean precipitation for the budget period is 179.20 inches, comparable to 29.87 inches per year. Converting the precipitation depth and recharge volume to comparable units documents the mean recharge value of 69.1 cubic feet per second to represent 9% of precipitation over the entire contributing and recharge areas. Runoff from the recharge area (total discharge for the streamflow stations downstream from the recharge area) represents a mean value of 79.8 cubic feet per second, which is equivalent to 10% of precipitation on the total contributing and recharge area. ET rates for the total area can be expressed as $ET = \text{Precipitation} - \text{recharge} - \text{runoff from the recharge area}$, thus ET calculates to represent 81% of precipitation on the total contributing and recharge area.

Maximum recharge rates in the main channels of the major streams

Due to limited infiltration of recharge in the streambeds, the main channel for each of the 6 major streams has a limiting capacity for the rate of recharge that can be conveyed to the aquifer (Slade 2014). With the exception of Little Bear Creek, streamflow gain-loss studies and gaged streamflow at the upstream and downstream boundaries of the recharge area were used to document the maximum recharge rate for each of the streams. These rates are presented in Table 3.

The main channel of Barton Creek has a maximum recharge rate that ranges from 30 cubic feet per second to about 70 cubic feet per second, depending upon the relative height of groundwater levels under the streambed (Slade 2014). When groundwater levels proximate to the lower reach of Barton Creek are low, the saturated zone is below the altitude of the entire main channel of Barton Creek, thus a maximum recharge

Table 3. 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

of about 70 cubic feet per second occurs in the main channel. When groundwater levels are relatively high, their altitudes are comparable to or higher than the altitude of the streambed reach immediately upstream from Barton Springs, and thus, that reach rejects recharge. During periods of extreme high groundwater levels, a maximum of only about 30 cubic feet per second of recharge will occur in the main channel of Barton Creek. Barton Springs discharge value is highly indicative of groundwater levels in the lower Barton Creek Basin. Therefore, a statistical relation was developed between values for Barton Springs discharge and the maximum recharge rate for Barton Creek (Slade 2014). As explained below, the best fit formula for that relation was used to calculate, for the water budget documented by Slade (2014) and for the budget in this paper, the recharge volume in the main channel of Barton Creek.

Recharge volumes in the main channels of the major streams

Calculation of recharge volumes in the main channels of the major streams is based on daily-mean streamflow values for each of the 5 streamflow stations upstream from the recharge area (Figure 1). Little Bear Creek was excluded from this calculation because a streamflow station was not installed at the upstream boundary of its recharge area. For each station and each day, the gaged daily-mean discharge was compared to the maximum recharge rate for the stream. The daily recharge rate on the main streambed was assumed to represent, for each stream, the lesser value of the maximum recharge rate or the gaged discharge upstream from the recharge area. The daily-mean recharge values were summed for each stream and for the budget period. For the Barton Creek streambed, the maximum recharge rate was based on the formula as discussed in the previous section.

Based on the calculations, the total mean recharge rate for the 5 main channels represents 43.2 cubic feet per second, which includes 3.8 cubic feet per second for Bear Creek. Little Bear and Bear Creek are adjacent basins and have similar drainage areas at the downstream boundaries of their recharge areas.

However, the contributing area for the Little Bear Creek Basin is only about 27% of that for the Bear Creek Basin, thus the main channel recharge for Little Bear Creek was assumed to be 1.0 cubic feet per second, a value representing 27% of the main channel recharge for Bear Creek (3.8 cubic feet per second). Therefore, total mean main-channel recharge from the contributing area represents 44.2 cubic feet per second.

However, 44.2 cubic feet per second of main channel recharge represents a minimum value because runoff from the recharge area sometimes enters the main channel when the main channel flow rate is less than its maximum recharge rate—such runoff would represent, for each major stream, additional recharge on the main channel. However, data do not exist by which to calculate this additional recharge. Based on analyses of the daily main channel recharge rates, about 52% of main channel recharge (22.9 cubic feet per second) occurred when the flow rate in the channels was less than its maximum recharge rate. During such periods, any runoff from the recharge area would increase the recharge rate in the main channels. For each basin, the assumption was made that main channel recharge from the recharge area represents one-half of the unit runoff from the contributing area when its flow rate was less than the maximum recharge rate. Based on such, the recharge area produces 7.0 cubic feet per second of main channel recharge, thus total main channel recharge represents 51.2 ft³, a value representing 74% of the total mean recharge of 69.1 ft³/3.

Interstream recharge

Of the 69.1 cubic feet per second of total mean recharge during the budget period, 51.2 cubic feet per second occurs in the main channels of the 6 streams crossing the recharge area, thus the remaining 17.9 cubic feet per second of recharge occurs in the interstream area outside the main channels. Based on the precipitation depth of 179.20 inches during the budget period, interstream recharge thus represents 9% of precipitation on the recharge area.

ANALYSIS OF OTHER RECHARGE DISCHARGE BUDGETS FOR THE AQUIFER

Five partial or complete recharge-discharge water budgets have been identified for the Barton Springs segment of the Edwards Aquifer (Table 4). However, only 2 of the budgets (Slade 1986 and 2014, and this paper) independently document and compare recharge and discharge volumes.

Budget for 2003 to 2007

Hauwert (2011) presents a recharge-discharge water budget for what he describes as the portion of the aquifer

that discharges to Barton Springs (82 square miles). In order to document daily recharge values for each stream, Hauwert subtracted the same-date daily-mean discharge value for the gaging station near the downstream boundary of the recharge area from the discharge at the station near the upstream boundary. However, this approach is inconsistent with several principles of surface-water hydrology and open-channel hydraulics. To obtain meaningful values, recharge calculations should be performed for discharges occurring only during steady-state flow conditions—conditions that do not occur except during very low-flow conditions. The vast majority of recharge to the aquifer occurs during storm runoff when only non-steady flow occurs. Additionally, the streamflow time of travel between the gaging station upstream of the recharge area and that downstream of the recharge area varies between streams and with flow conditions. For example, the 2 gaging stations on the Onion Creek main channel are separated by about 22 stream miles. Based on the mean streamflow velocity measured by the USGS, the time of travel between these stations varies from about 11 hours to about 7 days. Also, streamflow dispersion characteristics are not available for any of the streams, thus such characteristics are not considered in the Hauwert (2011) approach. Finally, Hauwert does not account for inflow to the streams from the intervening drainage area between the gaging stations.

Hauwert's (2011) approach assumes the difference between the total main channel recharge volume and the total discharge volume (Barton Springs discharge and gross withdrawals) to represent the interstream recharge volume. However, as demonstrated above, main channel recharge volumes as calculated by Hauwert (2011) likely are erroneous, as would be the values for interstream recharge. Additionally, the total recharge volume is not calculated independently from discharge volume and Hauwert could not compare the recharge volume to the total discharge volume for verification of a budget balance. As part of his calculations and estimations, Hauwert documented values for the volume of precipitation on the recharge area, deemed as 82 square miles (2011). The fate of such precipitation as a percent of the total precipitation volume is reported as follows: interstream recharge (15%); recharge on the main channels of the major streams (7%); and runoff from the recharge area (15%). The residual 63% of precipitation is assumed to represent ET from the recharge area (Table 4).

Within the recharge area, however, flow in the main channels of the major streams is a mixture of that from the contributing area and from within the recharge area. Likewise, runoff from the recharge area also is a mixture of water from both source areas. Data do not exist by which to distinguish the specific sources of recharge on the main channels or for runoff from the recharge area. Therefore, the volumes for both values should be treated as estimates, as should the resulting value for ET.

Table 4. Summary of water budgets conducted on the Barton Springs part of the Edwards Aquifer.

NA--Not applicable; NR--Not reported

	Portion of recharge area used as basis for budget	Budget Period	Budget duration (years)	% recharge exceeds or less than (-) discharge (%)	Mean discharge as % of long-term mean ¹
Woodruff (1984)	entire area	7/1979 – 12/1982	3.5	NA	110%
Slade (1986 and 2014)	entire area	12/1979 – 7/1982	2.7	3.3% ²	112%
Hauwert (2011) ³	most area	5/31/2003 – 9/19/2007	4.3	NR	128%
Hauwert and Sharp (2014) ⁴	0.07 square miles	4/2/2004 – 8/20/2005	1.4	NA	166%
This report	entire area	11/1/2003 – 10/31/2009	6.0	-5.0%	110%

	Fate of precipitation on contributing and recharge area as % of such precipitation				Recharge on main channels as % of total recharge	Runoff from contributing area as % of precipitation on contributing area
	Total recharge	Main channel recharge	Runoff	Evapo-transpiration ⁵		
Woodruff (1984)	6%	NA	9%	85%	NA	NA
Slade (1986 and 2014)	8%	6%	12%	80%	75%	17%
Hauwert (2011)	NR	NR	NR	NR	56-67%	NR
Hauwert and Sharp (2014) ⁴	NA	NA	NA	NA	NA	NA
This report	9%	7%	10%	81%	74%	16%

	Fate of precipitation on recharge area as % of such precipitation				% of total recharge from contributing area
	Interstream recharge	Main channel recharge	Runoff from recharge area	Evapo-transpiration	
Woodruff (1984)	NA	NA	NA	NA	NA
Slade (1986 and 2014)	6.6%	NR ⁶	NR ⁶	NR ⁷	NR ⁶
Hauwert (2011)	15%	7% ⁶	15% ⁶	63% ⁷	39-50% ⁶
Hauwert and Sharp (2014) ⁴	32%	0	0	68%	NA
This report	9%	4 ⁸	17% ⁹	70% ⁹	64% ⁹

¹ Based on 1917-2013 mean discharge of 57 cubic feet per second for Barton Springs plus withdrawals.

² Based on Cold Springs mean discharge of 5.5 cubic feet per second (Slade, 2014 p. 15)

³ Excludes the "Cold Springs Basin" thus represents only 82 square miles recharge area rather than 90 square miles

⁴ Based on small closed basin (0.07 square miles) within the 90 square mile recharge area

⁵ Recharge loss to Trinity Aquifer in contributing area not included—probably about 3% to 4% of precipitation on contributing and recharge areas

⁶ Data do not exist to calculate values for source (contributing area or recharge area) of main channel recharge, runoff from recharge area, or recharge from contributing area.

⁷ Without directly measured ET data at sites representative of recharge area, its value must be calculated as residual of recharge area water budget: ET = precipitation - recharge - runoff. However, 2 components of budget (total recharge within recharge area and runoff from recharge area) are unknown. See footnote 6.

⁸ Estimated as explained in section "Recharge volumes in the main channels of the major streams"

⁹ Based on estimation of main channel recharge

Finally, Hauwert’s (2011) budget was conducted for a period during which Barton Springs discharge plus withdrawals totaled 128% of its long-term mean value (Table 4). During such “wet” periods, recharge and runoff as a percent of precipitation would logically be greater than their long-term mean values and ET would be less than its long-term mean value.

Budget for 2004 to 2005

Hauwert and Sharp (2014) present a short-duration budget for a small basin (0.07 square miles) within the recharge area but closed to runoff from the recharge area. ET is measured directly via flux tower instrumentation within the basin. Because the small basin is closed to runoff from the basin, interstream recharge is calculated as the difference between the volume of precipitation on the basin and the volume of ET

from the basin. Based on these calculations, ET represents 68% of precipitation and interstream recharge was thus deemed to be 32% of precipitation (Table 4).

However, Hauwert and Sharp (2014) report that more than 90% of the 90 square-mile recharge area is not within a closed basin. Based on analysis of streamflow discharge data for the USGS gages on the streams providing recharge, much runoff from the interstream area of the entire recharge area becomes recharge in the main channels of the major streams—runoff that does not recharge the aquifer, discharges from the recharge area. For many “wet” durations within the Hauwert and Sharp (2014) budget period, the streamflow at the station downstream from the recharge area exceeds that at the upstream end, often by more than 100%. During such periods, the amount by which the downstream flow exceeds the upstream flow represents runoff from the recharge area. Therefore, the Hauwert and Sharp (2014) water budget for the small closed basin does not represent that for the entire recharge area.

Also, the budget represents an extremely “wet” period during which time discharge from Barton Springs plus withdrawals equaled 166% of its long-term mean value (Table 4). Therefore, for the budget period, recharge as a percent of precipitation would logically be much greater than its long-term mean value, and ET would be much less than its long-term mean value. Additionally, the budget period is short—less than 17 months. Although data apparently were collected for a much longer period representative of “more normal” flow conditions, the analysis of such data is not reported.

Hauwert and Sharp (2014) concluded that “Based on compilation of ET data from other flux towers in Central Texas under a wide variety of annual precipitation conditions, it can be estimated that under average precipitation conditions, 69% of rainfall leaves as ET; 28% of rainfall percolates as autogenic recharge into the Edwards Aquifer.” The flux tower study nearest to the Barton Springs watershed was conducted for the Edwards Aquifer on the Freeman Ranch near San Marcos in Hays County. However, for the Freeman Ranch study, which was not referenced by Hauwert and Sharp (2014), ET was found to be 92% of precipitation, thus limiting recharge to 8% of precipitation (Heilman et al. 2009).

The only ET study referenced by Hauwert and Sharp (2014) was conducted by Dugas et al. (1998); however, many problems deem the results of that water-budget study to be of little, if any, relevance to the Barton Spring Edwards Aquifer area. For example, the Dugas et al. (1998) study was conducted on the Trinity Aquifer rather than on the Edwards Aquifer. Additionally, the Dugas study was on the Seco Creek Basin in Uvalde County, which is of considerable distance from the Barton Springs study area. The annual-mean precipitation in the Uvalde study area is only 22% of that in the Barton Springs Edwards Aquifer area. Also, ET data were not

collected during the Dugas et al. (1998) study for the months of November through February, nor were they subsequently estimated. Finally, Wilcox (2008) states: “According to USGS streamflow measurements for the same years as the Dugas et al, 1998 study, Seco Creek streamflow makes up 20% of the water budget; therefore on the basis of the water budget method, ET would constitute around 80%, a figure 15% higher than that (65%) derived by Dugas et al, (1998).”

Additionally, Jones, et al. (2011) aggregate recharge rates for the Hill Country Trinity Aquifer from every creditable investigation. Table 5-1 in that report presents recharge as a percent of mean precipitation for each of the 10 studies. Based on the studies, the recharge rates range from 1.5% of precipitation to 11% of precipitation; the mean value for the 10 studies is 6% of precipitation. Most of the reports were authored by the TWDB or USGS. The TWDB Groundwater Availability Model used a recharge rate equivalent to 3.5% to 5% of average annual precipitation for the Hill Country Trinity Aquifer (Jones et al. 2011).

The following is a simple long-term budget of precipitation and recharge volumes, which indicates interstream recharge to be much less than 28% of precipitation on the recharge area as reported by Hauwert and Sharp (2014).

1. Based on long-term precipitation data from the National Weather Service gage in Austin, the annual-mean precipitation is about 33 inches per year, as documented online at <http://www.weather.gov/climate/xmacis.php?wfo=ewx>
2. Thirty-three inches of annual-mean precipitation over the 90 square-mile recharge area produces a precipitation volume of 158,400 acre-feet per year.
3. Applying 28% of that precipitation as interstream recharge produces 44,400 acre-feet per year, a value equivalent to 61 cubic feet per second.

As shown in Table 4, Hauwert (2011) concludes that 56% to 67% of total recharge occurs on the main channels of the major streams; Slade (1986 and 2014) indicate 75% of total recharge to occur on the main channels; and this (Slade) paper documents 74% of total recharge to occur on the main channels. Based on these reports, interstream recharge (61 cubic feet per second as referenced above) thus ranges from 25% to 44% of total recharge. Therefore, based on Hauwert and Sharp’s (2014) interstream recharge rate of 28% of precipitation, long-term total mean recharge would represent a range of 139 cubic feet per second to 244 cubic feet per second. However, as documented in the section “Long-term mean discharge from the Edwards Aquifer”, the long-term (1917–2013) mean discharge, and thus recharge, for the Barton Springs segment of the Edwards Aquifer is 67 cubic feet per second. Accordingly, an interstream recharge rate of 28% of precipitation produces recharge values that range from 207% to 364% of the documented long-term mean recharge value.

This same type of analysis documents that interstream recharge as 15% of precipitation, as claimed by the Hauwert 2011 budget (Table 4), also would produce total long-term recharge volumes much greater than documented.

Because the long-term mean recharge and recharge contributed by the major streambeds is known, the long-term mean interstream recharge to the aquifer can be calculated and expressed as a percent of mean-annual precipitation on the recharge area. Table 4 documents recharge on the main channels as a percent of total recharge. Based on the 3 studies with such values, 70% represents the mean value for main channel recharge as a percent of total recharge. Therefore, 30% of total recharge occurs as interstream recharge. As documented earlier, the long-term mean discharge from the aquifer is 67 cubic feet per second, as is the long-term mean recharge. Therefore, interstream recharge calculates to be 20 cubic feet per second or 14,500 acre-feet per year. Interstream recharge thus represents 0.25 feet of depth over the recharge area of 90 square miles or 57,600 acres. Based on the mean-annual precipitation value of 33 inches (2.75 feet) per year over the recharge area, interstream recharge thus calculates to be 9% of precipitation. As Table 4 shows, 9% of interstream recharge as a percent of precipitation on the recharge area represents a value much less than those produced by Hauwert (2011) and Hauwert and Sharp (2014).

SUMMARY AND RECOMMENDATIONS

The Barton Springs segment of the Edwards Aquifer represents a small, relatively independent part of the aquifer. Data for the sources of recharge and especially for discharge from the aquifer are well documented. Based on the 2 water budgets that include documentation of surface recharge and surface discharge values (Slade 2014) and the one herein, the volumes match within 5%, which is within the potential error limits of the recharge and discharge values. Each budget includes only surface sources of recharge and discharge. However, each budget represents discharges slightly greater than long-term mean-flow conditions, during which time subsurface recharge to the aquifer likely is minimal or nonexistent. During some low-flow conditions, subsurface recharge enters the Barton Springs segment of the Edwards Aquifer from south of the segment boundary through discharge from the Blanco River watershed.

All streamflow gaging stations needed to conduct water budgets for present or future periods remain in operation except for the station on Bear Creek near Brodie Lane. That station, located near the downstream boundary of the recharge area, was discontinued on September 30, 2010. An alternative station that could be used to calculate recharge volumes for the Bear Creek Basin does not exist. Additionally, this basin

is important for budget calculations because its recharge data are used to estimate recharge volumes for the adjacent Little Bear Creek Basin, which also is not gaged. Therefore, without a gaging station on Bear Creek downstream from the recharge area, water budgets for periods after September 2010 would potentially contain substantial errors.

Substantial urban development is occurring atop the Edwards Aquifer. About 60,000 people depend on the Barton Springs segment of this aquifer as their sole-source water supply. However, only 2 complete water budgets have been identified for the aquifer. Water budgets for future conditions should be compiled and used to document changes in the sources and volumes of recharge and discharge. For example, as groundwater withdrawals increase, it is likely that groundwater levels would decrease and therefore cause groundwater gradients to increase toward the area of pumping from south of the Barton Springs segment. Such steeping of the gradient could induce additional and more frequent subsurface recharge from the Blanco River.

Much data are being collected and many studies are continuing to document the quality of surface and subsurface water within the aquifer boundaries. Additionally, the city of Austin, BSEACD, and many other governmental and private organizations are documenting, evaluating, and regulating specific land-use practices within the contributing and recharge areas in order to protect the water quality of the aquifer. However, if subsurface recharge increases from the Blanco River, the water quality of the river and adjacent aquifer should be assessed. Additionally, land-use practices within the Blanco River Basin would need to be monitored and evaluated as potential sources of contamination. However, the best documentation of the occurrence and distribution of recharge from the Blanco River would be obtained from water budget recharge-discharge analyses—analyses that unfortunately cannot be decisively conducted since October 2010 because of the discontinuance of the Bear Creek streamflow station.

SUPPLEMENTAL INFORMATION

Other discharges

From 1916 to 1930 many discharge measurements were made on the Colorado River immediately downstream from the Austin Dam (now Tom Miller Dam). For many of these measurements, near same-date measurements were made for Barton Springs discharge, and, during the period, the USGS operated a streamflow-gaging station on the Colorado River at Congress Avenue (Table 5). When Barton Creek was no-flow upstream from Barton Springs, the springs represented the only major source of water to the river reach between Tom Miller Dam and Congress Avenue. The only other major sources

Table 5. Discharge measurements made on the Colorado River along the contact between the river and the Edwards Aquifer.

Date	Measured discharge at site (cubic feet per second)			Flow gain (+) or loss (-) in reach
	Below Austin Dam ¹	Barton Springs ²	Streamflow gaging station at Congress Ave. ³	
Sep. 06, 1916	109	28.0	138	1.0
Aug. 22, 1917	53.4	15.0	68	-0.4
Aug. 24, 1917	45.3	15.4	60	-0.7
Aug. 28, 1917	39.2	14.3	52	-1.5
Aug. 21, 1918	10.2	14.0	24	-0.2
Aug. 22, 1918	9.1	14.0	25	1.9
Aug. 08, 1921	66	39.0	112	7.0
Aug. 13, 1930	18.9	24.0	45	2.1
Mean values		20.5		1.2

Measuring sites other than Barton Springs are on the Colorado River

¹TBWE 1959

²TBWE 1959

³http://waterdata.usgs.gov/tx/nwis/nwisman/?site_no=08158000&agency_cd=USGS

represented discharge from Cold Springs, runoff from streams such as Shoal and Waller Creeks, and any discharges from the Edwards Aquifer to the river. In order to document the total discharge for the other sources, the sum of the same-date discharges for the river below the dam and Barton Springs was subtracted from the same-date discharge gaged at Congress Avenue. Selected dates represent those which occurred during relatively steady-state flow conditions, had discharges less than 150 cubic feet per second at Congress Avenue, and had no flow for Barton Creek upstream from Barton Springs. The potential error for gaged discharges is about 5%; discharges exceeding 150 cubic feet per second could have potential errors that adversely affect the values of the components of the budget.

The calculated gain in the river represents the discharge for Cold Springs plus stream runoff and discharges from the Edwards Aquifer to the river. As Table 5 documents, the gain is minor. In some cases a minor loss rather than gain in the reach is indicated, likely due to errors in the discharge measurements. The mean discharge gain for the 8 measurements is only 1.2 cubic feet per second, part of which could represent stream runoff. Therefore, based on the dates, the gain from the Edwards Aquifer is limited to a maximum of only 1.2 cubic feet per second. However, the mean discharge for Barton Springs for the measurement dates is only 20.5 cubic feet per second, which, based on springflow data from 1917 to 1982, is about 38% of its long-term mean discharge of 54 cubic feet

per second as documented earlier. Therefore, the discharge for Cold Springs and any other Edwards springs likely is minimal during low-flow conditions for Barton Springs.

Recharge

Selected for analysis within the city of Austin (2009) report is all but one streamflow-gaging site with less than about 60% IC and located in or near the contributing area for the Edwards Aquifer (Figure 2). The gaging site designated as WBA was excluded because it is a civic center, which is not representative of typical urban development. Those sites within the recharge area were excluded from this analysis because some of the runoff would likely be lost as recharge thus not gaged as outflow from the basin. An upper limit for IC densities is used herein because the coefficient of determination between values of IC and RC substantially decreases for sites that include the full range in IC values. Additionally, the IC values for the contributing and recharge areas are less than 30% (Table 2). The relation between the IC densities and RC is presented in Figure 2 for the 8 sites that meet the criteria for inclusion. The equation for calculating the RC based on the IC value also is included in Figure 2. The coefficient of determination for the relation is 0.87.

An explanation for the use of urban runoff within the recharge volume calculation follows. The equation for calculating the

runoff coefficient is $RC = 0.47 (IC) + 0.05$ as shown in Figure 2. For example, the contributing area for Slaughter Creek has an IC density of 7.41% (Table 2); based on the RC formula, the RC calculates to be 8.5% of precipitation for the contributing area. The IC density for the recharge area is 11.5%; based on the RC formula, the RC calculates to be 10.4% of precipitation. Therefore, the RC for the recharge area exceeds that for the contributing area by 1.9%. In order to estimate runoff from the recharge area, the unit value (runoff per square mile) from the contributing area thus was multiplied by 1.019 and then multiplied by the drainage area for the recharge area.

However, for calculating the increase in RC (from the contributing area to the recharge area) based on the increase in IC, the formula offset of 0.05 would not be applicable. Therefore, the formula becomes $\Delta RC = 0.47 (\Delta IC)$, where ΔRC represents the increase in RC and ΔIC represents the increase in IC density. Based on the example for Slaughter Creek in the previous paragraph, the recharge area has an IC density about 4.1% greater than that for the contributing area. Therefore, based on the ΔRC formula, the RC for the recharge area calculates to be 1.9% greater than that for the contributing area.

For the contributing and recharge areas, the largest difference between IC values exists for Barton Creek; the recharge area has an IC density that exceeds that of the contributing area by 17.5% (Table 2). However, Little Barton Creek is a tributary to Barton Creek, thus with the inclusion of Little Barton Creek, the IC density for the entire Barton Creek contributing area calculates to be 4.8%, which is 17.3% less than that in the recharge area. For each of the Bear, Little Bear, and Onion Creek basins, the IC densities for the contributing and recharge areas are comparable; thus no IC adjustment was made for recharge calculations for those basins.

The recharge calculation adjustment is based on the IC density values for the year 2003. A later (2006) documentation of IC densities for the basins was provided by Erin Wood (City of Austin, written commun.). However, for the 2006 documentation, the IC densities are aggregated by total basin area and do not include separate density values for the contributing areas or recharge areas. For the entire basins, increases in the IC densities from 2003 to 2006 are as follows: Barton Creek (0%); Williamson Creek (3%); Slaughter Creek (3%); Bear Creek (1%); Little Bear Creek (0%); and Onion creek (2%). Based on these minimal increases in IC densities for each of the entire basins, it is likely, for each basin, that differences in IC densities between the contributing and recharge areas had minimal if any changes from 2003 to 2006. It is also likely that the IC differences had minimal if any changes from 2006 to the end of the budget period in 2009. Therefore, the difference between IC densities between the contributing and recharge areas as used herein are believed to represent that for the entire budget period.

REFERENCES

- Austin, City Of. 2009. Stormwater runoff quality and quantity from small watersheds in Austin, TX: Updated through 2008. Austin (Texas): City of Austin. Report number: CM-09-03. http://www.austintexas.gov/watershed_protection/publications/document.cfm?id=196394
- Brune G. 1975. Major and historical springs of Texas. Austin (Texas): Texas Water Development Board. Report 189. 94 p.
- Brune G, Duffin GL. 1983. Occurrence, availability, and quality of groundwater in Travis County, Texas. Austin (Texas): Texas Department of Water Resources. Report 276, 219 p.
- Casteel R, Hunt B, Smith B. 2013. Evaluating the hydrologic connection of the Blanco River and Barton Springs using discharge and geochemical data: BSEACD Report of Investigations 2013-0701. http://bseacd.org/uploads/Blanco_Barton-Report_FINAL.pdf
- Dugas WA, Hicks RA, Wright P. 1998. Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek Watershed. *Water Resource Research*. 34(6):1499-1506. doi:[10.1029/98WR00556](https://doi.org/10.1029/98WR00556)
- Garza S. 1962. Recharge, discharge, and changes in groundwater storage in the Edwards and associated limestones, San Antonio area, Texas, a progress report on studies, 1955-59. Austin (Texas): Texas Board of Water Engineers. Bulletin 6201. 51 p. <https://www.twddb.texas.gov/publications/reports/bulletins/doc/B6201.pdf>
- Hauwert N, Johns D, Aley T, Sansom J. 2004. Groundwater tracing study of the Barton Springs segment of the Edwards Aquifer, Southern Travis and Northern Hays counties, Texas. Report by the Barton Springs/Edwards Aquifer Conservation District and City of Austin Watershed Protection and Development Review Department. 110 p. http://www.austintexas.gov/watershed_protection/publications/document.cfm?id=186140
- Hauwert N. 2011. Water budget of stream recharge sources to Barton Springs segment of Edwards Aquifer: 14th World Lake Conference. Austin (Texas): Oct. 31 - Nov. 4, 2001, p. 46.
- Hauwert NM, Sharp JM. 2014. Measuring autogenic recharge over a karst aquifer utilizing eddy covariance evapotranspiration. *Journal of Water Resource and Protection*. 6:869-879. <http://www.scirp.org/journal/PaperInformation.aspx?paperID=47399>
- Heilman JL, McInnes KJ, Kjølgaard JF, Owens MK, Schwining S. 2009. Energy balance and water use in a subtropical karst woodland on the Edwards Plateau. *Journal of Hydrology*. 373(3-4):426-435. <http://www.sciencedirect.com/science/article/pii/S0022169409002960>

- Johnson S, Schindel G, Veni G, Hauwert N, Hunt B, Smith B, Gary M. 2012. Tracing groundwater flowpaths in the vicinity of San Marcos Springs, Texas. San Antonio (Texas): Edwards Aquifer Authority. 139. http://bseacd.org/uploads/blanco-report-8-17-2012_low-res.pdf
- Jones IC, Anaya R, Wade S. 2011. Groundwater availability model: Hill Country portion of the Trinity Aquifer of Texas. Austin (Texas): Texas Water Development Board. Report 377. 165 p. http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R377_HillCountryGAM.pdf
- Naismith Engineering Inc. 2005. Regional water quality protection plan for the Barton Springs segment of the Edwards Aquifer and its contributing zone, Part 1. <http://www.waterqualityplan.org/index.php?BODY=finaldraft>
- Puente C. 1978. Method of estimating natural recharge to the Edwards aquifer in the San Antonio area, Texas. Austin (Texas): U.S. Geological Survey Water-Resources Investigations Report 78-10, 34 p. <http://pubs.usgs.gov/wri/1978/0010/report.pdf>
- Slade RM Jr, Dorsey ME, Stewart SL. 1986. Hydrology and water quality of Barton Springs and associated Edwards aquifer in the Austin area, Texas. Austin (Texas): U.S. Geological Survey Water-Resources Investigations Report 86-4036, 117 p. <http://pubs.er.usgs.gov/pubs/wri/wri864036>
- Slade RM Jr. 2014. 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. Texas Water Journal. 5(1):12-23. <https://journals.tdl.org/twj/index.php/twj/article/view/6988>
- [TBWE] Texas Board of Water Engineers. 1959. Summary of peak flood flow measurements and other measurements of stream discharge in Texas at points other than gaging stations. Austin (Texas): Texas Water Development Board. Bulletin 5807 C. 255 p. <http://www.twdb.texas.gov/publications/reports/bulletins/doc/B5807C.pdf>
- [TBWE] Texas Board of Water Engineers. 1960. Channel gain and loss investigations. Austin (Texas): Texas Water Development Board. Bulletin 5807 D. 270 p. <http://www.twdb.texas.gov/publications/reports/bulletins/doc/B5807D.pdf>
- Wilcox BP. 2008. Juniperus woodland and the water cycle on karst rangelands. In: Van Auken OW, Smeins F, editors. Western North American Juniperus communities: a dynamic vegetation type.. New York (New York): Springer Ecological Studies. Vol. 196, 2008, p. 202-215, http://link.springer.com/chapter/10.1007/978-0-387-34003-6_11