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Stream Recharge Water Balance for the Barton Springs Segment of the Edwards Aquifer

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Abstract: Channel water balance analysis based on streamflow loss coupled with traced groundwater basins allow refinement of upland autogenic recharge values comparable to those derived from more precise site-scaled measurements. Based on total discharge and calculated flow loss in major stream channels, the channel contributions to recharge on the Barton Springs Segment of the Edwards (Balcones Fault Zone) Aquifer are: Onion Creek (32.6%), Barton Creek (less than 10.5%), Slaughter Creek (7.2%), Bear Creek (6.2%), Blanco River (6%), Little Bear Creek (3.4%), and Williamson Creek (1%). Major stream channels contributed from 56% to 67% of total groundwater recharge to the groundwater system, 17% of which was stream autogenic recharge, while upland autogenic recharge and other smaller sources contributed the remaining 33% to 44%. As a percent of precipitation over the Edwards Aquifer outcrop source area, autogenic recharge (upland and tributary recharge in the major stream channels) was 22% to 28%, compared with a recharge value of 28% of precipitation from climate tower water balances in Central Texas. Prior to delineation of groundwater basins using injected tracers, older channel water balance studies determined that upland autogenic recharge was only 15% of the total groundwater recharge (about 1% of precipitation). This study suggests that the channel water balance approach, based on gauged streamflow and spring discharge, is more accurate when one incorporates groundwater basins delineated by groundwater tracing, especially in karst aquifers. Refinement of an appropriate catchment area for the calculation of autogenic recharge also significantly affected the results of a precipitation water balance.

Keywords: *water balance, karst, Edwards Aquifer, Barton Springs, recharge*

The amount of rainfall that recharges an aquifer varies more directly with rock type than soil characteristics, surface morphology, or annual precipitation patterns (Maxey 1964; Weyer 1971; Misstear et al. 2009). Karst terranes are generally composed of limestone and contain internal drainage morphology that allows rainfall to infiltrate rapidly and recharge the aquifers (Jennings 1985). Much surface runoff over karst limestone areas flows only short distances before infiltrating into sinkholes (dolines) or highly permeable soils (Meinzer 1923, 123; White 1977). Autogenic recharge originates from direct precipitation over the recharge zone, a portion of which recharges within the intervening area (upland autogenic recharge) and the remaining recharges via runoff to the major stream channels (stream autogenic recharge). In karst areas of the world, autogenic recharge is typically 20% of precipitation or greater (Hauwert and Sharp 2014). Allogenic recharge sources originate as runoff from upstream of the outcrop of a karst aquifer.

The limitations of recharge measurement techniques are summarized by Lerner et al. (1990); Scanlon et al. (2002); De Vries and Simmers (2002); Taylor and Greene (2008); and Sophocleous (2009). "*Because recharge is not easy to measure directly, estimates of its value are prone to large errors... The most serious and common type of error is an error in the conceptual model. It arises when the recharge process is not fully understood, or when too many simplifying assumptions are made"* Sophocleous (2009, 21). The channel water balance method measures recharge using the difference in upstream and downstream flow stations; flow diversions and additions; stream evapotranspiration; and storage that does not reach the water table (Lerner 1997; Nimmo et al.

2005). Runoff and infiltration occurring between the gauging stations are difficult to distinguish. Furthermore, in areas where adequate direct groundwater tracing is not incorporated, it is not known with certainty where the measured stream recharge actually discharges from an aquifer (Lerner et al. 1990). Recharge and storage characteristics of aquifers are also quantified using hydrograph separation of stream baseflow and spring discharge recessions (Rorabaugh 1964; Hobbs and Smart 1986; Tallaksen 1995; Florea and Vacher 2006), although the results can be misinterpreted in areas where the water sources are not known (Anderson and Burt 1980; Halford and Mayer 2000). For example, stream flow measured in a watershed may originate from recharge in another watershed (Omernik 2003). Springflow recessions are commonly used to distinguish quick and slow components of karst aquifer discharge, but tracing data is rarely available to identify what the water sources are (Long 2009). In water balances of karst systems, traditional methods of delineating groundwater basins such as water-level mapping, hydraulic well testing, geochemical characterization, and modeling alone are not adequate and direct groundwater tracing techniques are necessary (Ford and Williams 1989; White 1993; Taylor and Greene 2008). Historically, channel water balances were the primary method on which groundwater recharge of an area was estimated in Texas (Bennett and Sayre 1962; Garza 1962; Maclay 1995), but these older studies lacked direct tracing of source areas and relied on assumptions of groundwater divides and groundwater sources.

The Barton Springs Segment of the Edwards (Balcones Fault Zone) Aquifer (or Barton Springs Segment, Figure 1) is a karstic, federally designated sole source aquifer that discharges to the Colorado River through Barton Creek. Its largest discharge site is Barton Springs (Figure 2), a set of at least four springs which are the habitat of the federally listed endangered Barton Springs Salamander (*Eurycea sosorum*) and Austin Blind Salamander (*Eurycea waterlooensis*). Cold Springs is another major spring that discharges from the south bank of the Colorado River 2.5 km (1.5 mi) upstream from the mouth of Barton Creek (Figure 1).

The Barton Springs Segment is bounded by the incised Colorado River to the north, the outcrop limit of formations (Small et al. 1996) comprising the Edwards Aquifer to the west, the boundary of fresh water and non-potable Saline Water Zone to the east, and a southern groundwater divide that shifts between the Blanco River to Onion Creek (Figure 1). Hydrologic zones associated with the Barton Springs Segment are the recharge zone, confined or artesian zone, and contributing zone. Within the 243 km^2 (94 mi^2) recharge zone of the Barton Springs Segment, surface water can recharge the aquifer. The recharge zone is based on surface geological mapping (Hill and Vaughn 1898; Guyton and Associates 1964; Slagle et al. 1984; Small et al.1996; Hauwert 2009). Barton, Williamson, Slaughter, Bear, Little Bear, and Onion Creeks and the Blanco River cross the recharge zone and carry streamflow from the upstream contributing zones as well as storm runoff from the upland intervening area across the recharge zone (Guyton and Associates 1964; Slade et al. 1986; Johnson et al. 2012). Swallets are point features, generally sinkholes, within the stream channels where discrete flow loss occurs. The intervening area comprises upland portions of the recharge zone between major stream channels, and includes tributaries to the major stream channels. Runoff from about 10% of the recharge zone does not flow to surface streams under natural conditions but is contained within internal drainage sinkhole basins (Hauwert et al. 2005) that reflect the tendency of the recharge zone to infiltrate runoff (Williams 1972). The confined zone is a 129 km^2 (50 mi^2) area east of the recharge zone where the Edwards Aquifer is overlain by confining clays and limestone. Groundwater levels are below the top of the aquifer along much of the western edge of the confined zone, such that artesian aquifer conditions may not necessarily be present. The upstream contributing zone of Barton, Williamson, Slaughter, Bear, and Onion Creeks is about 673 km^2 (260 mi^2) and is underlain primarily by rocks of the Trinity Group (Mace et al. 2000) that may serve as sources of allogenic inflows to the Barton Springs Segment.

The mean flow of Barton Springs was calculated in Slade et al. (1986) to be 1.5 m^3/s (50 ft^3/s), based on 728 flow measurements taken over 62 years and three years of continuous measurement

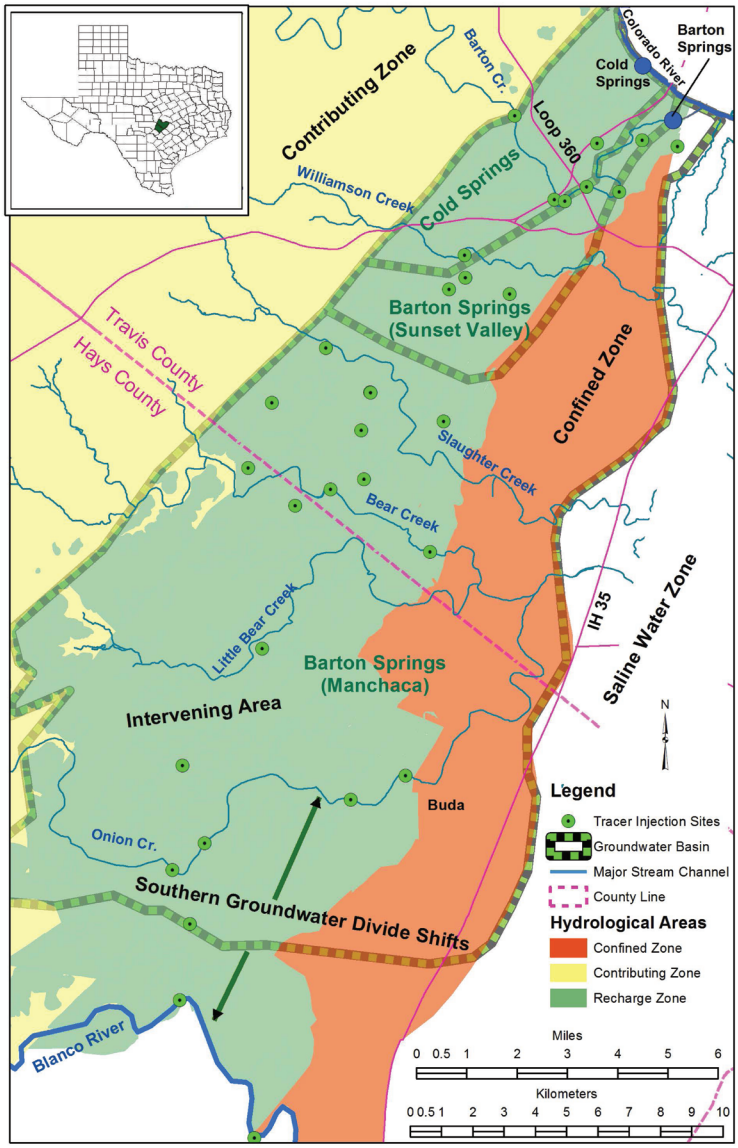

Figure 1. Map of the Barton Springs Segment.

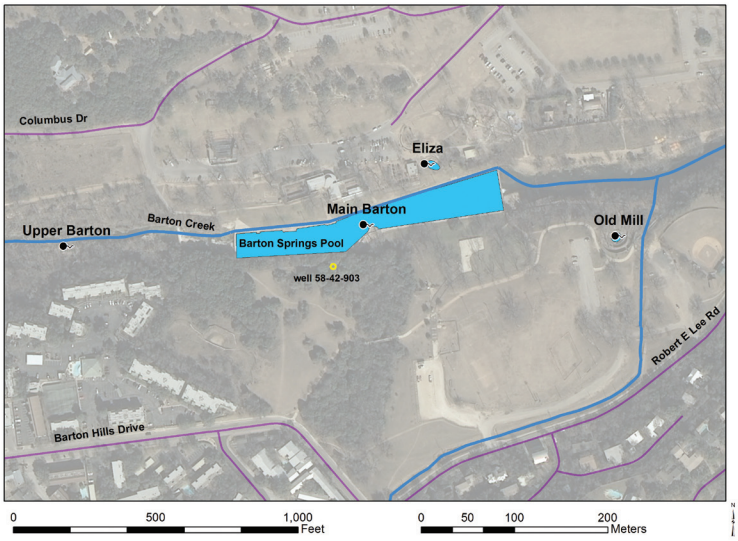

Figure 2. Map of Barton Springs.

based in part on stage discharge rating curve from a nearby well (state well 58-42-903, Figure 2). However, Barton Springs discharge, continuously measured over 36 years from 1978 to 2014 by USGS, show a higher discharge mean of 1.74 m^3/s (62 ft^3/s) and mean pumpage of 0.17 m^3/s (6 ft^3/s), for a mean total discharge of 1.9 m^3/s (68 ft^3/s) (Hunt et al. 2012; Johns 2015). Note that USGS excludes Upper Barton Springs discharge as well as other spring discharge to Barton Creek upstream of Barton Springs pool from its reported Barton Springs discharge. Record low discharges from Barton Springs of 0.27 m^3/s (9.6 ft^3/s) were measured on March 29, 1956 and 0.34 m^3/s (12.1 ft^3/s) on February 26, 1918 (Grover 1922; Twichell 1958). On May 10, 1941 a high discharge of 4.7 m^3/s (166 ft^3/s) was measured (Parker 1943). The long-term average rainfall for Austin is 85.1 cm (33.5 inches, Johns 2015).

Urbanization of the study area expanded during the 1980's, and the USGS, with the support of the University of Texas, the Texas Water Development Board, and the City of Austin, conducted a study of the Barton Springs Segment. This study established permanent stream-flow gauging stations on the upstream side of the recharge zone, continuously gauged Barton Springs discharge, mapped the groundwater-level surface, produced hydrogeological cross sections of the Barton Springs Segment, and evaluated Barton Springs water quality (Senger 1983; Senger and Kreitler 1984; Baker et al. 1986; Slade et al. 1986). Perhaps the most frequently cited aspect of the study was a channel water balance that first calculated the stream contributions to Barton Springs based on continuous and intermittent gauging stations on five of the six streams within the assumed source area for Barton Springs discharge (Slade et al. 1986). Groundwater basins had not yet been directly delineated using injected tracers. Slade et al. (1986) concluded that 85% of Barton Springs discharge was recharged from the major stream channels and only 15% was from upland autogenic recharge attributed to the upland intervening areas. A precipitation water balance calculated 85% evapotranspiration, 6% (allogenic + autogenic) recharge, and 9% runoff from the recharge zone (Woodruff 1984; Slade et al. 1986). Of the 6% recharge to the Edwards Aquifer from precipitation, 5% was calculated as stream (allogenic + autogenic) recharge and 1% as upland autogenic recharge (Woodruff 1984). The calculation utilized precipitation over the entire recharge and contributing zone.

The channel water balance calculation of recharge heavily shaped the growth of Austin over the recharge zone since the 1980's. These relatively low upland recharge and high evapotranspiration values have frequently been cited (URM 1983; Texas DOT 1989; Woodruff 1998; Woodruff 2010) as evidence that these recharge sources outside of the major stream channels are relatively insignificant sources of recharge to the Barton Springs Segment. Common land management practices during the 1980's and 1990's included diverting storm-water runoff into sinkholes; converting sinkholes into water-quality ponds and livestock ponds; building over caves and sinkholes; and irrigating treated wastewater over the Edwards Aquifer (Veni and Hauwert 2015). During this period, the Edwards (Balcones and Edwards Plateau Zones) Aquifer also experienced a number of pathogenic outbreaks and petroleum pipeline ruptures (Rose 1986; Hernandez 2015). In 1986, the Hays County Soil and Water District petitioned the Environmental Protection Agency to protect the Barton Springs Segment for an estimated 22,800 people reliant on water supply wells, and it was designated as a federally-designated sole source aquifer in 1988 (Federal Register 1988). In 1991, citizens of Austin petitioned and voted to enact the non-degradation Save-Our-Springs ordinance, providing Barton Springs with more protection from development. Maintaining the quality and quantity of water in the Barton Springs Segment is deemed important by the City of Austin and over 155 million dollars of voter-approved bonds have been utilized to preserve 22% of the recharge zone (Thuesen 2013). The watersheds of the recharge and contributing zone remain relatively rural, but urbanization continues to expand over the Barton Springs Segment. As recently as 2010, the low (less than 1%) autogenic recharge from precipitation estimate derived from the channel balance method was used to minimize the potential impacts of large-scale wastewater irrigation over the recharge zone (Woodruff 2010). The groundwater basins assumed in the 1980's channel water balance were also incorporated in

groundwater models (Slade et al. 1985; Barrett and Charbeneau 1996; Passarella et al. 2012) including Groundwater Availability Models used by the State of Texas to manage groundwater pumpage (Scanlon et al. 2001; Hutchinson and Hill 2011). Herrington et al. (2010) calculated the density of impervious structures exclusive of roads and some parking lots using 2008 county tax appraisal district records and measured values for Barton (2%), Williamson (11%), Slaughter (4%), Bear (1%), and Onion (0.2%) Creeks, or about 18% total impervious cover.

Beginning in the 1990's, site specific water balances utilized climate towers in Central Texas to measure evapotranspiration directly using eddy covariance or Bowen ratio systems combined with weirs and flumes to measure surface runoff. The autogenic recharge is calculated by subtracting from measured precipitation the measured actual evapotranspiration, measured runoff, and any change in soil moisture storage. A five-year water balance utilizing a Bowen ratio climate tower, rain gauges, and flumes measured that, out of total precipitation, 65% evapotranspirated, 5% flowed downstream into streams, and the residual 30% recharged the Trinity Aquifer of Uvalde County (Dugas et al. 1998). Huang and Wilcox (2005) observed that autogenic recharge was 18% less in precipitation water balance measurements based on channel water balance method when compared to measurements of the site specific climate tower water balance reported by Dugas et al. (1998). Wilcox (2008) also noted a 35% precipitation water balance discrepancy between evapotranspiration calculated by stream gauging in a channel water balance study (Maclay 1995) and direct climate tower measured evapotranspiration (Dugas et al. 1998) within the same Seco Creek watershed. In their compilation of published annualized Central Texas climate tower and runoff data, including data from one station within the Barton Springs Segment, Hauwert and Sharp (2014) note that of average annual precipitation over Central Texas Edwards and Trinity Aquifers, 69% evapotranspirated, 28% recharged, and 3% ran off upland areas. These data also show that recharge and evapotranspiration vary directly with annual precipitation, but the difference in values between sites across Central Texas karst aquifers was not so great as to account for the variation in results derived from channel water balance and climate tower methods. Wilcox (2008) noted that the measurement of precipitation water balance components using site scaled climate towers and flumes is more precise, and questioned why the channel water balance method underestimated recharge and overestimated evapotranspiration.

A long-distance groundwater tracing study by the Barton Springs/Edwards Aquifer Conservation District (BS/EACD) and City of Austin commenced in 1996. The results from 40 groundwater traces with 88% successful recovery rate delineated groundwater basins and flowpaths within the Barton Springs Segment (Hauwert et al. 2004a; Hauwert 2009; Hauwert 2015; Figure 1). Study conclusions are:

1. Rapid groundwater flow rates measured directly by tracing, with mean residence times of one to eight days, contradict some previous estimates of residence times of three to five years (Texas DOT 1989; Alexander 1990) that have been used to plan responses to accidental spills.
2. The entire portion of Barton Creek upstream of the streamflow gauge at Loop 360 (Figure 1), estimated by the channel water balance method to contribute 28% of the recharge to Barton Springs (Slade et al. 1986), was traced, under varying aquifer conditions, to Cold Springs rather than Barton Springs. An attempted groundwater trace by the USGS in 1981 on Barton Creek upstream of Loop 360 also was not detected at Barton Springs (Slade 2008).
3. The upstream 2 km (1.3 mi) of Williamson Creek over the recharge zone lies in the Cold Springs groundwater basin (Hauwert et al. 2004a).
4. The recharge zone of the Barton Springs Segment contains groundwater basins contributing to Barton and Cold Springs that are 212 km^2 and 31 km^2 (82 mi^2 and 12 mi^2), respectively (Hauwert 2009, 94 and 149), although portions of these areas contain the outcrop exposure of some overlying confining units. Excluding isolated internal portions of the recharge zone covered with clays, shales, and other overlying confining units, the

Edwards Aquifer outcrop area recharging to Barton Springs is 176 km^2 (68 mi^2).

5. The tracers flowed as pulses under conduit flow, 1,000 to 60,000 times more than the disperse flow component under non-drought conditions (Hauwert 2015). Based on the tracer breakthroughs, attenuation of tracer transport through the aquifer would be negligible from injections as far as 24 km (15 mi) away.
6. A number of injections from the Blanco River have been traced to Barton Springs in 2008 and 2009, during a period when Barton Springs discharge had declined from 1.08 to 0.54 m^3/s (38 to 19 ft^3/s) (Hauwert 2011; Johnson et al. 2012). The tracers injected in 2008 and 2009 also were recovered in wells to the south and may have also discharged from San Marcos Springs. At an unknown higher flow condition, the Blanco River ceases supplying water to Barton Springs and a portion of Onion Creek recharge diverts to San Marcos Springs (Hunt et al. 2004; Hauwert 2009).

In a channel water balance of the entire Barton Springs Segment, when comparing stream flow loss to aquifer discharge, if Cold Springs discharge is underestimated then the residual upland autogenic recharge would also be underestimated by the same amount (Hauwert 2009). For instance, Slade (1984, 24) stated that Cold Springs "*consistently flows between 3 to 4 ft^3/s*" (0.085 to 0.113 m^3/s) based on Brune (1975), and that its groundwater basin was 10 km^2 (4 mi^2). Slade (2014, 2015) increased the estimate for a long term mean discharge of Cold Springs in 2014 to 0.156 m^3/s (5.5 ft^3/s) and in 2015 to 0.238 m^3/s (8.4 ft^3/s). However, direct measurement of the submerged discharge of Cold Springs into the Colorado River was not possible even prior to the 1960 construction of Town Lake (renamed to Lady Bird Lake in 2007). The USGS (Hill 1892, 94) evaluated Cold Springs prior to the construction of a downstream dam and found "*this group of springs flows a great volume, but inasmuch as they break out in the river's edge, it is impossible to gauge them. The aggregate volume of these springs near Austin is so great that the volume of the river is materially increased by their accession*". Brune (1975) noted that Cold Springs consisted of at least seven spring orifices, although only two orifices are usually exposed. There are no well-documented direct measurements that include discharge from all seven of Cold Springs's known orifices. During lake drawdown conditions on January 29, 2008, I found that four of the (at least) seven Cold Springs orifices were exposed and the combined discharge from these measured to be 0.23 m^3/s (8.2 ft^3/s), and this partial measurement of Cold Springs was 12% of the 1.87 m^3/s (66 ft^3/s) that Barton Springs measured the same day. Other spring outlets from Cold Springs can be detected under some conditions as sites on the mud floor of the river where cool discharging water can be sensed. Tracing results suggest that submerged Cold Springs orifices discharged from recharge sites at least 5 km (3 mi) away, and that, similar to Barton Springs, discharge from the various Cold Springs orifices are derived from different sources (Hauwert et al. 2004a; 2004b). Tracing also showed the Cold Springs groundwater basin is about 31 km^2 (12 mi^2), significantly larger than the previous estimates.

While Cold Springs discharge cannot be measured directly, it has been measured indirectly. Sellards (1934, 366) observed: "*Many of the large springs of Texas are unknown because they are beneath river beds and therefore hidden from view. During dry periods most of the water in surface streams is derived from springs and seepages...The presence of these hidden springs can be determined by gauging stream flow at stations closely spaced in distance*."

Prior to the upstream dam construction in 1940, creating Lake Travis and Lake Buchanan, and downstream dam completion in 1960, the flow of the Colorado River ranged from 0.215 to 6.68 m^3/s (7.6 to 236 ft^3/s) during selected surveys. This would be sufficiently low to measure the discharge indirectly to infer discharge of Cold Springs and other spring discharge between measurement sites. Four discharge surveys of the Colorado River, between Tom Miller Dam and one quarter mile downstream of Deep Eddy, taken on August 1, 1918; August 6, 1918; August 8, 1921; and August 13, 1930, measured increases in discharge of 0.21, 0.12, 0.30, and 0.34 m^3/s (7.5, 4.2, 10.7, and 12.0 ft^3/s) (Grover 1922; Grover and Ellsworth 1923; TBWE 1959). The river gains attributable primarily to Cold Springs discharge were 27% to 54% of Barton Springs discharge measured the same day. A later water balance of Lady Bird

Lake found average gains of 0.82 m^3/s (29 ft^3/s) or roughly half of average Barton Springs discharge in the portion of the lake where Cold Springs is the only known significant spring discharge (Stecher et al. 1992). Using measured flow loss from Barton and Williamson Creeks within the Cold Springs groundwater basin, Hauwert (2009) calculated that Cold Springs has a minimum average discharge greater than 0.42 m^3/s (15 ft^3/s). The combined historical indirect discharge measurements of Cold Springs and other discharge from the Barton Springs Segment along the south bank of the Colorado River suggest an average discharge within the general range of about 0.4 to 1 m^3/s (15 to 35 ft^3/s).

The southern divide for the Barton Springs Segment has also been reevaluated by direct tracing. Prior to direct tracing studies in 2008 and 2009 (Johnson et al. 2012), most studies based on groundwater-level mapping (Petitt and George 1956; Garza 1962; Stein 1995) interpreted that Onion Creek was the southern divide for the Barton Springs Segment under all conditions. The Blanco River was not considered a source to Barton Springs in earlier water budgets. The 2008 and 2009 direct tracing results, short term correlations in flow response, and a shift in Barton Springs recession curve during droughts mirroring Blanco River channel flow loss suggests that the Blanco River may sustain Barton Springs discharge during drought conditions (Hauwert 2011). Because the Blanco recharge is hypothesized to travel to Barton Springs along two groundwater flow paths, one largely confined by overlying clays under artesian conditions and the other largely unconfined, there are both short-term pressure pulses and approximately three month delayed recharge responses (Figure 3). Casteel et al. (2013) included only the portion of recharge from the Blanco River that corresponds with short-term, instantaneous increases in discharge at Barton Springs and quantified a pressure pulse recharge addition of about 0.074 m^3/s (2.6 ft^3/s).

Other potential water sources contributing to the aquifer include: 1) leakage inflows including cross formational groundwater flow from the Trinity Aquifer (Senger 1983); 2) flow from the Saline Water Zone (Senger 1983; Hauwert et al. 2004b); 3) groundwater flow from the San Antonio Segment of the Edwards (Balcones Fault Zone) Aquifer (Hill 1892; Taylor and Schoch 1922; Johnson and Schindel 2008; Land 2010); and 4) municipal water and wastewater that infiltrates and recharges the aquifer (Garcia-Fresca and Sharp 2005; Sharp 2010; Passarella et al. 2012). City of Austin municipal water is derived from the Colorado River and can be considered a type of artificial allogenic recharge. It is not included here in calculations of allogenic recharge, but Passarella et al. (2012) estimated total anthropogenic urban leakage in the Barton Springs Segment to average about 0.098 m^3/s (3.5 ft^3/s). The Saline Water Zone contribution to Barton Springs is calculated to be as much as 3% of Old Mill Springs discharge during drought conditions, but on average contributes a negligible 0.2% to Main and Eliza Springs discharge (Hauwert et al. 2004b).

This study compares measured upstream and downstream streamflow loss to measured total aquifer discharge and average precipitation in order to calculate upland autogenic recharge, stream autogenic recharge, allogenic recharge, and evapotranspiration. It reexamines whether a streamflow loss study can derive recharge values consistent with other recharge measurements once the recharge sources are directly delineated using injected tracers. A water budget for a karst aquifer includes the components of precipitation, discharge through spring discharge and pumpage, downstream runoff, allogenic recharge from upstream contributing areas, autogenic recharge that directly enters the intervening upland outcrop of the aquifer, and autogenic recharge from direct precipitation over the recharge zone that runs off, infiltrates, percolates, and recharges within the major stream channels.

Methods

Streamflow loss sources to Barton Springs were measured using the channel water balance method. Groundwater tracing defined the groundwater basins (Hauwert 2015; Figure 1). Manual low-flow surveys taken from 1998 to 2008 across the recharge zone, combined with similar flow surveys by the USGS from 1980 to 1985, distinguished gaining from losing stream stretches and identified swallets where infiltration is focused. For the first time, beginning in 2003, continuous downstream

and upstream gauging stations were operating on Onion, Bear, Slaughter, Williamson, and Barton Creeks. A 4.3-year time period from May 31, 2003 to September 19, 2007 was selected as the water budget interval containing the best gauging station data from the streams and where starting and ending discharges at Barton Springs were equal. Thus, effects from change in groundwater storage were eliminated.

Total groundwater discharge from the groundwater basins discharging at Barton Springs was calculated as the sum of Barton Springs discharge reported by the U.S. Geological Survey (USGS), lower Barton Creek spring discharge, and pumpage calculated by the BS/EACD. Well pumpage was metered for permitted wells and estimated for unregulated wells (Hunt et al. 2006; Banda et al. 2010). The USGS measures the combined discharge of Main, Eliza, and Old Mill springs, but excludes lower Barton Creek spring discharge, including Upper Barton Springs (Figure 2). On many occasions, where Loop 360 flow gauge reported less than 0.4 m^3/s (15 ft^3/s), lower Barton Creek springflow can be quantified as all stream discharge measured upstream of Barton Springs pool. At the stream gain between Barton Springs pool and a site one mile upstream, discharge was measured manually 19 times between January 1998 and October 2003 by City of Austin (CoA) and BS/EACD staff. These data established a correlation between measured Lower Barton Creek spring discharge and USGS-reported Barton Springs discharge for calculating mean daily lower Barton Creek spring discharge (Table 1).

Because discharge measurement of Cold Springs cannot be directly measured, its discharge was excluded from the total groundwater discharge calculation for this study. Barton Creek downstream of Loop 360 (see Figure 1) generally represents a groundwater divide between Barton Springs and Cold Springs, and the distribution of recharge downstream of Loop 360 to each spring is not yet measured (Hauwert 2009). Consequently, the entire possible range of recharge in Barton Creek channel downstream of Loop 360 was included.

Streamflow loss was calculated from upstream minus downstream daily mean flow at gauging stations in daily time steps to distinguish allogenic and autogenic runoff sources. Gauging stations were located upstream and downstream of the groundwater basins, based on groundwater tracing and low-flow stream surveys (Figure 4). The sensitivity of mean daily intervals was tested on April 2, 2003 by the opening of a single plugged swallet, Crippled Crawfish Cave, resulting in an abrupt increase in potential flow loss from 1.0 m^3/s (35 ft^3/s) up to 1.8 m^3/s (63 ft^3/s) (Figure 5).

Net stream channel recharge was distinguished according to its source, as either intervening area or contributing zone for the major stream channels, except for the Blanco River. Typically, when intervening runoff to the streams is not occurring and there is no autogenic recharge, the allogenic recharge originating from the contributing zone is directly calculated as upstream flow minus downstream flow, and runoff originating from the contributing zone is simply any flow passing the downstream flow station. Downstream runoff is mean daily flow measured at the downstream gauging station.

For relatively short time intervals associated with some precipitation events, the downstream gauging station flow could be higher than the upstream gauging station flow. During such events, short-lived runoff from the intervening area between stream gauges reached the major creek channels and the distinction of recharge and contributing zone major stream channel recharge and runoff

Table 1. Correlation of Lower Barton Creek to Barton Springs Discharge.

Barton Springs Discharge (m^3/s)	Barton Springs Discharge (ft^3/s)	Lower Barton Creek Springflow (m^3/s)
0 - 1.1	0 - 40	0
1.1 - 1.7	40 - 60	0.015*BS
1.7 - 2.8	60 -100	$0.003*(BS)^2 - 0.3336*BS + 0.28$
>2.8	>100	not modeled, but estimated by other means

BS = USGS Reported Barton Springs Discharge.

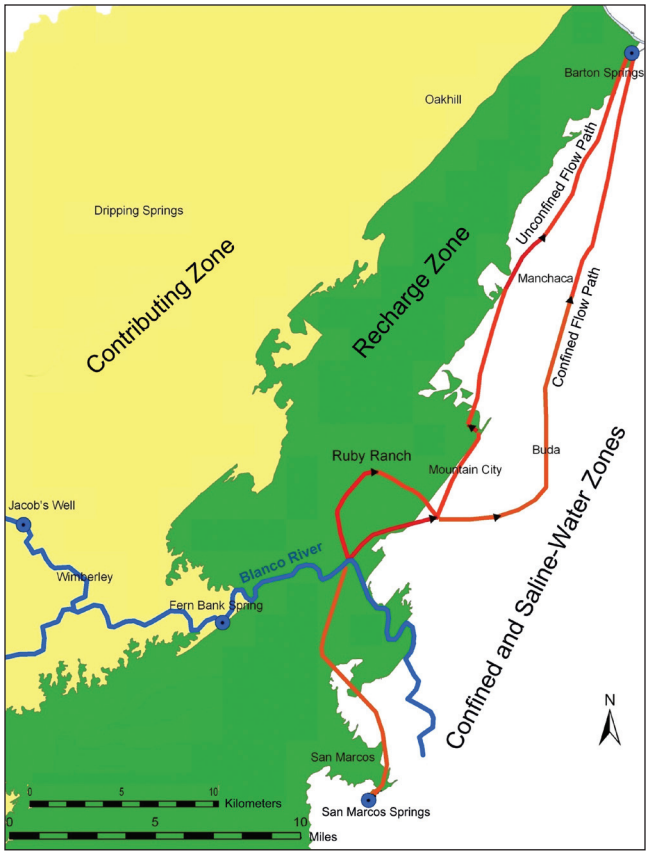

Figure 3. Map of 2008 to 2009 Blanco River Injections and Interpreted Groundwater Flow Paths.

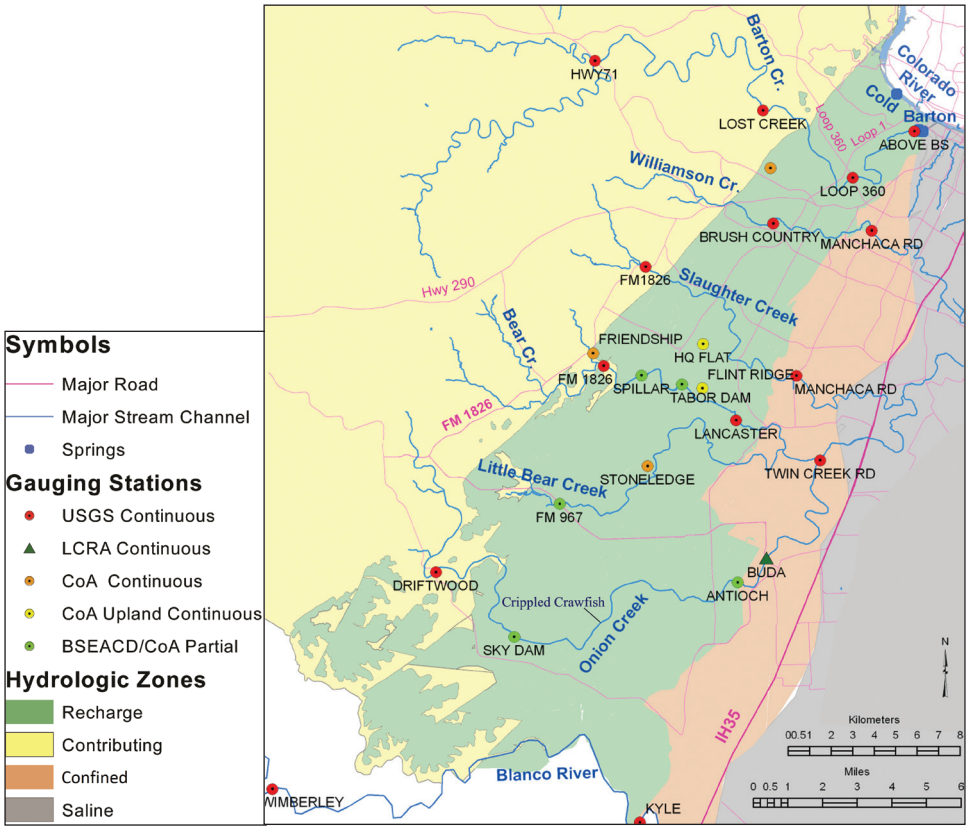

Figure 4. Map of Flow Gauging Stations.

were balanced on daily time steps because:

1. Some intervening area runoff potentially infiltrates in the major stream channels and is not directly measureable from comparing upstream and downstream gauging stations.
2. The amount of contributing zone and intervening area runoff mixtures that runs off beyond the recharge zone cannot be precisely distinguished, although the combination is measured.

Around precipitation events, a time series of potential streamflow loss was plotted versus elapsed time (Figure 6). The corrected flow loss was calculated by extrapolating from declining potential flow loss values back to the start of increasing flow in the stream, using best fit (generally exponential) recession curves. In a few cases, early potential flow loss values did not appear to be greatly affected by intervening runoff and served as data points for extrapolating recession curves. The recession curves were also constrained by the maximum flow loss rate calculated for each stream (Table 2). By comparing upstream minus downstream flows over the period of record, (as applied by Barrett and Charbeneau 1996) the maximum expected flow loss capacity of each stream was estimated and used as a constraint. The amount of intervening area runoff that reached the downstream end of the major stream channels was generally measured as the difference between calculated stream flow loss and potential streamflow loss (Figure 6).

Recession curves were extrapolated for each new runoff event and varied within the same stream due to factors including antecedent rain period, soil moisture, and ground water-levels. For some runoff events on some streams, such as Bear Creek, the recession curve of potential flow loss can be nearly flat over time when the water table is shallow and recharge is temporarily rejected. The effect of correcting potential major streamflow loss increased the net calculated streamflow loss by 27% for Onion Creek, 8% for Bear Creek, 50% for Slaughter Creek, and 67% for Williamson Creek.

Measurements from upland gauging stations (Figure 4) in representative areas at Headquarters Flat (0.19 km^2 or 0.072 mi^2) and Flint Ridge (0.28 km^2 or 0.108 mi^2) were used to calculate the runoff from intervening areas that reach the major creek channels. Both basins are rural former ranchland with oak and juniper-dominated forests mixed with intervening savannahs. The site slopes are generally less than one degree. The runoff is completely contained within internal drainage basins and runs off to cave drains instead of discharge to major streams. Additional details on the upland gauging sites, including topography, soil depths, soil moisture, and vegetation lists are provided by Hauwert (2009). Internal runoff from the upland stations was multiplied by the difference in intervening catchment area for the lower stream gauging station to calculate anticipated runoff. Stream autogenic recharge is calculated around precipitation events on daily time steps to balance runoff to the major stream channels from both the contributing zone and tributaries of the recharge zone minus runoff downstream of the recharge zone.

Eight drought intervals were selected to examine the potential contribution of the Blanco River to Barton Springs during drought conditions. For the selected drought intervals, the daily corrected flow loss of the Blanco River and daily average Barton Springs discharge was summed and compared. By taking entire drought intervals, the effects of both short term pressure pulses with arrival within several days and long-term flow of Blanco River recharge to Barton Springs with roughly three-month delay times can both be quantified.

Corrected and summed streamflow loss was compared to total groundwater discharge in order to calculate the percentage of recharge attributed to each major stream and the Blanco River. The remainder of the total groundwater discharge was assumed to consist of upland autogenic recharge or direct infiltration from the intervening area, with the addition of Trinity Aquifer leakage, Saline Water Zone leakage, urban leakage, and potentially other sources such as groundwater leakage from adjacent segments of the Edwards (Balcones Fault Zone) Aquifer (Figure 7).

The assumptions were that over the water-budget interval:

1. Gauged flow loss in the stream channels completely infiltrated into the subsurface and recharged the aquifer.
2. Evapotranspiration of stream flow in major creek channels was negligible. If the evapotranspiration of stream flow in the major

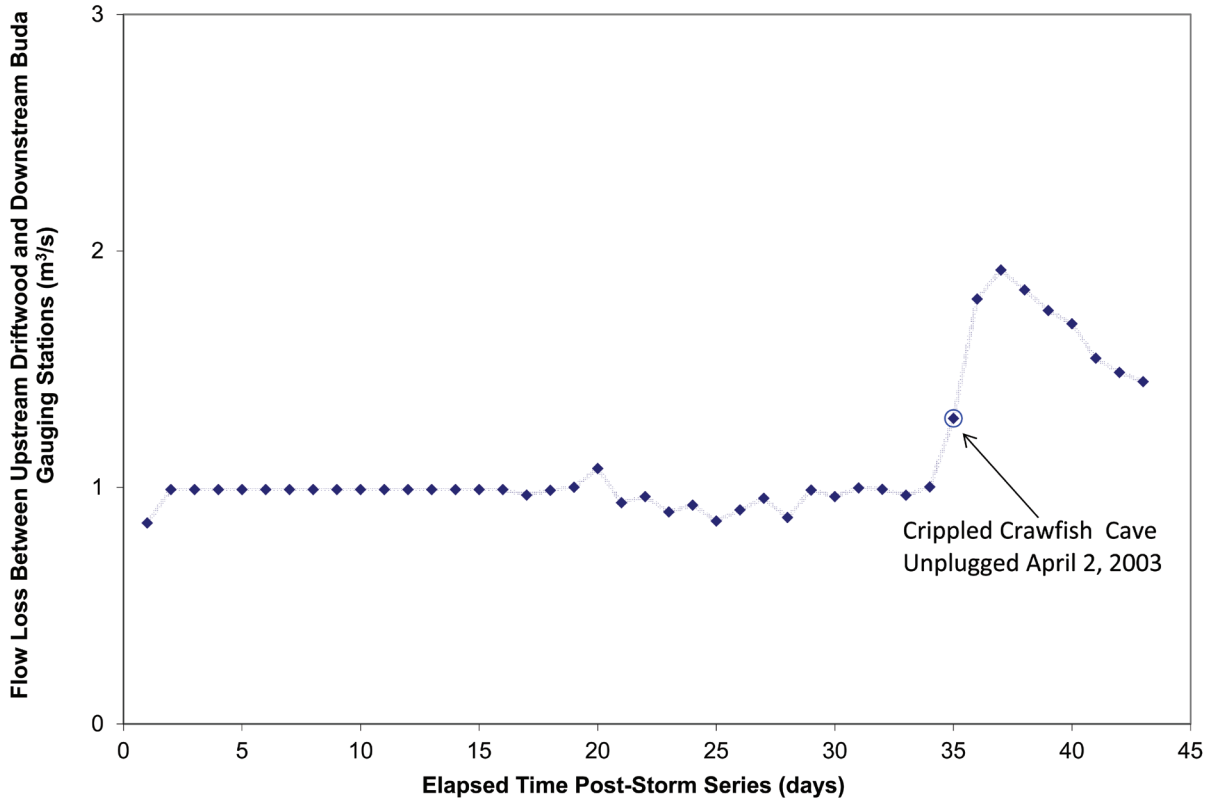

Figure 5. Flow Loss Response of Onion Creek Flow Gauging Stations to Unplugging of Crippled Crawfish Cave.

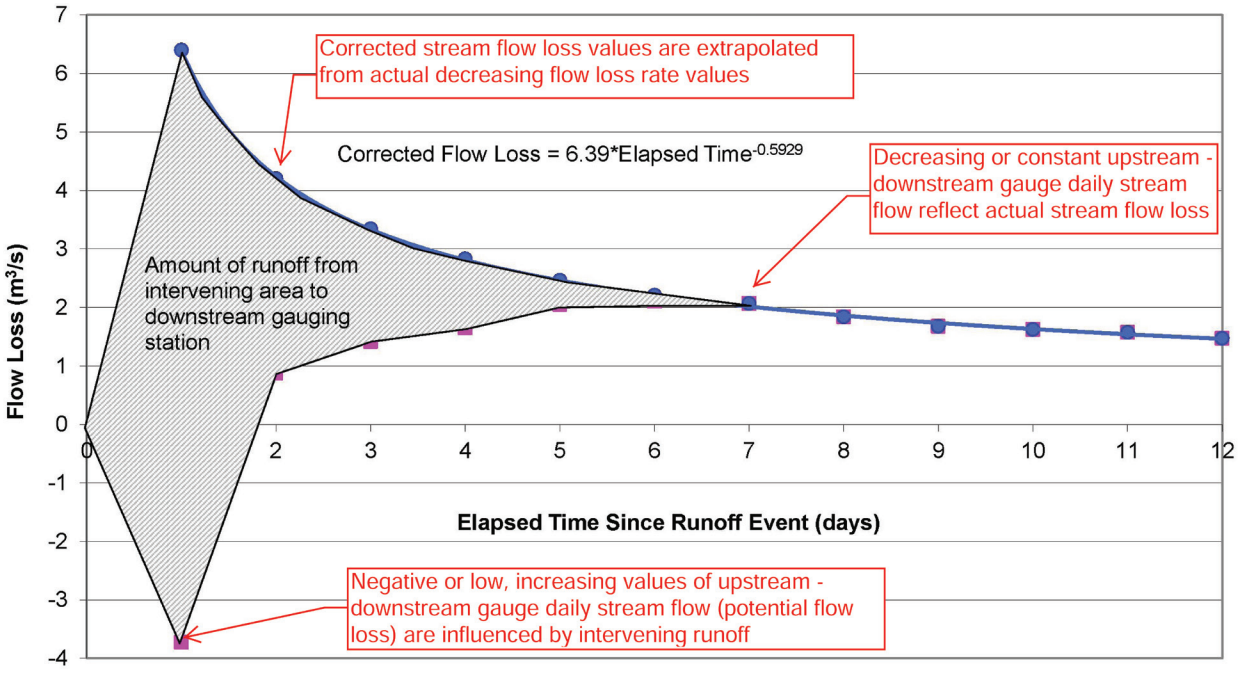

Figure 6. Example Correction of Potential Flow Loss.

Table 2. Maximum Flow Loss for Major Stream Channels.

Source	Maximum Channel Flow Loss Rate							
	Slade et al. 1986		Barrett et al. 1996		This Study			
					Flood		Low Flow	
	(m^3/s)	(ft^3/s)	(m^3/s)	(ft^3/s)	(m^3/s)	(ft^3/s)	(m^3/s)	(ft^3/s)
Barton Upst 360	0.85-2.0	30-70	7.10	251	1.41	50	0.85	30
Barton Dnst 360	---	---	---	---	1.10	40	0.57	20
Williamson	0.37	13	1.00	14	0.57	20	0.37	13
Slaughter	1.47	52	1.50	53	2.40	85	0.79-1.56	28-55
Bear	0.93	33	0.91	32	0.99	35	0.79-0.93	28-33
Little Bear	0.85	30	0.91	32	0.99	35	0.71	25
Onion	3.40	120	3.40	120	7.10	250	0.57-2.80	20-100
Blanco River	---	---	----	---	---	---	0.28-0.51	10-18

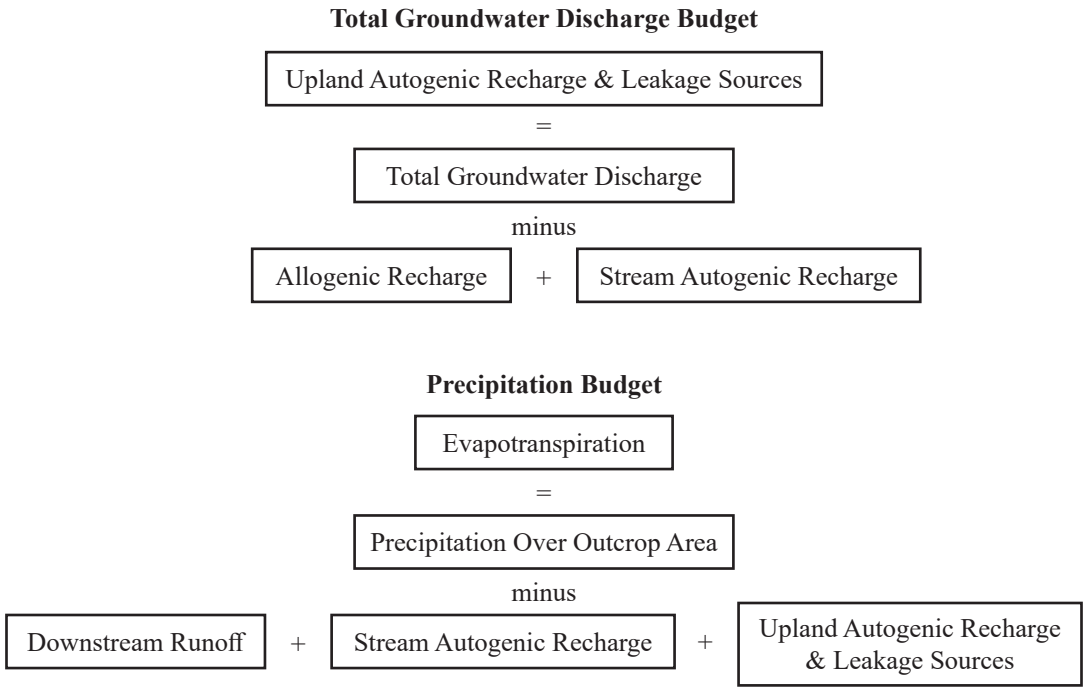

Figure 7. Channel Water Balance Calculations for Upland Autogenic Recharge and Evapotranspiration.

channels was significant, then the portion of major stream channel recharge could potentially be less than calculated in this channel water balance.

3. No stream-channel infiltration in Barton Creek upstream of Loop 360 contributes to Barton Springs. For the three mile stretch of Barton Creek downstream of Loop 360 (Figure 1), a range of potential recharge was calculated with both all and none of recharge in the Barton Creek channel contributing to Barton Springs. This accounts for range of values calculated for recharge components as a percent of total discharge.
4. On Bear Creek, the Spillar Ranch low water crossing (Spillar, Figure 4) was more representative of upstream recharge zone than the FM1826 USGS gauging station site, because of considerable spring discharge between the two sites. We took periodic flow measurements at Spillar, correlated flow gains between the two sites and adjusted FM1826

USGS gauging data to reflect the discharge expected at Spillar. Without this correction the stream flow loss occurring in Bear Creek would be underestimated.

5. All significant recharge to the groundwater system from the channel of Little Bear Creek occurs within the upstream half of the recharge zone between FM967 and the Stoneledge flow gauging stations. A flow loss survey of Little Bear Creek on July 4, 2002 by BS/EACD measured less than 10% total flow loss occurred downstream of the lower gauging station used in this study.
6. The recharge to the groundwater system from Onion Creek is assumed to discharge at Barton Springs. Note that on one occasion under high-flow conditions, tracers injected in Onion Creek were detected at both Barton Springs and at San Marcos Springs. The distribution of recharge from Onion Creek to Barton, San Marcos Springs, and other unknown destinations has not been measured.
7. The flow loss from the Blanco River between the Wimberley and Kyle gauging stations was assumed to discharge completely at Barton Springs for intervals when Barton Springs discharge is less than 1.13 m^3/s (40 ft^3/s). This assumption can underestimate recharge from the Blanco River because of additional spring discharge downstream of Wimberley, such as Fern Bank Springs (Figure 3). As discussed below the direct comparison of Blanco River flow loss to Barton Springs discharge recessions tends to underestimate Blanco River contribution, but this contribution of Blanco River could be overestimated because of diversions of some Blanco River channel recharge to San Marcos Springs or water wells.

Major stream channel flow loss was also compared to precipitation over the 176 km^2 (68 mi^2) outcrop source area to Barton Springs, which excludes 31 km^2 (12 mi^2) of Cold Springs groundwater basin and 36 km^2 (14 mi^2) of overlying confining units within the recharge zone of the groundwater basins discharging to Barton Springs. Monthly average rainfall from May 31, 2003 to September 19, 2007 was summed from four Flood Early Warning System (FEWS) sites distributed across the northern half of the recharge zone. The net precipitation from the four sites, varying from 348 to 371 cm (137 to 146 in) over the 52 months, had an arithmetic mean of 358 cm (141 in). The annual averaged rainfall for the water balance interval of 83 cm (32.5 in) is 97% of the long term average rainfall for the Austin area. After subtracting upland autogenic recharge and runoff downstream of the recharge zone over the 4.3 year water budget interval from rainfall, the remainder of rainfall is assumed to be an approximate measure of evapotranspiration over the recharge zone (Figure 7).

Results

The results of the water budget are presented in Tables 1 and 2. From May 31, 2003 to September 19, 2007 (1,573 days), the total groundwater discharge consisted of 86% USGS-reported Barton Springs discharge of Main, Eliza, and Old Mill Springs, 11% well pumpage, and 3% lower Barton Creek spring discharge upstream of Barton Springs pool (Table 3). Over the 4.3-year water budget interval, total discharge averaged 2.15 m^3/s (76 ft^3/s), which is representative of average discharge. As stated above, discharge from Cold Springs and recharge in its groundwater basin are not included in this analysis. The stream channel recharge sources of total discharge were calculated as 33% from Onion Creek, less than 10.5% from Barton Creek downstream of Loop 360, 7.2% from Slaughter Creek, 6.2% from Bear Creek, 6% from the Blanco River, 3.4% from Little Bear Creek, and 1% from Williamson Creek. Major stream channel recharge (including the Blanco River) accounted for 56% to 67% of total groundwater discharge. The range of values encompasses the potential Barton Creek channel recharge distribution to Barton Springs. The residual 33% to 44% of total groundwater discharge largely originated from upland autogenic recharge, along with possible contributions from other sources including subsurface Trinity Aquifer leakage, Saline Water Zone leakage, urban leakage, and leakage from the San Antonio Segment of the Edwards Aquifer. Intervening area runoff was a higher portion of total streamflow and major stream channel recharge in watersheds having relatively low contributing zone drainage

areas or high relative impervious cover, such as Williamson Creek. The percentages of flow loss of each stream from 2003 to 2007 were within 3% of channel flow-loss estimates for a 1978 to 1982 water budget (Slade et al. 1986) except for Barton Creek and the Blanco River (Table 4).

The portion of the allogenic stream channel recharge originating as runoff from the contributing zone and measured directly from upstream gauging stations is 39% to 50% of total groundwater discharge. A large portion of total groundwater discharge of Barton Springs originates from the recharge zone, including 33% to 44% largely composed of upland autogenic recharge and an additional 17% of total groundwater discharge which runs off the intervening area and becomes autogenic stream recharge within the major stream channels (Figure 8). Consequently, 50% to 61% of Barton Springs discharge is derived as total autogenic recharge from the recharge zone.

The recharge sources measured in this study were compared to precipitation over the water balance interval. Using a 176 km^2 (68 mi^2) outcrop source area to Barton Springs, the rainfall volume over the water budget interval is 633,437,330 m^3 (22,369,628,160 ft^3). The total groundwater discharge between May 31, 2003 and September 19, 2007 was 292,781,028 m^3 (10,339,464,433 ft^3), which is 46% of precipitation over the 176 km^2 (68 mi^2) outcrop source area to Barton Springs. Measured streamflow loss to Barton Springs was 26% to 31% of precipitation over the outcrop source area. The largely autogenic upland recharge over the intervening outcrop area of the recharge zone, constitutes 15% to 20% (18% mean) of precipitation (Figure 9) and 8% of precipitation was estimated to originate as stormwater runoff from the intervening recharge zone that recharged within the major stream channels. The residual of the precipitation water

Table 3. Total Groundwater Discharge.

Start to End Date	Interval (days)	Barton Springs Discharge (Reported by USGS) (m^3)	(%)	Lower Barton Creek Spring Discharge (m^3)	(%)	Total Pumpage (Reported by BS/EACD) (m^3)	(%)	Total Groundwater Discharge (m^3)
5/31/2003 - 9/19/2007	1,573	252,445,005	86	8,159,329	3	32,176,694	11	292,781,028

Table 4. Major Stream Channel Flow Loss Contributions to Total Groundwater Discharge.

Barton Springs Source	----------Recharge----------					Downstream Runoff	
Major Stream Channel	Channel Flow Loss (m^3)	Channel Flow Loss/ Total Groundwater Discharge		Channel Recharge Source		Downstream Runoff Source	
		2003-2007 This Study (%)	1978-1982 Slade 2014 (%)	Contributing Zone (m^3)	Intervening Area (m^3)	Contributing Zone (m^3)	Intervening Area (m^3)
Onion	95,547,515	32.6	34.6	69,279,477	26,298,841	144,567,178	62,540,930
Little Bear	10,057,872	3.4	6.0	0	10,057,872	0	10,057,872
Bear Creek	18,050,834	6.2	6.0	11,978,434	6,084,633	15,203,020	8,254,746
Slaughter	20,948,219	7.2	4.2	13,446,137	7,502,081	3,992,588	7,588,962
Williamson	2,813,569	1.0	2.5	2,679,376	391,452	3,545,088	11,361,897
Barton	<30,877,204	<10.5	25.3	<30,876,715	489	145,085,483	13,961,908
Blanco River (only when Barton Springs discharge is <1.3 m^3/s)	17,566,412	6.0	0	---	---	---	---

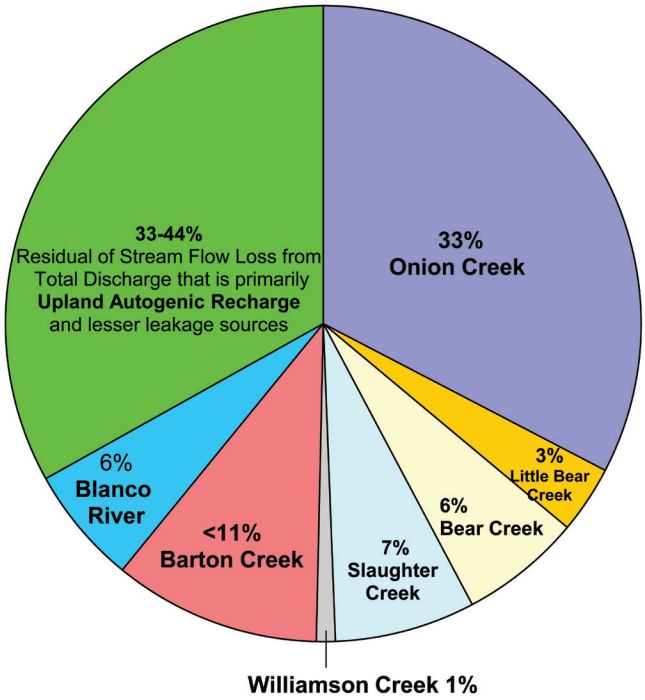

Figure 8. Source Components of Total Groundwater Discharge.

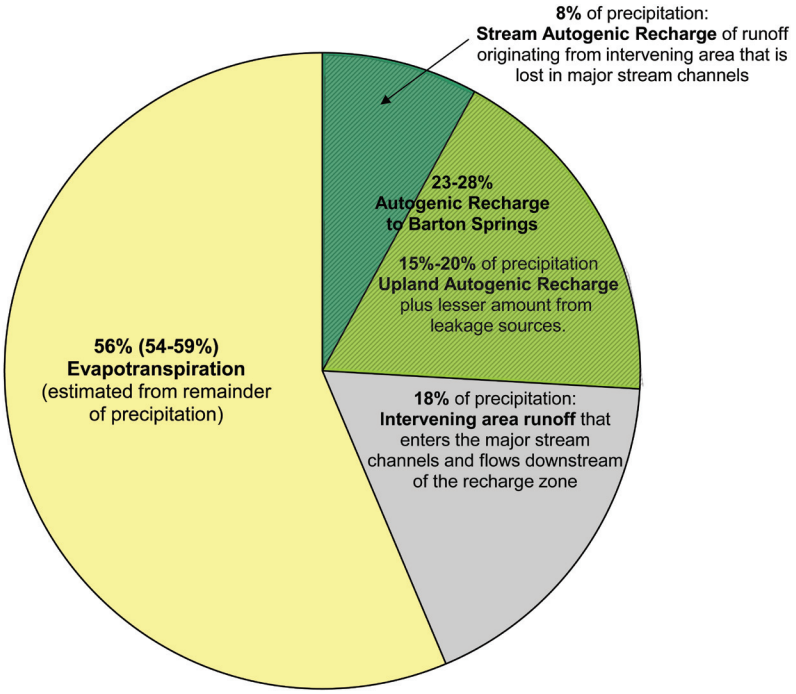

Figure 9. Components of Precipitation over 176 km^2 Outcrop Area.

balance across the 176 km^2 (68 mi^2) outcrop source area to Barton Springs is calculated to be 54% to 59%, averaging 56% of precipitation, that is attributed to evapotranspiration.

For the eight drought comparison intervals between Barton Springs discharge and Blanco River flow loss, Barton Springs discharge recessions experienced abrupt inflections at discharge rates varying from 0.54 to 0.96 m^3/s (19 to 34 ft^3/s), as seen in Table 5 and Figure 10. For the three months prior to each of the eight recession inflection points, Barton Springs discharge generally showed similarity with the Blanco River flow loss. Blanco River flow loss for the three months prior to the

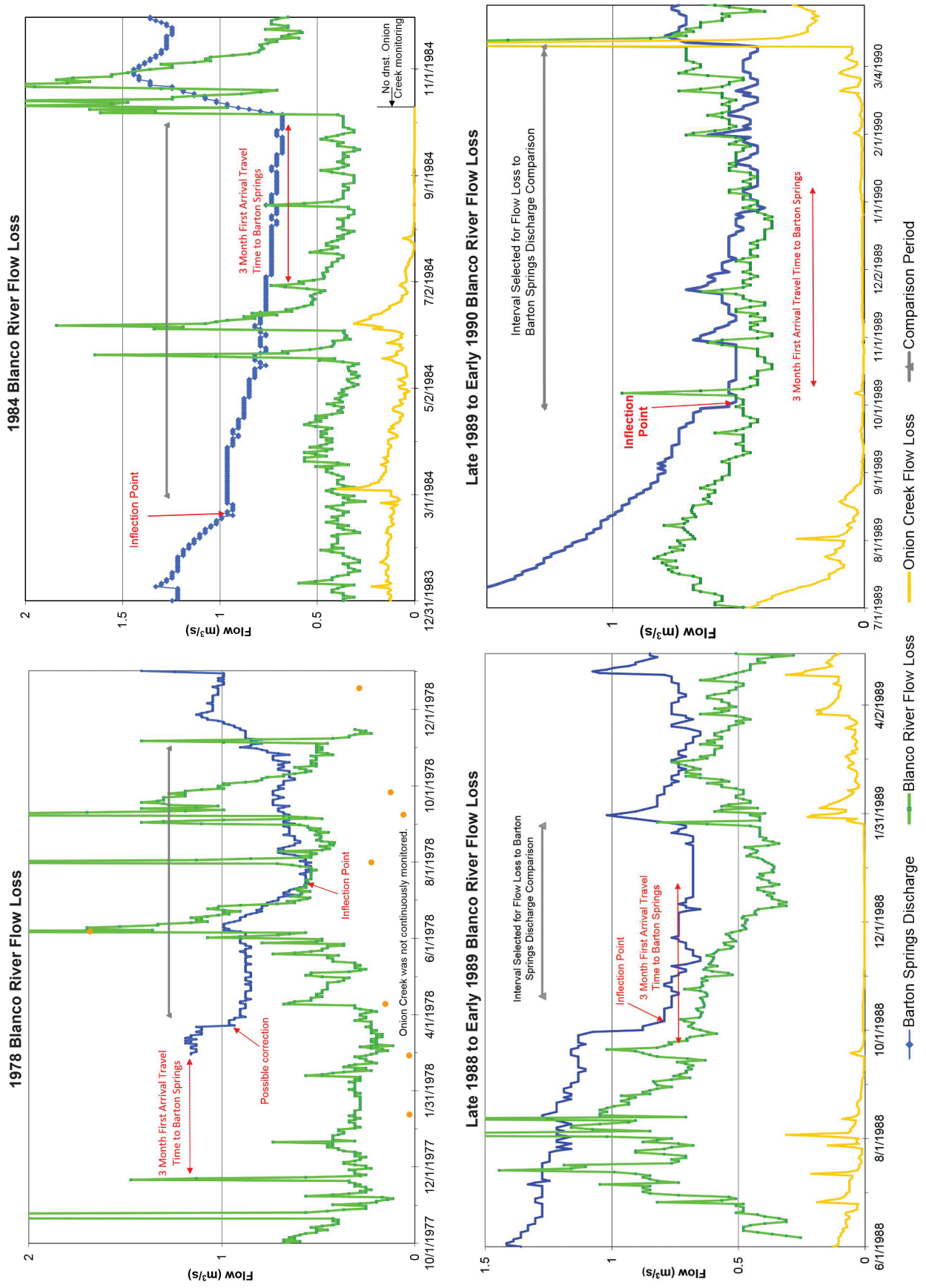

Figure 10. Blanco River Flow Loss and Barton Springs Discharge Recessions.

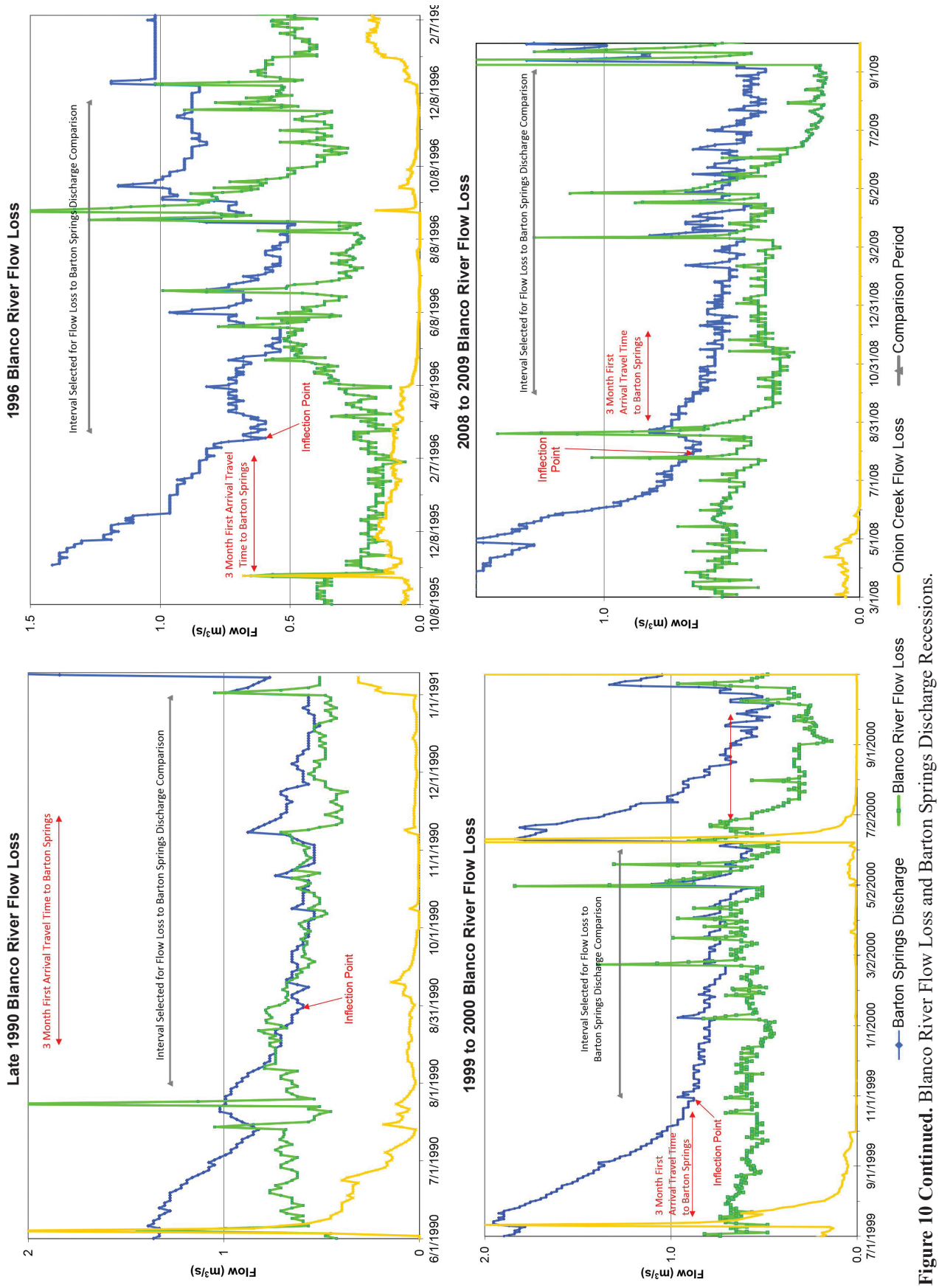

Figure 10 Continued. Blanco River Flow Loss and Barton Springs Discharge Recessions.

characteristic inflection in Barton Springs discharge varied from 27% to 110% of Barton Springs discharge, with an arithmetic mean of 76%. This, together with multiple successful groundwater traces from the Blanco River to Barton Springs, supports the hypothesis that the Blanco River sustains Barton Springs discharge during drought conditions. During the 2008 and 2009 drought, the groundwater tracers required about three months for first arrival. During the eight selected drought intervals, the total recharge on the Blanco River ranged from 49% to 84% of total groundwater discharge from the groundwater basins supplying Barton Springs, with a time-weighted arithmetic mean and median for the eight intervals of 62% with a standard deviation of 0.15. During these eight drought intervals, the flow loss measured from Onion Creek, by far the largest stream source to Barton Springs under average flow conditions, was relatively small, between zero and 7% of total groundwater discharge. Based on this comparison, I estimate that the Blanco River supplies at least half or more of Barton Springs discharge during droughts.

Discussion

The stream channel losses measured in this study were within 3% of 1980's total groundwater discharge estimates for Williamson, Slaughter, Bear, Little Bear, and Onion Creeks (Table 4; Slade et al. 1986; Slade 2014). This suggests that despite different approaches, relatively consistent values can be derived using the channel water balance method on data sets collected decades apart. However, on Barton Creek and the Blanco River, groundwater tracing defined a different fate for recharged water. The measurement differences between this study and the 1980's channel water balances in stream flow recharge compared to total groundwater discharge were greater than about 15% to 25% for Barton Creek and 6% for Blanco River.

Autogenic recharge on the recharge zone is estimated as 23% to 28% of precipitation in this study, with 15% to 20% occurring directly over the intervening area and 8% originating from intervening area runoff that recharges within the major stream channels (Figure 9). For comparison, 26% of rainfall was measured to directly infiltrate through soil-covered areas of an upland research site in the center of the Barton Springs Segment, using a climate tower and flumes (Table 6; Hauwert and Sharp 2014). This 1.4 year water balance period was selected as an interval where starting and ending volumetric soil moisture was 20% to eliminate the variable of changes in soil moisture storage. Although this interval had 34% higher than a mean annual rainfall of 85 cm, a compilation of annualized data from other climate towers over the Edwards and Trinity Aquifers showed that 28% autogenic recharge from precipitation was representative of mean precipitation conditions.

Evapotranspiration is estimated to be 54% to 59% of mean precipitation, calculated as the residual from the precipitation water budget, which averaged 56% in this study. The most precise measurement of actual evapotranspiration, using eddy covariance and Bowen ratio climate towers on karst limestone across Central Texas, measures evapotranspiration as 69% of precipitation under average conditions (Hauwert and Sharp 2014). Prior to groundwater tracing delineation of groundwater basins, evapotranspiration was estimated to be 85% based solely on channel water balance (Woodruff 1984; Slade et al. 1986; Table 6).

The total precipitation budget reported from the 1980's channel water balance differs from those derived from site-scaled climate towers across Central Texas (Hauwert and Sharp 2014) and this study not only because of differences in groundwater basin divides, but also because the 1980's studies used precipitation over the entire recharge and contributing zones. The allogenic source contributing zone was not included for the reference precipitation area in the channel water balance study presented here, since the upgradient Trinity Aquifer is not an impermeable catchment area, but potentially recharges to lower water-bearing intervals (Mace et al. 2000). Furthermore, it has not yet been determined if the springflow that discharges allogenic recharge from the contributing zone streams originates entirely within the watershed boundaries. The outcrop area of Edwards Aquifer within the recharge zone is the hydrologically-relevant catchment area for a precipitation water balance measurement of autogenic recharge. The difference between

Table 5. Comparison of Blanco River Flow Loss to Barton Springs Discharge.

Cumulative Flow Interval Start	End	# of Days	Barton Springs Inflection Point Discharge (m^3)	Blanco River Flow Loss 3 Months Prior Discharge (m^3)	Barton Springs Discharge (m^3)	Blanco River Flow Loss (m^3)	Onion Creek Flow Loss (m^3)	Pumpage (m^3)	Blanco River Flow Loss/ Barton Springs Discharge (%)	Blanco River Flow Loss/ Total Discharge (%)	Onion Creek Flow Loss/ Total Discharge (%)
4/1/1978	10/31/1978	213	0.57	0.54	13,881,870	13,501,354	not gauged	2,130,388	97	84	---
3/1/1984	9/30/1984	213	0.96	0.37	14,801,782	8,453,016	1,292,991	2,476,740	57	49	7
10/20/1988	1/24/1989	96	0.79	0.82	5,945,179	4,000,885	28,258	1,062,354	67	57	0.40
10/1/1989	3/13/1990	163	0.54	0.59	7,163,573	7,065,710	216,130	1,352,779	99	83	2.54
8/1/1990	12/31/1990	152	0.59	0.48	8,467,598	7,718,701	370,412	1,512,893	91	77	3.71
3/1/1996	11/30/1996	274	0.59	0.17	17,422,064	10,330,616	507,151	3,852,665	59	49	2.38
11/1/1999	5/31/2000	212	0.88	0.68	14,427,456	11,652,452	200,644	3,073,280	81	67	1.15
10/1/2008	9/1/2009	335	0.65	0.51	15,391,407	10,141,545	0	5,672,479	66	48	0.00

Table 6. Comparison of Channel and Site-Scaled Preciptation Water Balances.

Water Balance Component of Precipitation	Channel Water Balance				Site Scale Field Meas.
	Slade et al 1986; Woodruff 1984	Slade 2014	Slade 2015	This Study	Hauwert et al. 2014
Catchment Area Used	917 km^2	233 km^2	233 km^2	176 km^2	0.19 km^2
Upland Autogenic Recharge	0.89%	<6.6%	9%	15-20%	28%
Stream Autogenic Recharge	5%*	---	4%	8%	---
Evapotranspiration	85%	---	70%	54-59%	69%
Downstream Runoff	9%	---	17%	18%	3%

*combined stream autogenic and allogenic recharge

comparing recharge of a 917 km^2 (354 mi^2) area versus a 176 km^2 (68 mi^2) area alone would explain that the 1980's autogenic recharge and downstream runoff values would be about 20% of values measured using the smaller outcrop infiltration area used in the study presented here. Slade (2014) recalculated autogenic recharge using his estimated area for the recharge zone without the contributing zone, based on data collected for the 1980's channel water method budget, and derived <6.6% of precipitation.

Limitations in the channel water balance methodology used in this study may also account for the difference between site scaled and aquifer-wide scale evapotranspiration and runoff. From July 31, 2004 until October 11, 2006, which includes most of the water balance interval, the Onion Creek Buda gauging station was not operating due to bridge repairs and a replacement Twin Creek station was the representative downstream station for Onion Creek. The Twin Creek gauging station includes more than 39 km^2 (15 mi^2) more area as well as perennial flowing springs downstream of the recharge zone. About 54% of the total downstream runoff from the recharge zone measured in this study was attributed to Onion Creek. Likely much of the runoff measured at this gauging station was locally derived and not runoff from the recharge zone, although the data were not available to distinguish the two sources. The additional spring-fed area upstream of the Twin Creek gauging station but downstream of the recharge zone may exaggerate downstream runoff and underestimate autogenic recharge and evapotranspiration.

While the Blanco River averaged only a 6% contribution to total groundwater discharge including Barton Springs over the water budget interval, during drought conditions it may sustain a half or more of the discharge of Barton Springs. Because the tracer arrival time from Blanco River to Barton Springs is about three months, the direct flow comparison of any two recessions during a given time interval that was used in this study tends to underestimate the potential contribution to Barton Springs. Tracing conducted during drought intervals suggests that Blanco River recharge arrives at Barton Springs through two separate groundwater flow routes, one primarily under confined artesian pressure capable of transmitting instantaneous pressure pulses to Barton Springs and a separate groundwater flow path under unconfined conditions whose effects are experienced several months later. The new direct tracing and flow comparison results infer that the low-gradient springflow recession that Barton Springs experiences during drought conditions appears to vary with delayed arrival of baseflow from the Blanco River. The Barton Springs discharge recession inflection point varies between droughts, consistent with the hypothesis that the slower rate of discharge diminishment is caused by external factors, such as variability of Blanco River recharge, rather than internal hydrogeological characteristics of the Edwards Aquifer.

Conclusion

Using the channel water balance method, incorporating mean daily flow gauging upstream and downstream of the recharge zone for the Barton Springs Segment, and flow loss in the major stream channels of the Blanco River and Barton, Williamson, Slaughter, Bear, Little Bear, and Onion Creeks accounted for 56% to 67% of the total groundwater discharge of Barton Springs and wells. The remaining 33% to 44% of total groundwater discharge originated as upland autogenic recharge from the intervening area and, to a lesser extent, as unquantified leakage sources from the Trinity Aquifer, the Saline Water Zone, urban water, and possibly adjacent Edwards (Balcones Fault Zone) Aquifer Segment groundwater inflows. Stream autogenic recharge measured 17% of total groundwater discharge. Allogenic recharge from contributing zone runoff measured 39% to 50% of total groundwater discharge, depending on the distribution of recharge in Barton Creek downstream of Loop 360. About 50% to 61% of Barton Springs discharge is autogenic recharge that originates from the recharge zone. Because of limited resources for the protection of water supplies, endangered species habitat, and treasured recreational pools, understanding water sources for the aquifer is critical for focusing management efforts. The findings establish the importance of the recharge zone in providing recharge to wells and Barton Springs. Although both Barton Springs and the Blanco River flowed through the drought on record, the results of this study suggest that

future water diversions that lead to the drying of Blanco River baseflow could significantly affect Barton Springs discharge.

The findings are consistent with the concept of the Edwards Aquifer as a relatively mature karst aquifer with well-developed recharge structure. This study demonstrates the need for intensive data for characterizing recharge in karst areas and shows that streamflow loss water balances can be consistent with site-scaled water balances, but only after source areas are sufficiently delineated using direct groundwater tracing. Streamflow gauging water balances must be evaluated on whether the source areas were sufficiently delineated to eliminate the possibility for alternate interpretations. Between the channel water balance methods applied in the 1980's and in this study, stream flow loss as a fraction of total groundwater discharge differed less than 3% for channels of Williamson, Slaughter, Bear, Little Bear, and Onion Creeks, but 6% to as much as 25% for the Blanco River and Barton Creek, where groundwater basins were significantly redefined with groundwater tracing. In precipitation water budgets, more representative values of autogenic recharge were calculated using the Edwards Aquifer outcrop within the recharge zone area as a reference area, rather than the combined recharge and contributing zones.

In general, evapotranspiration cannot be precisely measured from channel water balances. Water balances could be improved by collecting continuous flow data on Onion and Little Bear Creeks closer to the edge of the recharge zone and monitoring all gauging stations for a longer interval. While the Barton Springs Segment is one of the most intensely traced aquifers in the world, additional tracing studies can help to refine the distribution of recharge across groundwater divides along Barton Creek downstream of Loop 360, Onion Creek, and Blanco River.

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