



**Response to undated comments by Raymond Slade provided August 13, 2014, titled:
“Review comments for report "Measuring Autogenic Recharge over a Karst Aquifer
Utilizing Eddy Covariance Evapotranspiration" by Nico M. Hauwert and Jack M. Sharp”**

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DR-15-05

Introduction

A list of comments regarding this paper:

Hauwert, N.M. and Sharp, J.M. 2014. Measuring Autogenic Recharge over a Karst Aquifer Utilizing Eddy Covariance Evapotranspiration. *Journal of Water Resource and Protection*, **6**, 869-879. <http://dx.doi.org/10.4236/jwarp.2014.69081>

were provided on August 13, 2014, by Mr. Raymond Slade, adjunct professor at Austin Community College and former U.S. Geological Survey hydrologist. Below are the comments submitted by Mr. Slade and response by the primary author.

Introductory Comment:

“The subject report presents selected data and information contained in Nico Hauwert's PhD Dissertation, which was supervised by Jack Sharp. Much of the material also is published by Hauwert and Sharp (2005).

The report presents a 505-day water budget (April 2, 2004 to August 20, 2005) for HQ Flat--a 46-acre internal drainage basin within the recharge area for the Edwards aquifer associated with Barton Springs. The fate of runoff in the basin is a sinkhole--runoff cannot escape the basin. The report admits that such a basin represents only about 10% of the entire 94 mi² recharge area. Precipitation for the 505-day period was 142% of normal. For this basin and period, based on the water budget below, recharge was reported to represent about 31% of precipitation.

The authors estimate diffuse recharge volumes as the residual in the following equation:

$$I = P - ET + DR + S \quad (1)$$

where:

P = precipitation volume (m³);

ET = evapotranspiration flux volume (m³);

I = percolation from soil and lesser karst features into the underlying bedrock (diffuse recharge, m³);

DR = internal runoff that enters the cave drain (discrete recharge, m³);

S = change in water storage in soil during the reference period (m³).

The report concludes that recharge as a percent of precipitation from this much wetter than normal period and from this small closed basin is representative of average precipitation conditions for the entire recharge area. The report also concludes that "under average precipitation conditions" recharge from the recharge area of the Barton Springs Edwards aquifer represents 31 % of precipitation."

Response: This introductory comment mischaracterizes the article. Measured evapotranspiration and internal runoff was subtracted from measured precipitation over a 505-day water balance from a South Austin (J17 HQ Flat Sink) research site in order to measure diffuse infiltration at a site scale. In order to compare the results for a larger scale, published data from other evapotranspiration sites across Central Texas were compiled. Nowhere in the article do we state that 31% of precipitation represents average recharge values, instead the subject article concludes on p. 877 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."

On p. 869 Abstract of our subject paper summarizes that "ET flux tower data from other sites across Central Texas indicate that under average precipitation conditions, autogenic recharge is about 28% and intervening recharge area runoff is about 3% of precipitation."

The subject article compares the results of the site specific measurement of upland recharge in several ways to establish how representative the findings are. The article compiles recharge measurements from karst areas around the world for comparison. The results from J17 HQ Flat Sink research site are compared with published results from other climate stations across Central Texas.

In general, the comments provided below mischaracterizes the subject report and source references, fails to discuss high potential for error in stream-flow loss studies, and omits significant data sources. Despite allegations in the comment, no published eddy covariance or Bowen ratio tower data from Central Texas were omitted from our subject paper of which I am aware. Unspecified references to "substantial data" and "published reports" are not sufficiently

clear to address with a response. Additional information is provided in the responses below to explain unclear issues in greater detail.

Review Comments Responses

Comment 1.

1. “Discharge from aquifer proves average recharge rate to be substantially less than 31%

Based on recharge as 31% of average precipitation (32 inches per year), the mean recharge from the 94 mi² recharge area calculates to be about 49,700 acre feet per year which is equivalent to 69 ft³/s. However, the mean discharge from the aquifer is only about 56 ft³/s--a value based on published water budgets and on discharges from Barton Springs and Cold & Deep Eddy Springs as documented by Slade (2014) and other reports. An independent calculation, based on USGS gaged streamflow values, of surface recharge for the study area reveals the mean surface recharge to the area to be within 3 % of the 56 ft³/s surface discharge value (Slade, 2014, p. 18). Additional data and many other reports verify the mean recharge and discharge to the study area to be about 56 ft³/s.

As reported by Slade (2014, p. 17-18), David Johns (written commun, 2013) stated that dye injected into the aquifer was visible in Lady Bird Lake and not discharged from Barton or Cold and Deep Eddy Springs. Therefore, discharge from the aquifer other than Barton and Cold & Deep Eddy might exist. However, despite many studies that have documented springs in the Austin area, no such additional springs have been identified in the reach along the Colorado River--therefore, if such springs exist, they would be minor. Also, two streamflow gain-loss studies conducted on the Colorado River prior to the construction of the lake prove any such discharges to be zero or limited (Slade, 2014, p. 18). Additionally, the recharge budget discussed above also proves any such discharges to be zero or limited. Based on the potential error in the 3 studies, any such non-identified discharges, if existent, would be limited to about 2 ft³/s. The addition of this possible but improbable discharge would not affect the validity of the review comments herein.

Additionally, the recharge area represents only about 25% of the total area (contributing area and recharge area) providing recharge to the aquifer. Substantial data and many reports document that the contributing area provides more recharge than the recharge area. For example Smith and others (2005) state "From 50 to 85 percent of recharge to the aquifer is derived from streams originating on the contributing zone, located up gradient to the north and west of the recharge zone". Additionally, based on a long-term data-based water budget for the entire aquifer, recharge originating within the recharge zone is limited to no more than 6.6% of precipitation, and about 75% of total recharge is documented to occur on the main channels of the 6 major streams crossing the recharge area (Slade, 2014, p. 20). The remaining 25% of recharge occurs within the recharge area and outside the 6 major channels. Therefore, it is obvious that diffuse interstream mean recharge as a percent of precipitation is less than 1/4 of the rate of 31% claimed by the authors.

Response #1:

In Comment 1, Mr. Slade is wanting a verify the accuracy of a fairly precise measurement of evapotranspiration, runoff, and recharge with “published” water balances performed more than

30 years ago based on much less refined measurements of long-term mean total discharge, erroneous assumptions in the delineation of recharge source areas, and an incomplete creek flow gauging network. The Slade et al., 1986 water balance has been found to underestimate Barton Springs discharge, underestimate Cold Springs discharge, and overestimate the creek recharge to Barton Springs, as discussed below. Any similarity between recharge and discharge values in the Slade et al., 1986 water balance is random coincidence, and not a measure of accuracy. The Slade 2014 article is a similar repetition of Slade et al., 1986, and does not incorporate new information.

In order to make the calculations that Mr. Slade suggests, it is necessary to have an accurate delineation of the autogenic source area, an accurate measurement of total discharge (springflow and pumpage from the groundwater basin), precipitation, and measurement of the allogenic recharge contribution from the upstream Contributing Zone, along with leakage, fully accounting of sources such as Trinity, Saline Water Zone, southern boundary, and urban leakage into and out of the Barton Springs Segment. There are potentially large errors associated with each of these measurements using a stream flow loss water balance approach.

While the exact methodology describing how evapotranspiration was determined in Woodruff, 1984 is not provided in that source, Dr. Woodruff states “no direct measurements are available for this process, the main way to obtain an approximation for overall rates of evapotranspiration across the area contributing to the recharge zone is to subtract the debits from the credits in the water budget.” Slade et al., 1986 explains that evapotranspiration is calculated by subtracting measured runoff and calculated recharge from precipitation over the assumed recharge area. This water budget based on stream flow loss uses a relatively small portion of precipitation allocation, in this case 9% measured runoff and 6% calculated recharge or only 15% of precipitation to estimate the remaining 100% of precipitation. Our subject paper water budget uses measured evapotranspiration and runoff, constituting 71% of precipitation allocation, to calculate the remaining third to one quarter of precipitation

Papers by Huang and Wilcox (2005) and Wilcox (2008) also noted large discrepancies between recharge values derived from stream-flow loss and evapotranspiration towers and concluded that stream flow loss, as applied in Texas, greatly underestimates recharge. In Texas, as in much of the nation, stream flow loss has historically been a preferred method of recharge calculation due to the relative ease of stream-flow data collection and lack of climate tower technology which is available today. Since groundwater flow has been (erroneously) assumed to flow through porous media systems and would require years of monitoring, few if any stream flow water balances have groundwater basins and spring source areas delineated with any confidence. Even where groundwater basins have been delineated with high confidence, the stream flow water balance method can choose to ignore them (as in Slade, 2014).

In the 1989 environmental impact statement for state highway 45 southwest, Mr. Slade is cited as stating that groundwater flow required three years to arrive 10 miles away at Barton Springs (TxDOT, 1989). Since 1996, tracing has been shown as a valuable tool to delineate groundwater basin and transport properties. I tested this hypothesis by injecting four tracers in three caves and a one mile stretch of Bear Creek adjacent to SH45SW and Mopac South (Hauwert, 2012). All four traces required only two to four days to arrive and peak at Barton Springs. As scientists

we all should be making new discoveries and refining our old understandings and not committed to conclusions developed 30 years before that are no longer totally valid. I am continually refining my old discoveries with new findings. Hauwert, 2009 (p. 100-101), suggested that if the stream flow loss data presented by Slade et al., 1986 were simply adjusted for directly traced groundwater basins, that authogenic recharge values similar to those derived more precisely at site scale by evapotranspiration towers are achieved.

For the purposes a of water balance calculation where rainfall evenly recharges using the measured autogenic recharge values that I derive, it is necessary to define the groundwater basins. Groundwater tracing commencing in 1996 and reported by Hauwert et al, 2004 and updated in Hauwert, 2009 used more than 40 groundwater traces to define source areas to Barton Springs and Cold Springs, the two major discharge sites. This tracing data were not available for Slade et al., 1986 water balance nor was it used in the 2014 rewrite of that water balance.

It is not adequate to use partial flow measurements to attempt to characterize Cold Springs discharge as having low significance in the water balance or to use this to suggest that the Cold Springs groundwater basin cannot be as large as direct tracing has mapped. The U.S. Geological Survey determined that Cold Springs could not be directly gauged since an undermined proportion occurs below the water level of the Colorado River, even prior to the downstream dam construction that created Lady Bird Lake. Brune notes that Cold Springs “include at least seven springs” and cites this quote from USGS geologist Robert Hill (1892, p. 94): *“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”*

Direct measurement of Cold Springs has become even more challenging after the construction of Longhorn Dam, creating Lady Bird Lake, in 1960. I have tried measuring the discharge of exposed spring orifices of Cold Springs, but even when the lake was drawn down, only four spring orifices were exposed and I could detect additional submerged spring orifices. Slade 2014 assumes the reported partial discharge measurements for Cold Springs are representative of total discharge. Having visited Cold Springs dozens of times to collect dye receptors, collect water samples, or measure partial discharge, I am aware that Cold Springs discharge varies considerably as do all karst fed springs, and any statements that its discharge is minimal and constant are misleading. Since the USGS determined that Cold Springs could not be directly measured, no study has come forth providing a method and data by which all the discharge of Cold Springs can be directly measured. It appears that all direct measurements for Cold Springs, including my own taken during lake drawdown, are only discharge measurements of the exposed springs and not all of Cold Springs discharge.

Given that Cold Springs discharge cannot be directly measured, several attempts to measure flow indirectly consistently provided a more precise measure of its discharge. A water balance for Town Lake measured excess flows averaging 29 ft³/s which could be largely attributed to Cold Springs (Stecher et al., 1992). I have used measured stream-flow loss within the Cold Springs groundwater basin to calculate average discharge of **at least** 15 ft³/s (Hauwert, 2009). Prior to the upstream Tom Miller and Mansfield Dams construction in 1941, annual USGS reports list four flow surveys of the Colorado River between Tom Miller (formerly “Austin”) Dam and one

quarter mile downstream of Deep Eddy (approximately current Loop 1/Mopac crossing). The flow gains are shown on Figure 1 below.

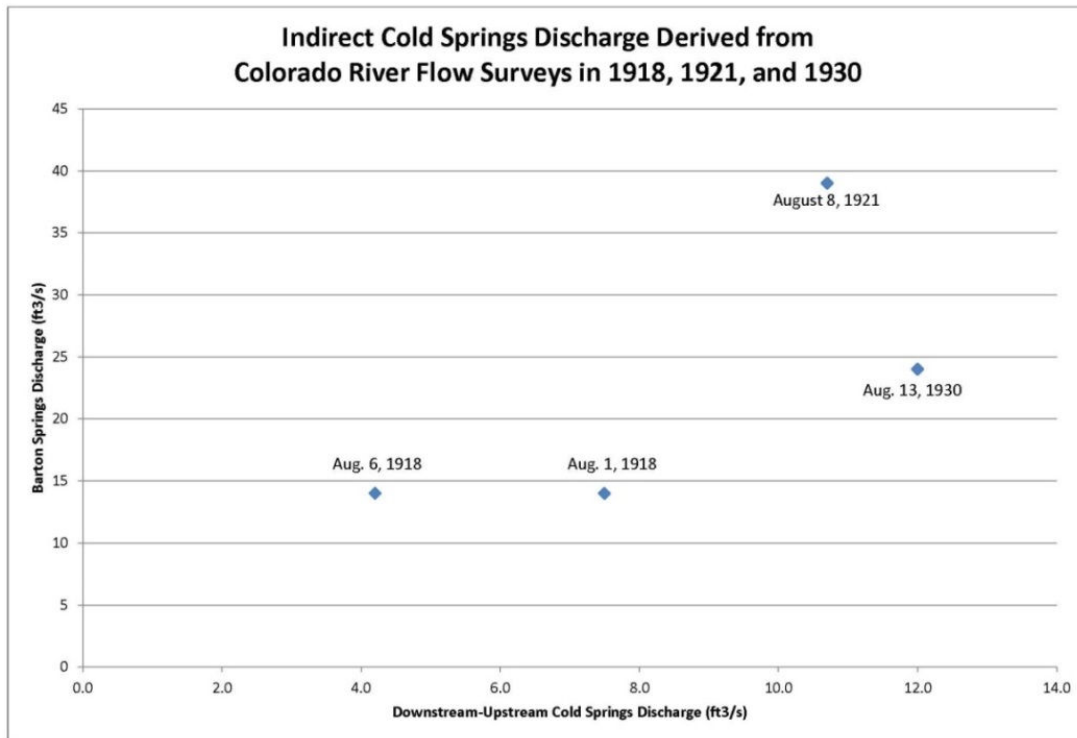


Figure 1. Four Colorado River flow surveys between 1918 and 1930 indirectly quantify Cold Springs discharge. Most of these gains between Tom Miller Dam and one quarter mile downstream of Deep Eddy can be attributed to Cold Springs and other springs discharging from the south side of the Colorado River. The discharge of Cold Springs is 27 to 54% of Barton Springs discharge within the same day.

In the four Colorado River surveys, the flow gain was 27 to 54% of Barton Springs discharge measured within a day. I don't discount that the flow gain estimated in all three analysis above could come from other submerged springs to the Colorado River within Lady Bird Lake upstream of Loop 1 that are unknown. Because during high river flow conditions do not provide sufficient resolution to measure flow gains attributed to Cold Springs, using Colorado River flow surveys to measure the discharge of Cold Springs could only be done indirectly during low-flow conditions prior to 1941. For this reason, there is a strong bias of measurements taken during drought conditions, such that simple averaging of flow values is misleading. Insufficient data are available to state long-term average Cold Springs discharge precisely, but indirect Colorado River flow gain measurements can be related to Barton Springs discharge taken within the same day. From the data available, the discharge of springs to Lady Bird Lake upstream of Loop 1 from the south ranges between a quarter to half of Barton Springs discharge. A Cold Springs discharge of about 27 to 54% of Barton Springs discharge is consistent with the range of average Cold Springs discharge between more than 15 ft³/s (Hauwert, 2009) and 29 ft³/s (Stecher et al, 1992). These flow surveys were overlooked in Slade 2014 and contradict the comment:

“However, despite many studies that have documented springs in the Austin area, no such additional springs have been identified in the reach along the Colorado River--therefore, if such springs exist, they would be minor. Also, two streamflow gain-loss studies conducted on the

Colorado River prior to the construction of the lake prove any such discharges to be zero or limited (Slade, 2014, p. 18)."

Although the referenced "two streamflow gain-loss studies on the Colorado River" are not mentioned in the comment, two USGS flow reports were provided by Mr. Slade in 1996 that are inexplicably not shown in the USGS annual reports. These are transcribed and described on page 11 of a 1996 addendum to Hauwert and Vickers 1994 (link in reference section). One survey reported for August 10, 1918 had similar results to one in Figure 1 above for August 6, 1918 where the gain between Austin Dam and ¼ mile below Deep Eddy was 3.7 ft³/s and Barton Creek discharge was 14.3 ft³/s, thus Cold Springs discharge is indirectly measured to be 26% of Barton Springs discharge. A second flow survey combines flow measurements from April 23, 1925 to April 25, 1925 and the results are ambiguous since Austin Dam daily average flows were reported by annual reports to vary from 188, 238, and 244 ft³/s, respectively (USGS 1925 Water Supply Papers, Surface Water Supply, part VIII, p. 120). The relatively high April 1925 Colorado River flows provide poor resolution. The variation in river flow over the three days prevents comparing measurements taken on different days. In addition, the downstream Colorado River measurement site for April 1925 was not ¼ mile downstream of Deep Eddy, but the Congress Avenue Bridge, that is downstream of several diversions and creek additions to the Colorado River. Additional discussion on measurement of Cold Springs is provided in Hauwert and Vickers, 1994 (1996 addendum p. 11); Hauwert et al., 2004 (p. 7, p. 48-49, p. 55, p. 76, p. 87-88) and Hauwert, 2009 p. 149—155.

A detailed surface geology coverage for the Barton Springs Segment was mapped by John Hanson and myself (Small, Hanson, and Hauwert, 1995), which I have continued to refine (Hauwert, 2009). Because Cold Springs discharge cannot be directly measured, for the calculation of infiltration generated for Barton Springs. I think it is best to use only the Edwards Aquifer outcrop area over the groundwater basins to Barton Springs and exclude the Cold Springs groundwater basin. Below on p. 871 the subject article references 68 square miles for the appropriate outcrop area derived from the surface geology coverage (rather than 94 square miles that Mr. Slade cites):

" The recharge area of the Barton Springs Segment that discharges at Barton Springs is a smaller subset of the Barton Springs Segment, 212 km² (82 mi²) [26]. After eliminating areas covered with Del Rio Clay and other overlying confining units, the Edwards Aquifer outcrop area contributing to Barton Springs is only 176 km² (68 mi²). A 30 km² (12 mi²) recharge area of the Barton Springs Segment provides discharge to Cold Springs [26]—a group of springs partially submerged below the Colorado River that cannot be directly gauged [27]."

What then is the long term total discharge from the portion of the Barton Springs Segment discharging at Barton Springs? Mr. Slade (2014) states the entire Barton Springs Segment has a long-term mean total discharge of about 56 ft³/s. If so, then under current conditions, given current 11 ft³/s of pumpage and Cold Springs discharge of 15 to 30ft³/s, Barton Springs discharge should currently average only 15 ft³/s to 30 ft³/s. According to Slade et al., 1986, USGS-reported Barton Springs mean discharge was 50 ft³/s based on 60 years of estimated mean monthly discharge and only three years of continuous measurement (direct and stage-discharge

measurements from a monitor well). Some years were averaged based on only 3 or 4 discharge measurements. However by 2014 there are 36 years of continuously reported Barton Springs discharge data by the USGS that were not considered by Slade 2014. Using the daily average of those data produces an average discharge of 62 ft³/s since 1978, excluding pumpage which is currently about 11 ft³/s. USGS reported Barton Springs discharge includes only Main, Eliza, and Old Mill Springs, and does not include pumpage. In 2011, I calculated, that for a 2003 to 2007 reference period, the additional lower Barton Creek discharge upstream of Barton Springs pool from Upper Barton Springs and other small springs averaged 3% of total discharge. More precise recent data suggests total discharge for the portion of the Barton Springs segment discharging from Barton Springs averages closer to 70 ft³/s than 56 ft³/s.

Rather than seeking a long-term mean conditions with incomplete data, because Barton Springs is a dynamic spring system with changing recharge sources not necessarily tied directly to rainfall, a better approach is use a shorter term stream flow water balance under average rainfall conditions where each of the major streams can be monitored. So for a 2003 to 2007 water balance interval, during which precipitation averaged 32.5 inches per year and all the major creek sources to Barton Springs were gauged a water balance was presented to the 2011 World Lake Conference. Instead of assuming Little Bear Creek recharge as the Slade 2014/Slade et al., 1986 balance does, I gauged daily average Little Bear Creek flows using visual staff gauge readings and periodic manual discharge measurements. This stream flow loss water balance included measured upstream flows from the contributing zone, measured downstream flows, pumpage calculated by Barton Springs/Edwards Aquifer Conservation District, USGS-reported Barton Springs discharge, and calculated lower Barton Creek springflows. The Cold Springs groundwater basin was excluded from the water balance area. In this stream flow balance, where many stream flow components could be measured under 4 years of average rainfall conditions, Barton Springs discharge was 66 ft³/s, total discharge was 76 ft³/s, contributing zone source recharge to Barton Springs was 33 ft³/s, and the residual was autogenic recharge, measuring 26% of precipitation. Here the larger scale but less precise stream-flow water balance compares favorably to site scaled evapotranspiration water balance. Since the major creeks are typically flowing when upland runoff reaches then, it can be expected that runoff to the major streams would be higher values than those measured at upland research sites.

Comparison of Rainfall Water Budget Results at Local and Aquifer-Wide Scales

| Water Balance Component | Stream Flow Loss Study (2003-2007 68 mi²) (Hauwert, in review) | Site Scale Field Meas. (Hauwert and Sharp, 2014) |
|--------------------------------|--|---|
| Autogenic Recharge | 26% | 28% |
| Evapotranspiration | 56% | 68% |
| Downstream Runoff | 18% | 3% |

Table 1. Comparison of autogenic recharge, evapotranspiration, and downstream runoff from HQ Flat Sink on J17 upland research site (reported in subject paper) with aquifer-wide stream

flow loss water balance study based on precipitation. The 3% internal runoff entering the sinkhole drain at HQ Flat sink compares to upland runoff outside internal drainage basins.

Regarding the comment:

"Substantial data and many reports document that the contributing area provides more recharge than the recharge area. For example Smith and others (2005) state "From 50 to 85 percent of recharge to the aquifer is derived from streams originating on the contributing zone, located up gradient to the north and west of the recharge zone".

This BS/EACD study did not measure the amount of recharge in the creek but provides the information as background information consistent with various proposed recharge water balances. The referenced statement does not necessarily state that 50-85% of recharge originates from the contributing zone, only that 50-85% of recharge occurs in the major creeks, a portion of which could be autogenic recharge from the uplands Edwards Aquifer outcrop area. A water balance such as I presented at World Lake Conference in 2011 has more than 50% of total recharge occurring in the major creeks and still balanced with upland recharge similar to what we suggested in the subject paper.

In conclusion, with the best available data, the amount of rainfall attributed to recharge in the subject paper can be compared to recharge calculated by other methods, but with the understanding that you should not use rough methods with poorly supported assumptions to establish the validity of more precise measurements. It is true that the Slade et al., 1986 water balance was not challenged until recently and the low Edwards Aquifer recharge values formed the foundation for how Central Texas was built over the recharge zone for the last 30 years. Perhaps local scientists should have looked more at world-wide karst studies and questioned how a highly transmissive aquifer could have the low infiltration properties more typical of a shale.

Comment 2

2. Missing components of water budget for entire recharge area lowers recharge rate for 505-day period from 31 % to less than 11%

The authors suggest the water budget for this closed basin to be representative of the entire recharge area. However, this closed internal basin represents only 0.076% (less than 1/10 of one percent) of the recharge area and the authors admit that such basins represent only about 10% of the total recharge area. However, for the entire study area, the authors did not consider, within the water budget, runoff from the remaining 90% of the recharge area (basins not closed). Not included in the water budget is recharge that occurs in the main channels of the 6 major streams that cross the recharge zone. Also not included is runoff that exists the recharge area as flow in the major streambeds. In a previous report on recharge based on the same HQ Flat basin, Hauwert and others (2005) stated "The water balance data from this study shows that internal drainage basins appear to be relatively efficient in recharging runoff for a

given amount of source area because: 1) they do not lose runoff to areas downstream of the Recharge Zone;...". Therefore, the author recognizes runoff from the recharge area to be a component of the water budget for non closed basins, but did not include such runoff in the water budget of the subject report.

For the 505-day period, recharge that occurs in the major channels is difficult to document thus is excluded from computation here. However, runoff from the recharge area is easily calculated based on gaged streamflow discharge values at USGS streamflow gaging stations (details for the calculations are presented in the Appendix below). Such runoff is at least 63,000 acre feet, which is equivalent to a minimum of 12.57 inches of runoff from the 94 mi² recharge area. Based on the 63 inches of precipitation that occurred during the 505-day period, runoff from the recharge area calculates to be at least 20% of precipitation. Therefore, for the period, diffuse interstream recharge for the entire recharge area should be reduced from 31 % to less than 11% of precipitation. Precipitation for the period is 142% of normal, thus, for average precipitation conditions, recharge as a percent would be decreased more.

Response #2:

This comment does not refer to the 2014 Hauwert and Sharp paper, but to calculations in a 2005 paper. The first paragraph relates to how representative the J17 HQ Flat Sink research site is to the rest of the Recharge Zone, similar to comments 3 and 4, and the general question is pertinent to the 2014 article and will be addressed in response #3. The second paragraph indicates that the water/recharge produced from rainfall in a 94 square mile recharge area is too much for the water budget, as in comment #1. As described in response #1, the 68 square mile outcrop of the Edwards Aquifer that contributes to Barton Springs is a better estimate of the source area for water discharging from Barton Springs. In addition, as described in response #1, the reference long-term mean Barton Springs discharge is higher than calculated in Slade 2014 from Slade et al., 1986 because pumpage and discharge data collected over the last 32 years were not used.

I suggest that the measured runoff reaching the HQ Flat Sink drain (3% of average precipitation) is comparable to runoff reaching the creeks outside of internal drainage basins.

Comment #3

3. ET at HQ Flat basin likely not indicative of that for entire recharge area

The authors state "Other than the cave drain, the basin slopes are indistinguishable from other slopes across the Barton Springs Segment of the Edwards Aquifer". However, the depth, infiltration rate, and storage properties of soil, and the type and extent of vegetation are more

related to ET volumes than land slopes. The authors don't discuss the characteristics of soils and vegetation at the HQ Flat site with respect to the remainder of the recharge area. However, an aerial view of the vegetation in the area of HQ Flat reveals the vegetation in the area to be less pervasive than that for the recharge area south of the HQ Flat area. Therefore, ET for the HQ Flat basin could be less than that for the remainder of the recharge area.

Response #3

A more detailed investigation of geology, soil depth and infiltration characteristics, and vegetation of the J17 HQ Flat Sink research site is included in Hauwert, 2009. The surface geology and karst development are the most important factors influencing infiltration. The J17 HQ Flat Sink research site centers on a 46-acre internal drainage sinkhole catchment. Because the instruments are raised about 50 feet on a tower, the evapotranspiration data are measured over a roughly one square mile area. Part of the reason I selected the site was to gather the most direct data on recharge on the karst area. The results were surprising to me, in that only 3% of precipitation on long-term average entered the sink drain, and 28% rainfall over a 1.4 year interval infiltrated through the gentle slopes within the catchment area. Because other studies of the Edwards and Trinity aquifer measure upland runoff of about 3% of precipitation, I conclude that the reason these internal drainage sinkholes are outstanding compared to other areas of the recharge zone is that they capture this 3% of annual average precipitation, instead to releasing it to local creeks. In my study, I continuously gauged water entering Headquarters Flat Sink as well as another comparison sink, Flint Ridge Cave. There is no indication that the soils on the slope of sinkholes are inherently more permeable than soils outside sinkholes, except that the accumulation of fines at the lower portions of the sinks may potentially reduce infiltration and increase evapotranspiration to a small amount. On Figure 3 of the subject report (reproduced as Figure 2 below), other studies have measured the difference in paired watersheds where the effects of vegetation were tested and showed slight variation in evapotranspiration, both positive and negative. The 3% of recharge that enters the sinkhole drain was metered separately and not included in the estimate of recharge that was deemed most representative with other portions of the recharge zone.

The use of my single site specific research site is limited due to varying characteristics over the recharge zone to estimate recharge across the recharge zone, which is why in the subject paper I utilize all published Central Texas eddy covariance and Bowen ratio evapotranspiration data and associated runoff to establish representative data. You can see from Figure 3 in the Hauwert and Sharp 2014 paper (reproduced in Figure 2 below) that evapotranspiration measured at HQ Flat Sink on the J17 research site is actually higher for the same rainfall compared to other ET towers, not lower, as stated by Mr. Slade.

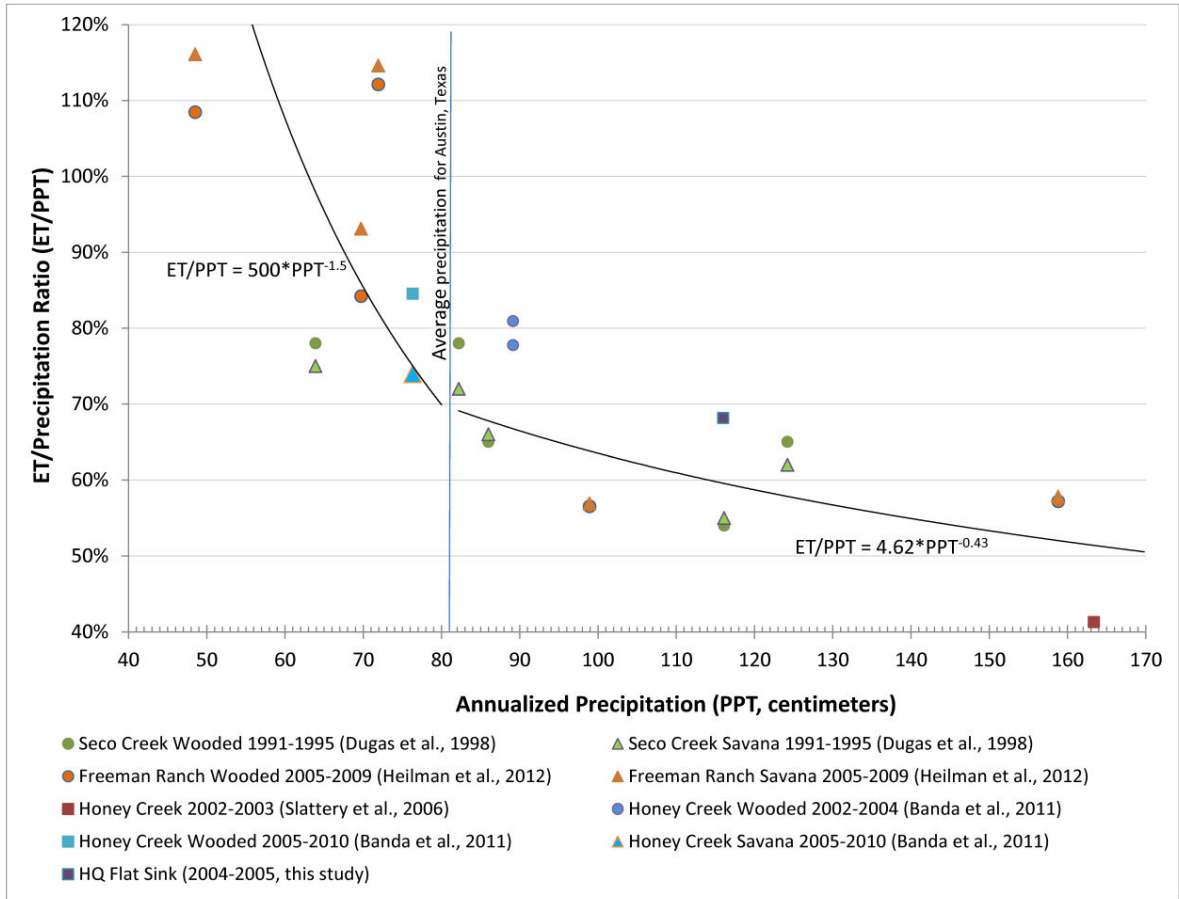


Figure 2. Compilation of Central Texas climate tower data. Note that except during lower than average rainfall periods, when soil moisture storage is being depleted, the combination of evapotranspiration, runoff, and autogenic recharge should be about 100%. Figure from Hauwert and Sharp, 2014.

The average 69% evapotranspiration of precipitation derived in the article also falls just below the 70-79% range of evapotranspiration calculated for Travis County by the USGS in a nation-wide study (Sanford and Selnick, 2012). I would argue that the smaller portion of Travis County that contains outcrop of the Edwards Aquifer likely has lower than average evapotranspiration and higher than average recharge since the karst is naturally developed to rapidly infiltrate precipitation compared to large areas of the county that are underlain by clay and shale. The 85% evapotranspiration calculated from stream flow loss water balance (Woodruff, 1984; Slade et al., 1986; Slade, 2014) falls fairly high of this range and are inconsistent with the USGS 2012 results.

Comment #4

4. ET rate at HQ flat much lower than that for entire recharge area

In the Conclusions section, the authors state "...under a wide variety of annual precipitation conditions, it can be estimated that under average precipitation conditions, 69% of rainfall leaves as

ET;...". However, five studies of ET rates for the Edwards aquifer have been identified, each of which produce much greater ET rates than 69%. The most conclusive study was conducted by Woodruff (1984) and presented by Slade (1986, p. 53-54)

The study involved precipitation (P) on the contributing and recharge area and its direct fate: recharge (Re), Runoff (Ru) from the area, and ET as the residual in the equation $ET = P - Re - Ru$. A 42-month period was used for which the precipitation was based on 12 USGS precipitation gages located throughout the basin. The study area included the entire watersheds of Barton, Williamson, Slaughter, Bear, Little Bear, and Onion creeks and is totally independent from discharge from the aquifer and from any subsurface recharge to the aquifer. The mean evapotranspiration calculated to be 85% of precipitation or 0.23 acre-ft per acre over the entire area.

The Woodruff ET value is within 8 percent of the rate of 0.25 acre-ft per acre per month as reported from field tests of evapotranspiration in the Edwards aquifer in the San Antonio area (Rugen and others, 1977).

A USGS study using gaged ET and gaged runoff on a basin in Comal County (near the subject study area) found that ET represented 81% of precipitation (Banta and Slattery, 2011). However, during the study precipitation was greater than average, thus ET during average conditions is expected to be greater than 81% of precipitation.

Additionally, a two-year study using eddy covariance measurements of the turbulent fluxes was conducted for the Edwards aquifer on the Freeman Ranch near San Marcos (Hays County), proximate to the Barton Springs Edwards aquifer. For the study, ET averaged 22.87 inches per year, which represented 92% of precipitation (Heilman and others, 2009).

Finally, for the San Antonio part of the Edwards aquifer, ET was reported to represent 85-90 percent of precipitation (Maclay, 1995).

Response #4

The subject paper describes that evapotranspiration as a percent of rainfall varies with the amount of rainfall during the monitoring period. Consequently, in the subject paper we predict that Central Texas sites might experience “*much greater ET rates than 69%*” during lower than average rainfall conditions. In Figure 3 of the subject report it is clear that evapotranspiration measured at the J17 research site was actually higher, not lower than other Central Texas climate tower sites for the amount of rainfall during the monitoring interval. The climate tower results from Banta and Slattery, 2011 and Heilman et al., 2009 are included in Figure 3 of the paper and analysis. The Heilman et al., 2012 cited in our subject paper is an update to the 2009 report and includes more years of data. There is no omission of published eddy covariance or Bowen ratio evapotranspiration data from the subject article of which I am aware.

The Woodruff, 1984, Slade et al., 1986, and Maclay, 1995 are all based on stream flow loss water balances and do not directly measure evapotranspiration, but roughly estimate evapotranspiration and upland recharge using only a small fraction of the precipitation budget, as discussed in Response #1. Evapotranspiration derived from stream-flow losses are subject to potential error, particularly where the groundwater basins are not directly traced (as in Woodruff, 1984; Slade et al., 1986, Maclay, 1995) or where existing direct groundwater tracing data are not incorporated (Slade, 2014). Using the same USGS flow loss data as, Woodruff (1984, as clarified in 2010) calculates that representative upland recharge is 0.89% percent of precipitation, while Mr. Slade (2014) calculates recharge derived from the Edwards outcrop to be 6.6% of precipitation. Using the Slade et al., 1986 water balance values, Hauwert (2009) found similar potential upland recharge values as he measured at site specific scale at HQ Flat Sink, once the correct groundwater basins were applied. The Hauwert 2009 comparison was only intended as a very rough comparison to show the potential for reinterpretation in the stream flow loss water balance. Specific recharge values as a percent of precipitation were not calculated from the Slade et al., 1986 results by Hauwert, 2009.

The comment confuses potential evapotranspiration with actual evapotranspiration. The Rugen et al., 1977 study referenced by Mr. Slade as verification of evapotranspiration values obtained by Woodruff (1984) and Slade et al., 1986 was derived from a lysimeter in a septic field. This is a potential evapotranspiration method because a septic field receives constant water and is not limited by rainfall and as such that in a semi-arid environment it would be expected to overestimate actual evapotranspiration occurring under natural conditions. Under natural conditions, soils tend to dry out during periods of low rainfall, which limits actual evapotranspiration. The J17 HQ Flat Sink climate tower measures actual evapotranspiration, and as described on p.874 of the subject paper, potential evapotranspiration from an Austin weather stations reported 25% higher evapotranspiration. If Rugen et al., 1977 reported 92% potential ET of precipitation, if the same relation holds, then his actual ET might be roughly 67% of rainfall, roughly consistent with our findings.

Comment #5

5. Author acknowledges decreased ET and increased recharge during wetter periods but ignores such for aquifer-wide average-conditions water budget

On page 97 of his PhD dissertation, Hauwert states "Preliminary measurements from a 348-day water balance of ET of 58%, diffuse infiltration of 34%, and discrete recharge of 8% (42% total recharge) were reported for this research by Hauwert et al. (2005; Table 3.3)". However, in the longer 505-day budget, ET is reported as 68 % of precipitation and thus recharge calculates to be 31% of precipitation. Hauwert further states that the reduced recharge percentage for the longer period is due to the fact that the longer period produced precipitation that was only 121 % of normal while the shorter period had precipitation that was 130% of normal. Therefore, Hauwert recognizes that recharge as a percent of precipitation is reduced with decreasing precipitation. Note that the 121% value reported by Hauwert is incorrect--the correct value should be 142%.*

However, in the subject report, the authors correctly states that the 505-day period produced 142% of normal precipitation but also states that the 31% recharge rate for the 505-day period also is representative of "average conditions" for the entire recharge area. This assumption is contrary to Hauwert's observation as documented in the previous paragraph.

Response #5

This comment primarily refers to the Hauwert, 2009 dissertation, but raises an interesting question about the effects of levels of annual precipitation on recharge that is addressed in the subject paper. In both Hauwert, 2009 and Hauwert and Sharp 2014, the discrete recharge entering the sinkhole drain increases with increasing precipitation and saturated soils as expected. While on the long-term average 3% of precipitation enters the two sinkholes monitored, under heavy rain conditions when soils were largely saturated from prior rainfall, I measured about half of the event rainfall entering the sinkhole drain.

In respect to diffuse recharge through soils, Figure 3 in Hauwert and Sharp 2014 clearly shows evapotranspiration decreasing with increasing annual precipitation, hence the combination of runoff and recharge increases proportionally. Note on page 7 of the subject paper we wrote:

“On an annual scale, most autogenic recharge occurs during years of higher than average precipitation when measured ET/precipitation ratios ranged from 70% to 55%, allowing 30% to 45% of precipitation to be distributed as the combination of recharge and runoff.”

The evapotranspiration measured over the 505-day water balance at the J17 HQ Flat Sink research site when rainfall was 142% of annual average rainfall matched the average conditions for all of the Central Texas climate tower data combined, as shown of Figure 2 (Figure 3 in the

subject report). This is because evapotranspiration measured over the reference interval at J17 HQ Flat Sink research site was slightly higher than average for the stations combined. I looked at the rainfall references in the subject paper and it correctly states that precipitation during the J17 HQ Flat Sink research site water balance interval is 142% higher than average annual.

Note that Slade et al., 1986 also had to deal with higher than average rainfall conditions in that water balance and states “the calculated evapotranspiration, while based on precipitation higher than normal, is reduced by recharge and runoff higher than normal and thus may be representative of long-term conditions.”

Comment #6

6. Author does not report collected data for more pertinent water budget

Hauwert analyzed the water budget for several periods as shown in the table below from his dissertation. However, the 348-day budget referenced in the first sentence of item number 4 above is not reported in the table. Additionally, other than for the much wetter than normal 505-day period, ET and diffuse recharge are not reported for any of the other time periods. Note that the 1140 day period for the Flat HQ basin is much longer than the 505-day period and represents 100% (normal) precipitation. Therefore, the 1140 day period might provide ET and recharge values representative of "average conditions" but Hauwert did not report the ET or diffuse recharge for this period. It is likely that the ET and recharge from the longer "normal" period, rather than that from the shorter wetter period should be represented by Hauwert and Sharp in the subject report.

Table 3.3. Results of internal drainage basin water balance

| Component | Interval Start | End | Interval Duration (days) | Amount/ Unit Area (cm) (% of rainfall) | Water Volume (m ³) | Potential Error (% of total) | rainfall/avg (%) | |
|---------------------------------|------------------|------------------|--------------------------|--|--------------------------------|------------------------------|------------------|-------|
| HQ Flat Microbasin | 4/2/2004 | 8/20/2005 | 505 | | | | | |
| Rainfall | | | | 160 | 100.0% | 297,850 | 5% | 12.1% |
| Evapotranspiration | | | | 109 | 68.1% | 202,910 | 3.4% | |
| Soil Moisture Storage | | | | 0 | 0.0% | 0 | 0.4% | |
| Discrete Recharge | | | | 8.8 | 5.5% | 16,300 | +0.1 to -0.8% | |
| Diffuse Recharge | | | | 42 | 26.4% | 78,640 | (±11%) | |
| Total Recharge | | | | 51 | 31.9% | 94,940 | 5% | |
| Flint Ridge Microbasin | 4/2/2004 | 8/20/2005 | 505 | | | | | |
| Rainfall | | | | 165 | 100.0% | 237,587 | 5% | |
| Discrete Recharge | | | | 6.7 | 4.0% | 18,600 | +0.1 to -0.6% | |
| HQ Flat Microbasin | 7/16/2003 | 8/29/2006 | 1,140 | | | | | |
| Rainfall | | | | 261 | 100.0% | 485,603 | 5% | 100% |
| HQ Flat Discrete Recharge | | | | 8.8 | 3.4% | 16,322 | +0.1 to -0.5% | |
| Flint Ridge Microbasin | 7/16/2003 | 8/29/2006 | 1,140 | | | | | |
| Flint Ridge Discrete Recharge | | | | 6.8 | 2.6% | 18,890 | +0.1 to -0.4% | |
| Barton Springs Discharge | 7/16/2003 | 8/29/2006 | 1,140 | | 176,505,749 | 5% | | |
| HQ Flat Microbasin | 7/1/2002 | 5/26/2003 | 329 | | | | | |
| Rainfall | | | | 70 | 100.0% | | 5% | 150% |
| HQ Flat Discrete Recharge | | | | 7.2 | 10.3% | 13,402 | +0.2 to -1.5% | |

HQ Flat Catchment Area 186,156 m²
 Flint Ridge Catchment Area 279,200 m²

Finally, within the 505-day budget, shorter periods that would approximate average precipitation conditions could have been selected for water budget analysis. However, the authors did not provide precipitation, ET, or recharge data for average conditions based on a shorter period. It is likely that data for such a period would reveal lower values for recharge and greater values for ET.

Response #6

This comment refers to the Hauwert, 2009 dissertation from which the table was derived, and not the subject Hauwert and Sharp 2014 paper. In a 2005 paper that presented the preliminary results of the J17 research site for HQ Flat sinkhole basin, I reported a 348-day water balance interval. However for the Hauwert 2009 dissertation, I refined the evapotranspiration data by making energy balance corrections described in that report, which generally increases the evapotranspiration values measured directly by the flux instruments. I didn't report the corrected evapotranspiration from the 348-day water balance since I had more confidence in a longer interval. While we collected an additional four years of evapotranspiration data, I spent considerable effort processing the data for the 505-day interval and didn't have resources for more. The selected water balance intervals also had to have the same beginning and ending soil moisture to eliminate the effects of change in storage at a site scale. Of course, longer monitoring intervals are preferable, but our reported interval was appropriate.

Comment #7

7. Authors discredit, without merit, several long-term data-based aquifer-wide water budgets contrary to their findings.

In the Introduction of the subject report, the authors identify several long-term data-based water budgets for the entire aquifer area--each report documents recharge to the Barton Springs Edwards aquifer. However, the authors dismiss the results of the studies--all of which document diffuse interstream recharge to be substantially lower than the 31% of precipitation as reported by Hauwert and Sharp.

Additionally, the authors state " Slade (2014) utilized the same presumed source areas and stream flow data from his earlier 1979 to 1983 study and determined that intervening areas contribute a maximum of 25% of total recharge and that this recharge constituted a maximum of 6.6% of precipitation using the same assumed groundwater basins [33]. Groundwater tracing conducted since 1996 has significantly refined groundwater basins contributing to Barton Springs [26]. Errors in groundwater basin delineation can account for the relatively low authogenic recharge to rainfall ratios calculated by the earlier recharge studies [26]."

However, the recharge values are not "determined"--data were (USGS streamflow values and measured springflow discharges) to document the recharge values. Also, USGS streamflow data document that about 75% of total recharge occurs on the 6 major streams crossing the recharge area, and the remaining 25% occurs as diffuse recharge. Based on conversion calculations, the diffuse recharge calculates to be about 10,100 acre feet per year, a value equivalent to about 2 inches over the 94 mi² recharge area, or a little more than 6 % of the average precipitation of 32 inches per year. Also, the "refined groundwater basin" is not defined but represent the inclusion of Cold & Deep Eddy Springs as part of the aquifer and/or subsurface recharge from the Edwards aquifer south of the study area. However, the water budgets by Woodruff (1984) and Slade (2014) are totally independent and unaffected from any knowledge gained from the tracing studies. Subsurface recharge is address by Slade and others (1986, p. 65) and water budgets for recharge and discharge to the aquifer prove that subsurface recharge volumes are negligible with the possible exception of very dry conditions. Such flow is so minor that its flow rate cannot be determined.

Also, Slade's report was in 2014, many years after the groundwater tracer studies, which were referenced and discussed by Slade (2014) and include discharges from Cold & Deep Eddy Springs. Finally, any subsurface recharge would be contrary to the author's statement that such "can account for the relatively low authogenic recharge to rainfall ratios calculated by the earlier recharge studies." Actually, discharge from the aquifer is known thus any recharge-

discharge water budget used to calculate recharge would require the calculated surface recharge volume to be reduced by an amount equal to any subsurface recharge volume.

Response #7.

As noted above, stream-flow loss water balance studies have potential errors, including limited knowledge of water source areas or groundwater basins, limited stream flow loss gauging stations, and potential error in gauging discharge sites. Stream-flow loss water balances are not a direct measurement of either recharge derived from the recharge zone or evapotranspiration. I agree that *“the water budgets by Woodruff (1984) and Slade (2014) are totally independent and unaffected from any knowledge gained from the tracing studies”* and as described in Hauwert 2009 p. 100, this is primarily why their water budgets do not compare well to field measurements. Our paper does not discredit the previous efforts but do point out sources of potential error that should be acknowledged.

I disagree with the statement :*“Also, Slade's report was in 2014, many years after the groundwater tracer studies, which were referenced and discussed by Slade (2014) and include discharges from Cold & Deep Eddy Springs.”*

As described in Hauwert 2009, nine tracers were injected in eight sites along Barton Creek and its tributaries. One trace just below Loop 1/Mopac was traced twice under Barton Springs discharge conditions of 18 and 107 ft³/s. Many of these tracers were conducted under flowing creek conditions as the leading edge of flow reached the injection site. The results consistently showed that all recharge in Barton Creek upstream of Loop 360 does not discharge at Barton Springs, but instead discharge at Cold Springs and perhaps other springs along the Colorado River. The portion of Barton Creek channel downstream of Loop 360 is generally a groundwater divide between Barton and Cold Springs. Barton Creek is one of the most traced watersheds anywhere. It is true the tracing work in general is “discussed and referenced” in Slade 2014, but no alternate data are presented to offer a different hypothesis for how the groundwater basin is defined. The direct tracing data were simply ignored in Slade 2014. The Slade 2014 water balance assumes, contrary to findings by direct tracing, that Barton Creek is the second largest source of recharge to Barton Springs. Consequently the Slade 2014 article does not incorporate the best available information or consider limitations in the understanding of the groundwater flow system in the 1980's.

As discussed in Response #1, it is not possible to measure Cold Springs discharge directly, instead partial discharge from exposed spring orifices are presented as complete discharge measurements by Slade 2014. More representative indirect measurements are not included by Slade 2014. Presentation of the partial discharge data does not dismiss the significance of Cold Springs in the water budget.

Regarding the comment:

'Also, USGS streamflow data document that about 75% of total recharge occurs on the 6 major streams crossing the recharge area, and the remaining 25% occurs as diffuse recharge. "

Slade et al., 1986 states that 85% of recharge occurs in the 6 major creek channels and 15% of recharge occurs on the intervening areas between the creek channels. The source for different values (75%/25%) claimed in the comment is unknown.

Comment #8

8. Authors reference results from impertinent study in attempt to justify 31% recharge rate

The authors state "The results from the 505-day water balance at HQ Flat Sink are strikingly similar to results a similar water balance study reported by Dugas et al. (1998) where 65% of rainfall left as ET, 5% of precipitation became runoff, and 30% of precipitation recharged the Trinity Aquifer".

However, the referenced study is for a small watershed in distant Uvalde County, is based on a much wetter than normal period (precipitation during the studied period was 131% of normal), and represents the Trinity aquifer rather than the Edwards. Additionally, the referenced study states that normal precipitation in the area is about 7.23 inches per year, which is about 22 % of the normal precipitation for the Barton springs Edwards aquifer. Also, ET was measured only from March through October--ET was not measured from November through February thus the reported ET for the study does not represent complete years.

Finally, as stated by Wilcox (2008) "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, evapotranspiration would constitute around 80% (table 1), a figure some 15% higher than that (65%) arrived by Dugas et al (1998). These differences are intriguing and suggest that recharge to the Edwards Plateau may be significantly higher than previously suggested"

Table 1 A comparison of evapotranspiration (ET) estimated from Seco Creek for 1991–1995 using the water budget method and direct measurements from the Bowen ratio towers in the Dugas et al. (1998) study

| Year | P (mm) | Q (mm) | ET (mm) | ET (%) |
|-----------------------|--------|--------|---------|--------|
| Water budget method | | | | |
| 1991 | 1161 | 256 | 904 | 78 |
| 1992 | 1242 | 500 | 741 | 59 |
| 1993 | 639 | 99 | 539 | 84 |
| 1994 | 822 | 39 | 782 | 95 |
| 1995 | 860 | 81 | 778 | 79 |
| Average | 944 | 195 | 748 | 79 |
| Bowen ratio ET method | | | | |
| 1991 | 1161 | 545 | 47 | |
| 1992 | 1242 | 670 | 54 | |
| 1993 | 639 | 536 | 84 | |
| 1994 | 822 | 526 | 64 | |
| 1995 | 860 | 627 | 73 | |
| Average | 944 | 580 | 64 | |

In the water budget method, ET is estimated as the difference between precipitation (P) and streamflow (Q). Precipitation (P) values were taken from Dugas et al. (1998). Streamflow (Q) was measured by the USGS.

Therefore, ET from the Dugas et al (1998) study was 80% of precipitation and for the many reasons stated above, recharge as a percent of precipitation for this study is not representative of average recharge conditions for the Barton Springs Edwards aquifer.

Response #8

Dr. Wilcox probably explains it better than I and has great perspective. As referenced in the subject paper, Huang and Wilcox (2005) observed discrepancies between upland recharge derived by stream flow loss water balances and more direct derivation derived from evapotranspiration towers. They hypothesized that recharge values derived from stream-flow water balances were at least 10% too low, and that additional climate towers would help establish better recharge values.

The statement:

“Therefore, ET from the Dugas et al (1998) study was 80% of precipitation and for the many reasons stated above, recharge as a percent of precipitation for this study is not representative of average recharge conditions for the Barton Springs Edwards aquifer”

is erroneous in that Dugas et al (1998) did not derive ET values of 80% of precipitation, these were derived from a USGS stream flow loss study, that is being compared to the ET tower values by Dugas et al (1998). The ET numbers derived from stream flow loss (about 80%) do not match the much lower ET numbers Dugas et al. (1998) derived directly from climate towers. There is no question here that the lower ET numbers are more precise at a site scale, but there is obviously a problem with those derived using stream flow loss water balance.

The Dugas et al., 1998 study did measure 7.5 months, or roughly two thirds of each year:

“In this study, BREB measurements were made from about March 1 through mid-October of 1991 through 1995. Measurements were not made in the winter (November–February) because ET rates were low (average daily lake evaporation rate during this period is less than 3 mm/d, and average measured ET in October was less 1 mm/d) and access to the site was restricted.” (p. 1501)

In Hauwert and Sharp 2014 I did not go into great detail regarding the methodology of each published source. However, on Figure 3 of Hauwert and Sharp 2014 (reproduced as Figure 2 above), we show “annualized” data and make no claims that year study was monitored for exactly a year, and in some cases the source data covers more than a year long that were annualized. In the case of Dugas et al., 1998, because 4.5 months of relatively low ET were omitted, it might be argued that annual evapotranspiration may be lower, and recharge potentially higher, than indicated by annual averages of the 7.5 months. The comment does not support the claim that the article exaggerated recharge values, but in this case may have cited available data that may have under-represented recharge.

Comment #9

9. Recharge rates for hydrologic simulation models of aquifer much lower than that claimed by authors

Four identified hydrologic simulation models have been conducted for the Barton Springs part of the Edwards aquifer. Models reported by Slade and others (1985), Barrett and Charbeneau (1996), Scanlon and others (2001), and the Southwest Research Institute (2009) each designated 15% of total recharge of 50 ft³/s as diffuse interstream recharge. Additionally, the model reported by Scanlon and others (2001) represents the Groundwater Availability Model (GAM) as sponsored by the Texas Water Development Board (TWDB). The diffuse interstream recharge used by all the models calculates to be 5400 acre feet per year, a value equivalent to about 3% of the average precipitation of 32 inches per year.

Response #9

It is general practice to base models on field data, rather than to discount field data because models did not incorporate them. Groundwater models are typically developed using many assumptions and as a result may not accurately reflect the actual system being modeled. Since a modeled outcome is not unique, the degree of how well a model compares to discharge data is not a measure of the accuracy of the conceptual model. The Scanlon et al., 2001 model used the whole Barton Springs Segment and the basic conceptual model of recharge from Slade et al., 1986, but simply adjusted recharge values to match reported Barton Springs discharge. The SWRI model used the same recharge used in Scanlon et al., 2001, and assumed Cold Springs discharge was 6% of total springflow. None of the models incorporated the groundwater basins

delineated with groundwater tracing. Sometimes for the specific purpose of the model it is easier to modify pre-existing models than to create a new one with more refined information. For the purposes of many models, it is not deemed necessary to match the modeled system in high detail.

The Texas Water Development Board developed a groundwater availability model for the adjacent Northern Segment of the Edwards Aquifer (Jones, 2003). While originally inputting 5% of precipitation for recharge values, “calibrated recharge rates of 20 percent of annual precipitation were obtained by trial-and-error.”

Comment #10

10. Recharge rates for many local studies of Trinity aquifer much lower than rate claimed by authors

Many studies have determined recharge as a percent of precipitation for the Middle Trinity aquifer adjacent to the study area as identified in the table below from Jennings and others (2001). Each of the studies report recharge as a percent of precipitation to be substantially less than the value of 31% reported by Hauwert and Sharp. The mean recharge rate for the 7 studies below is 6.2%, a value comparable to the upper limit of 6.6 % as documented by Slade (2014).

Table 2. Estimates of annual recharge as a percent of annual rainfall in the Study Area, from Mace and others (2000).

| <i>Investigations</i> | <i>Recharge as percent of Rainfall</i> |
|--|--|
| <i>Muller and Price (1979)</i> | <i>4 (1.5 for “availability recharge”)</i> |
| <i>Ashworth (1983)</i> | <i>4</i> |
| <i>Kuniansky (1989)</i> | <i>11</i> |
| <i>Bluntzer (1992)</i> | <i>7</i> |
| <i>Mace and others (2000)</i> | <i>6.6</i> |
| <i>Investigations using groundwater models</i> | |
| <i>Kuniansky and Holligan (1994)</i> | <i>7</i> |
| <i>Mace and others (2000)</i> | <i>4</i> |

Additionally, the TWDB has identified recharge rates as a percent of precipitation for the Trinity aquifer. These values are used by the GAMs for the Trinity aquifer. The map below provides those rates as documented in the TWDB report online at <http://www.twdb.state.tx.us/groundwater/docs/GAMruns/GRO4-18.pdf>. Based on this map, the recharge rate in Travis and Hays County is 6 % of precipitation--a value comparable to the upper limit rate of 6.6% of precipitation as identified by Slade (2014).

Response #10

The finding that evapotranspiration values measured from climate towers over the Trinity Aquifer were similar in trend to those measured over the Edwards Aquifer was somewhat surprising to me and suggests additional study is needed, although I have not personally conducted recharge studies over the Trinity Aquifer or evaluated extensively how former recharge values were derived. In Hauwert (2009, p. 79, p. 110), I noted how Trinity studies reported in 1979 found that only 1.5% of rainfall recharged the Trinity Aquifer, while studies after 1989 estimated 6 to 11% of rainfall recharged the Trinity Aquifer, so perhaps our understanding of the Trinity Aquifer is increasing our and methodologies are improving over time. Dr. Veni estimated 20% of precipitation recharged the lower Glen Rose in the Guadalupe River basin. I had expected that overall that the Edwards Aquifer would have higher autogenic recharge values than the Trinity Aquifer, particularly the upper Trinity/Upper Glen Rose Formation, where karst development seems very subdued (if you don't look at Natural Bridge Caverns). The middle Trinity Aquifer has similar high karst development as the Edwards Aquifer, as seen in its extensive caves, cave streams, and internal drainage basins such as Honey Creek Cave, Grapevine Cave, and cave system feeding Jacobs Well. Any values from Trinity Aquifer research sites such as Seco Creek and Honey Creek shown in Figure 3 were taken from published reports completed by others. At a site scale, the methodology for measuring evapotranspiration, recharge, and runoff components of rainfall is far more precise using eddy covariance or Bowen ratio towers than a stream flow loss water balance study, particularly where groundwater basins are assumed and have not been extensively traced.

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