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Characterization and Water Balance of Internal Drainage Sinkholes

By Nico M. Hauwert[1], Marcy E. Litvak[2], and John M. Sharp, Jr.[3]

Abstract

Internal drainage microbasins were found constitute 10% of the 98 square km (38 square mile) portion of the Barton Springs segment of the Balcones Fault Zone Edwards Aquifer contributing to Barton Springs. Internal drainage basins have subtle geomorphological expressions that have historically been overlooked as a major recharge source within the Barton Springs segment. Internal drainage basins can be recognized and mapped based on large solution sinkhole bowls, internal contours on surface topographic maps, aerial photos, inspection of sinkholes during and after rain events, field delineation of catchment areas with GPS, and accounts from individuals such as property owners and cave explorers.

We measured water balance components within a large internal drainage basin, the 19-hectare (46-acre) Headquarter Flat Sink to more directly quantify the amount of recharge contributed from internal drainage microbasins to the Edwards Aquifer. The monitored water balance components of HQ Flat that were measured for a year period (348 days), included the discrete recharge to the cave drain, evapotranspiration flux using an eddy covariance system mounted on a 15-meter tower, and soil moisture using insitu sensors and gravimetric analysis. Over the year test period, where rainfall totaled 106 cm, 58% left as evapotranspiration, 8% recharged directly through the cave drain, and 34% recharged diffusely across the internal microbasin of the cave site. The total recharge was measured to be 42% of the rainfall within the test basin. Only the discrete recharge portion was directly measured in a second internal drainage microbasin, the 22-hectare (54-acre) Flint Ridge Cave, since June 2003. The discrete recharge from Flint Ridge Cave was measured to be 9% over the same test year. During the 348-day test period, it can be estimated that known internal drainage basins contribution comprises about 5% of the Barton Springs flow reported by the USGS of 62,297,153 m^3 (2,200,003,200 ft^3).

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; 2) naturally developed channels and bowls divert runoff rapidly into the subsurface; and 3) the recharge is typically limited to intervals during and shortly after rainfall events when the humidity is near saturation and net losses to evaporation are reduced. Recharge quantity can be significantly enhanced through preservation and restoration of flow to internal drainage basin sinkholes.

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Introduction

The Barton Springs segment of the Balcones Fault Zone Edwards Aquifer (Barton Springs segment) is a federally designated sole source aquifer (south of Williamson Creek divide) above which live an estimated 45,000 residents, including City of Sunset Valley, City of Buda, City of San Leanna, Ruby Ranch, Oakforest, Hays Country Oaks, and other areas (BSEACD, 1997). The aquifer is a reliable, inexpensive source of water important for industries such as Centex Materials and Texas Lehigh Cement Company. Most of the groundwater within the Barton Springs segment eventually discharges from Barton Springs, a cluster of four spring outlets near the center of Austin, Texas. The largest of the four spring outlets, Main or Parthenia Spring, discharges into a manmade pool that is a major local tourist attraction and receives 350,000 paid visitors annually. Barton Springs flow averages 1500 l/s (53 cfs). The four Barton Springs outlets host federally-listed endangered Barton Springs salamander, *Eurycea sosorum*, which is found only at these spring sites (Federal Register, 1997). Barton Springs also provides a portion of water supply to the City of Austin's Green Water Treatment Plant. The sustainability of the aquifer resource is threatened by rapid growth associated with the City of Austin and IH35 corridor. In an effort to preserve water-quality in the area, in 1997 residents of the City of Austin (COA) voted to approve the $65,000,000 Proposition 2 Bond for the acquisition of preserve lands. Other efforts include water quality ordinances in Austin, Edwards Aquifer Protection Rules by the State of Texas, regional planning in Travis and Hays Counties, water-quality measures recommended by U.S, Fish & Wildflife Service, as well as other local ordinances in Buda, Dripping Springs, and Bee Caves.

The Barton Springs segment is a subsoil karstic limestone and dolomitic aquifer. Karst aquifers are among the most difficult hydrogeological systems to characterize because groundwater recharge, flow, and discharge are largely discrete. The climate of the study area lies in a transition between subtropical subhumid and subtropical humid (Larkin and Bomar, 1983). The climate is strongly influenced by flow of tropical marine air from the Gulf of Mexico, decreasing in moisture content from east to west.

In the conceptual model of a karst aquifer, the recharge can be classified as: 1) *allogenic recharge*, where recharge enters recharge features in creek bottoms (swallets) draining upstream less permeable areas of the watershed such as the Contributing Zone to the west; 2) *diffuse infiltration*, where rainfall falling directly onto the karst outcrop, or Recharge Zone, enters the aquifer through the soil and fractured rock matrix; 3) *internal drainage* (also called *internal runoff*), where rainfall or runoff enters into closed depressions on the Recharge Zone and recharges the aquifer through sinkhole drains; or 4) *overflow from caprock or perched aquifers*, where overflow water enters the aquifer through vertical shafts, soil pipes, and widened fractures overlying less permeable material (White, 1999). Above the water table, water can be stored in the soils irregular bedrock features of the epikarst (or subcutaneous zone, White 1999), and perched above less permeable, unsaturated bedding layers of the aquifer's vadose zone (Small, Hanson, and Hauwert, 1996). In karst areas, surface runoff generally flows a short distance before recharging into sinkholes (dolines) or infiltrating into highly permeable karst soils (Jennings, 1985; White, 1977). Clay and iron-rich soils such as "terra rosa" may block the bottoms of some recharge features and create temporary ponds and swamps over karst areas.

The amount of recharge to an aquifer depends "largely upon the nature of the soil and rocks", particularly in basins underlain by limestone (Maxey, 1964). In karst areas, precipitation can rapidly infiltrate beyond the depth of transpiration and atmospheric evaporation. Karst landscapes have efficiently developed internal drainage compared to other aquifers, and provide less opportunity for extended evapotranspiration near the surface (Jennings, 1985). In the karst portion of the Mammoth Cave area, Hess and White (1974) found that 19% less evapotranspiration normally occurred than in nonkarst portions of the same river basin. The difference in evapotranspiration was attributed to the rapid internal drainage system that quickly absorbed surface runoff. This suggests that in water balances where evapotranspiration and recharge is not directly measured, the recharge portion to karst systems will often be underestimated. Dublyanskii and others (1984) evaluated the water balance of a 150 square kilometer upland sinkhole basin over 18 years in Crimea, Ukraine, utilizing precipitation gauges, soil and evaporation pans, condensation chambers, and 13 weir flow gauging stations. In this sinkhole basin, the amount of input water from precipitation and condensation left the system as evapotranspiration, runoff, and recharge, each amounting to one third of the input (33%, 33%, and 34% of the input water, respectively). In small non-karst catchment areas, the proportion of upland recharge is often greater than anticipated compared to recharge occurring in creek channels due to the greater rejection from shallow water table and the predominance of evapotranspiration within creek valleys (Weyer, 1972; Karrenberg et al., 1970). In some studied non-karstic watershed basins, differences in low-water runoff did not vary greatly due to soils, morphology, or annual precipitation patterns, but varied considerably with the type of bedrock (Weyer, 1971).

Previous work in the Edwards Aquifer

From the presence of relatively thin soils and the lack of well-defined surface drainage patterns, the Barton Springs segment overall is characterized as having relatively low runoff and high recharge (Woodruff, 1984). A water balance for the Barton Springs segment was conducted based on data from continuous flow or water level stations upstream and downstream of the Recharge Zone on Barton, Williamson, Slaughter, Bear, Little Bear, and Onion Creeks collected over a 42 month period between 1979 and 1981 (Slade, Dorsey, and Stewart, 1986; Woodruff, 1984). Flow loss data, supplemented with estimated runoff coefficients for the intervening upland Recharge Zone were used to estimate the proportion of recharge contributed by each watershed (Table 1). Fifteen percent of the recharge was estimated to occur in the intervening uplands between the major creek channels, while the remaining 85% recharges from the five major creek bottoms. Only about 0.09% of the mean rainfall was estimated to recharge the aquifer through upland intervening areas of the Recharge Zone, as 85% of the rainfall was lost to evapotranspiration, 9% left as surface runoff, and 6% recharged to the Edwards Aquifer (Woodruff, 1984). Over a 42-month water balance, changes in water storage of the soil zone, plant tissue, and mineral hydration were considered negligible. These earlier investigations contributed to understanding this complex aquifer and their results have strongly influenced the development of water-quality protection strategies. The relatively small proportion of total recharge attributed to upland areas in these studies have also been the rationale for lower levels of protection for upland recharge features.

It is not surprising that much recharge to the Barton Springs segment would occur within the major creek channels. Stream flow generated within the relatively large, upstream Contributing Zone generally flows over the Recharge Zone through the major creek channels. In addition, much of the intervening upland area of the Recharge Zone also generates flow to the major creek channels. However, because the

1980's water budget was based on limited data, the recharge contribution from the upland areas may have been underestimated. A recent geochemical study by the USGS of the Edwards Aquifer recharge sources in Bexar County suggests that only 44% of the recharge originated from stream channel losses, and the remaining 56% originated as direct infiltration on upland areas (Ockerman, 2002).

Descriptions of the Research Sites

The two research sites were the Headquarter Flat Sink and Flint Ridge Cave.

Headquarter Flat Sink (J17 Tract)

Headquarter Flat sinkhole and cave (HQ Flat) are located on the COA J17 Water-Quality Protection Land tract in South Austin. A detailed description of HQ Flat is provided by Russell (2004). In 1984, the previous landowner, Ira Yates, reported that the cave "takes considerable water after rains". Russell believed the cave was a significant recharge feature in 1984 and cleared rocks and debris around the entrance to enhance recharge there. He described an estimated 170 m^3 depressed area in the drainage leading to the sinkhole that had to fill before surface flow could continue to the cave. Russell estimated the catchment area drained "an extensive area to the south and west" of about 6.5 hectares (16 acres). Much of the known extent of the cave had been investigated by cave explorer Mike Warton in the 1980's. The cave was mapped to a depth of 10 m (32 feet).

A second hydrogeologic study (Ford, 2000) describes surface drainage and karst development on the J17 tract. This report described surface flow on the J17 tract to be primarily sheet flow toward Danz Creek tributary of Slaughter Creek. It describes HQ Flat as a "small sink" and noted "the recharge potential to the aquifer from the sink is probably small to medium since the surface opening is moderate in size but the drainage area affected by the sink is relatively small." From the surface entrance the report believed the cave "appears to pinch close at about 5 feet."

These two previous reports show divergent descriptions and evaluations of the same karst feature. These contradictory reports are not uncommon in recharge feature investigations.

Flint Ridge Cave (Tabor Tract)

Flint Ridge Sinkhole and Cave (Flint Ridge) are located on the COA Tabor Water Quality Protection Land tract in South Austin. The geology, hydrology, biology, speleological features, and the history of exploration in Flint Ridge has been extensively described by Russell (2004), Elliott (1997), and Veni (2000). The cave is listed in a joint USFW permit by the COA and Travis County as a preserve for karst invertebrate species of concern, including *Circurina cueva*, a rare cave spider. Veni (2000) estimated the surface catchment of the cave to be 16 hectares (163,300 m^2) in area, that 3.63% of the rainfall would recharge within the catchment of Flint Ridge, and that typical intense storms would yield an average of 415 to 593 m^3 of runoff to the cave entrance. From high water marks inside the cave after a 20 cm storm in October 1998, Veni estimated about 1,000 m^3 of flow had passed through the cave, but believed some of the recharge must have entered through other features rather than at the cave entrance of Flint Ridge. The report acknowledged the difficulty in estimating recharge from Flint Ridge and the need for installation of gauges to directly measure flow.

Objective

In this study we wanted to examine some of the most significant upland contributors of recharge. We hypothesized that as internal drainage basins, sinkholes like HQ Flat and Flint Ridge had similar recharge characteristics that varied directly with the size of their catchment area. In this study we examine the geomorphological features that characterize them, map the aerial extent of the ones we could identify across the Recharge Zone, measure the water balance components of one or more features, and estimate the total recharge contribution of internal drainage basins that we could examine.

Methodology

1) Locate and Map Recharge Features and Areas Using GPS and GIS.

First we looked at common geomorphological characteristics of internal drainage basins, then we identified and mapped the extent of these features across the Recharge Zone. A methodology and classification for quantifying the relatively recent surface dissolution associated with a recharge feature (as opposed to subsurface dissolution caused by more ancient groundwater flow processes or post depositional ancient dissolution that may have occurred during the Cretaceous Period) was developed for use in the Barton Springs segment, including drainage area, rim (characterized by a sharp break in slope around the entrance), and the conduit opening. Each feature was examined to determine whether solution or collapse processes were the primary agent in its development at the surface. As karst features mature, solution sinkholes originating along fractures mature into solution-enlarged fissures, and eventually into nearly circular bowls. Troester et. al.(1984) observed that at the highest stage of maturity, sinkholes develop a "star" pattern in aerial view as the sinkhole pirates more well defined channels. Sinkhole catchment basins similarly generally progress in maturity from linear to pentagon shaped, although this ideal morphology may be modified by topographical slope (Williams, 1972). Within the Barton Springs segment, sinkholes where solution was the primary agent in development of the surface opening were recognized by concave, "bowl-shaped" cross section.

Collapse sinkholes do not have entrances primarily created by surface solution, and therefore are expected to have very different recharge behavior and geomorphology. Collapse sinkholes are generally caused as the ground surface erodes near pre-existing caves in the subsurface. As the stress fields generated from an open cavity below reaches the surface, an unstable condition results that can eventually lead to a collapse sinkhole. Collapse sinkhole development can also be enhanced by other factors, such as loss of buoyant support of unstable materials from changes in the water table, enhancement of dissolution of supporting materials by surface flow diversion, and the placement of structures over underlying cavities, and other causes (Aley and others, 1982; Newton, 1984). Only very few instances of *recent catastrophic* sinkhole development have been documented within the Barton Springs segment, possibly because suitable conditions are not present. A detail karst assessment of Camp Bullis north of San Antonio found that only 6.9% of the karst features found were collapse sinkholes (Veni, 1998). In this study, collapse sinkholes were recognized by a convex cross section.

This study characterizes *internal drainage microbasins*, defined here as natural areas where at least 90% of the runoff generated within a given catchment area does not discharge from the basin on the surface under natural conditions. This condition is attributed to the combination of a solution-enlarged sinkhole bowl that is capable of temporarily storing surface runoff and the permeable drain present at the base of sinkholes that transmit runoff into the subsurface. As defined here, internal drainage features and catchment areas are not necessarily large; a small karst feature can capture more than 90% of a relatively small catchment area. *Ponded internal drainage microbasins* appear to be similar features in origin, but differ in that sediment and other debris has obstructed the drain to the extent that they drain more slowly. Greater evaporative losses can be expected from ponded internal drainage microbasins. A similar recharge feature is not a natural recharge feature at all, but drainage diverted to manmade depressions that are not imperviously lined, such as a rock quarry. Where the manmade depression extends to the water table, the recharge contributed by these features may be diminished to some extent by greater evaporative losses.

Internal drainage microbasin, ponded internal drainage microbasin, and artificial internal drainage microbasin features and their catchment areas were identified and mapped using a combination of tools including (1) interviews with local cave explorers and property owners, discovery by COA or BS/EACD staff, closed contours on 10 and two-foot contour topographic maps, aerial photos, and field global positioning system (GPS) delineation. A Trimble XRS GPS (acquired by BS/EACD through an Environmental Protection Agency 319h grant administered by the Texas Commission on Environmental Quality) was used to locate known recharge feature openings, measure sinkhole rim dimensions, and delineate drainage areas for sinkholes (Figure 1). Other recharge features and sinkhole drainage areas were located on a two-foot contour interval map (available for Travis County) or 10-foot contour interval map (for Hays County). This data was mapped in

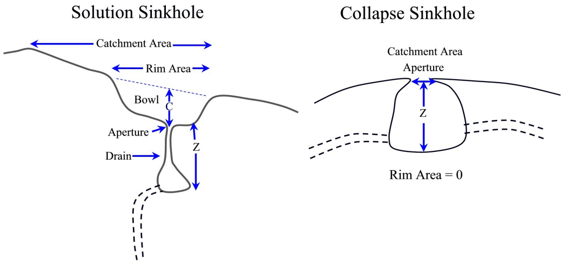


Figure 1. Sinkhole dimensions

ArcGIS version 9.1 software, produced by Environmental Systems Research Institute (ESRI). Sinkhole bowl volumes were calculated either by (1) simple application of an ideal cone formula utilizing the field measurement of the rim area and bowl depth (C) or (2) site survey of larger sinkhole bowls.

2) Water Balance of Sinkhole Microbasin

Two large sinkhole basins on the COA Water Quality Protection Land tracts, HQ Flat on the J17 tract and Flint Ridge on the Tabor tract, were continuously monitored for flow to the cave entrances since July 2002 and March 2003, respectively. These features were selected since nearly all of the surface runoff arrived at the cave through a limited number of discrete drainages, and long-term access could be obtained. The catchment area of each sinkhole was estimated using field assessment of drainage using a Trimble XRS global positioning system, accurate to 1 meter, as well as two foot contour interval map coverages derived from 2000 aerial surveys (COA). Over 95% of the catchment area for both features converge though drainages that were monitored during the study. The remaining areas drained around the measurement structures or directly to the sinkhole drains.

Within a closed sinkhole microbasin the amount of rainfall can be proportioned as follows:

$$P = ET + I + DR + S$$

Where:

P= Precipitation volume
ET = evapotranspiration flux volume
I = infiltration from soil and lesser karst features into the underlying bedrock (diffuse recharge)
DR = internal runoff that enters the cave drain (discrete recharge)
S = change in water storage in soil during the reference period

A 348 day period was selected for the water balance, from February 4, 2004 to January 17, 2005. The starting day represented the first time when the synchronized monitoring instruments were operational and producing the highest quality data.

Recharge to the underlying aquifer was assumed to consist of discrete recharge, where internal runoff enters the cave opening at the lowest point of the sinkhole, and diffuse infiltration, where surface runoff passes through the soil, epikarst, or smaller recharge features and percolates to the water table). Discrete recharge was measured using one ISCO 3230 flow meter, installed at a weir (June 30, 2002 until April 1, 2003) or flume (April 15, 2003 to present) on the drainage channel flowing to HQ Flat. An estimated 95% of the runoff to HQ Flat flows through this single channel from the west, which makes the site ideal for runoff monitoring. A slight dirt berm was placed south and west of HQ Flat to divert overland flow within the natural basin from the south to the channel entering the west side of the sink. The design of weirs and flumes used in this monitoring was adapted from Shaw (1988) and Kilpatrick (et. al., 1983).

Flow monitoring was also conducted at Flint Ridge in order to examine if other internal drainage microbasins had similar discrete recharge as HQ Flat in proportion to their catchment areas. Three defined drainages entering the sinkhole rim were monitored. Flow to the two largest drainages were metered using a two-foot H flume in each. The smallest of the three drainages was metered using a compound weir cut from unpreserved 0.75” plywood and edged with aluminum angle iron. Each drainage was monitored by an ISCO 3230 bubbler flow meter.

Precipitation data at each site came initially from visual plastic rain gauges (accurate to 0.254 cm or 0.1 inch until June 2004; and then replaced with 0.0254 cm or 0.01 inch graduated rain gauges) and continuous 0.0254 cm tipping bucket rain gauges on both the J17 and Tabor sites. For the period of record, continuous rainfall was also measured within a mile of both microbasins at a COA maintained Flood Early Warning station and a second 0.0254 cm tipping bucket rain gauge maintained by COA Wildlands Conservation staff.

Evaporation and transpiration (*evapotranspiration or ET*) were measured nearly continuously using eddy covariance. The eddy correlation approach is the most direct measurement of evapotranspiration on vegetated landscapes (Ham and Heilman, 2003). Eddy correlation relies on turbulent transfer of heat and water vapor to directly measure both sensible and latent heat flux above the canopy. Ten Hertz measurements of wind speed and acoustic temperature were made with a three dimensional sonic anemometer (CSAT-3, Campbell Scientific), while 10 Hertz measurements of water vapor concentration were made with an open path infra-red gas analyzer (LI-7500, LI-COR). The anemometer and gas analyzer were controlled by a micrologger (CR23X for first 10 months, then a CR5000, Campbell Scientific), and powered by solar power.

Thirty-minute fluxes of latent heat and sensible heat for a 348 day test period were calculated on 10 Hertz datasets following procedures outlined by Litvak and others (2003). Initial data gaps caused by power outages, lowering the instrument for annual calibrations, and particulates (including raindrops) obscuring the glass lens of the gas analyzer comprised 37% of the readings. The ET data were further filtered to remove poor-quality data, including readings taken when the wind approached the flux sensors from the north, where the tower distorts wind velocities and during rain intervals. One third of the actual evapotranspiration readings remained following this postprocessing. To fill in the gaps, monthly correlations of postprocessed ET data were related to net radiation readings. On a monthly basis the ET to net radiometer correlations had R^2 correlations between 0.35 and 0.83, averaging 0.6. Where gaps existed in the J17 tower net radiation record, readings from a sister ET tower located 21 km south on the Texas State University Freeman Ranch were used. In the interval prior to the activation of the Freeman Ranch ET tower in July 2004, 2,484 thirty minute day time gaps, or 15% of the 30 minute interval test period data had no associated postprocessed ET or net radiation readings. Data gaps of night-time of rain intervals were filled with values of zero ET. Single data gaps (172 intervals) were filled by averaging adjacent ET values. Most of these gaps occurred during the first half of the test period due to insufficient power, a condition that was later corrected..

Additional instruments used for meteorological and energy balance measurements include air temperature and humidity (HMP45C, Vaisala), net radiation (Q7.1, REBS), incoming and upwelling solar radiation (LI-200 SA, Kipp and Zonen), and photosynthetic photon flux density (PPFD, LI-190SA, Licor). All instruments are placed above the canopy on a 12-meter Rohn tower . The ET flux tower was placed near the center of the HQ Flat catchment, with a one degree slope to the north and southeast, and a maximum 3 degree slope to the south. The meteorological, water flux, and energy balance instruments were originally positioned on a 3 meter tower on the J17 site on July 2002. By January 2004, the instruments were placed on a new 15 meter tower, the instruments were repaired of software and hardware problems, factory calibrated, and connected to a field computer that stored the raw data files.

The *available soil-moisture storage* is the amount of releasable water held in the soil that varies at any given time between the field capacity and permanent wilting point (Ferguson, 1994). Gross soil thickness was estimated by 10 distributed test holes and outcrop observations, to determine the volume of soils across the internal drainage basin sites. In selected locations across both sites, holes were dug using hand tools to the bedrock surface and gravimetric analysis was conducted to determine the soil thickness and water content of the soils. A soil-moisture meter continuously measured the soil moisture in a test site near the ET tower. Continuous measurements of water content at 2.5 cm was made using a Campbell Scientific water content reflectometer probes (CS616) installed horizontally. Soil temperatures were measured continuously at depths of 2.5 and 10 cm using thermocouple probes. Soil heat flux was measured using the combination method at three locations as well. Heat flux plates (HFT3, REBS) were installed at a depth of 5 cm, and storage heat flux in the 0-5 cm layer was calculated from soil temperature measurements at 2.5 cm depth and estimates of heat capacity (Kimball and Jackson, 1979). The depth to bedrock and change in soil moisture from the start to end of a reference period were used to estimate the gross change in water storage within the soils. Where a monitoring period can be selected such that the starting and ending soil moisture at a test site is the same, the calculation of the gross amount of water locked in the soils of the site are unnecessary for the purposes of a water balance.

The diffuse infiltration through soil and minor recharge features is likely highly variable across both microbasins (Dingman, 1994, pp.247-249). Diffuse infiltration is the only component of the water balance not directly measured, but is estimated as the remainder of the water balance. Components of a complete water balance are available from February 4, 2004 until January 17, 2005, and the diffuse infiltration is separately calculated as:

$$I = P - DR - ET - S$$

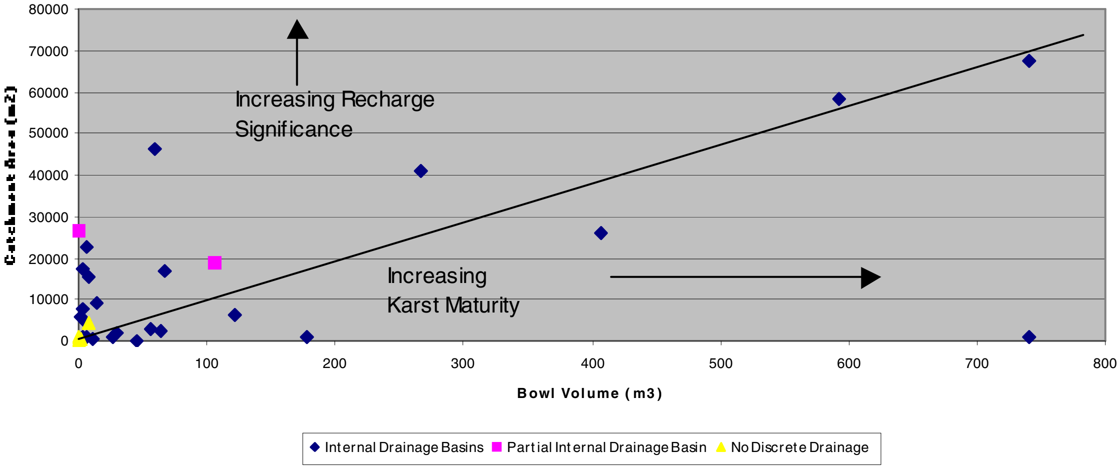
No runoff leaves either sinkhole basin under any flood conditions because of the bowl configurations of the basin and the capacity of the caves to absorb runoff generated within the microbasin. Following major flood events, high water marks along adjacent Danz Creek, a tributary to Slaughter Creek on J17 tract, were walked to insure no floodwaters from the creek entered the HQ Flat microbasin. Even after the largest rain event observed in November 2004, high water marks indicated that Danz Creek would have to rise an additional 2 to 3 feet before it could flow into the HQ Flat microbasin. A flood retention dam build on Danz Creek upstream of HQ Flat also serves to stabilize the downstream flood flows such that they are not likely to cross the topographic divide and enter HQ Flat.

Results

Fifty-five internal drainage basin sinkholes were identified within the portion of the Barton Springs segment recharging to Barton Springs, with a combined catchment area of 1,175 hectares. Seven internal drainage basins, with a net catchment area of 69 hectares, were identified within the portion of the Barton Springs segment that discharges to Cold Springs (or the Cold Springs subsegment). The catchment area for HQ Flat was determined to be 19 hectares (186,156 m^2 or 46 acres) in size, which was significantly larger than the 6.5 hectare area estimated by Russell. Our estimate of the catchment area for Flint Ridge was 22 hectares (218,531 m2 or 54 acres) in size which was also larger than the previous estimate of 16 hectares by Veni (2000). Eleven ponded internal drainage basins were identified, having a combined catchment area of 245 hectares. One artificial internal drainage basin identified was an abandoned quarry having an estimated catchment area of 86 hectares. The percent of the 98 km^2 Recharge Zone feeding Barton Springs that is comprised by internal drainage basins, ponded internal drainage basins, and artificial (quarry) internal drainage basins are 10%, 2%, and 1%, respectively.

The bowl volume of selected solution features was compared with its associated catchment area (Figure 2). In general, with increasing karst maturity, a solution feature's bowl volume increases in proportion to its catchment area. Some differences in the relation between bowl volume and catchment area could be due to varying hydrostratigraphic units-all of the larger features shown here developed in the Kirschberg or Leached/Collapsed Members. Large deviations of larger catchment area to bowl volume may suggest less mature karst features that by chance pirated larger drainages. Large shifts below the general trend in bowl volume to catchment area may suggest a feature that originally had a larger catchment area that was affected by anthropogenic drainage diversions. Quantification of bowl volumes in karst

Figure 2.
Bowl Volume to Catchment Area of Mapped Solution Features



assessments can help identify significant features such as internal drainage basins. In cases where sinkholes discovered on hilltops that appear to have large bowl volumes, a closer inspection may reveal these are actually *collapse* sinkholes.

The water balance for HQ Flat sink shows similar recharge and evapotranspiration percentages to other karst areas (Table 1). Over a one year period, about 42% of the rainfall within the HQ Flat microbasin recharged the Barton Springs segment, with 33.5% infiltrating through the soils into the underlying bedrock and about 8% flowing into the cave drain at the lowest point of the sinkhole as discrete recharge. The rainfall measured over the reference year was 30% above the local average rainfall of 81 cm. Over the 30.5-month period of record for HQ Flat, the discrete recharge declined from 8% to 5.7% of the total rainfall. The 30.5 month period had 20% higher than average rainfall. Barton Springs flow averaged 2050 l/s over the 348-day test period, which is 38% higher than long-term average flows of 1500 l/s. The USGS reported total volume of 62,297,153 m^3 (2,200,003,200 ft^3) discharged from Barton Springs over the 348 day test period. The HQ Flat microbasin represents 0.002% of the area within the Recharge Zone feeding Barton Springs, about 0.001% of the combined Contributing and Recharge Zones, but contributes 0.12% of the recharge to Barton Springs over the year test period.

Table 1. Water Balance Results for Test Sinkhole Basins

Period February 5, 2004 - January 17, 2005 (12 mo)

Component	Amount/ Unit Area (cm)	(%)	Volume (m^3)
HQ Flat Microbasin			
Rainfall	106	100.0%	6,832,631
Evapotranspiration	61.52	58.0%	4,193,044
Soil Moisture Storage	0	0.0%	(assumed)
Discrete Recharge	8.95	8.4%	16,663
Diffuse Recharge	35.53	33.5%	59,577
Total Recharge	44.48	42.0%	76,240
Flint Ridge Microbasin			
Rainfall	106	100.0%	6,832,631
Discrete Recharge	10.1	9.5%	22,135
Barton Springs Flow (USGS reported)			62,297,161
Period: June 30, 2002-January 17, 2005 (30.5 mo.)			
HQ Flat Microbasin			
Rainfall	247	100.0%	459,866
Discrete Recharge	14	5.7%	26,056

The volume of discrete recharge to Flint Ridge over the year test period was 25% more than HQ Flat, although this is expected since Flint Ridge has a proportionally larger catchment area. The percentage of rainfall over the catchment area that entered Flint Ridge over the same year was 9.5%, which is surprisingly similar to the 8.4% of discrete recharge measured at HQ Flat despite their apparent differences, such as the large surface depression diverting flow from HQ Flat.

For an ideal water balance, the selection of long test intervals where the starting and ending soil moisture values are relatively stable and approximately identical make examination of changes in soil moisture storage unecessary. Unfortunately, data from the soil moisture sensors were not sufficiently analyzed at the end of the test period to derive values of soil moisture on January 17, 2005. For the purposes of this initial water balance we will assume the change in soil moisture storage was about zero over the test period, such that no water was lost or gained from the soil. The soil moisture sensors and gravimetric analysis of the soil in selected areas indicate the extractable soil moisture is typically 20-25%

and ranges from 10% to 35%, except for short periods after rain events. Typical soil thickness depths within the HQ Flat microbasin were found to be 60 cm or less on the northern half of the catchment basin, and about 0.2 cm or less on the southern portion. Assuming an average 30 cm soil depth, the estimated maximum change in soil moisture storage from a very wet period to a dry period (or vice versa) is 7 cm. The typical variation in soil moisture storage of 7 cm represents 7% of rainfall over the 12-month test period and declines to 3% over the 30 month test period.

Discussion

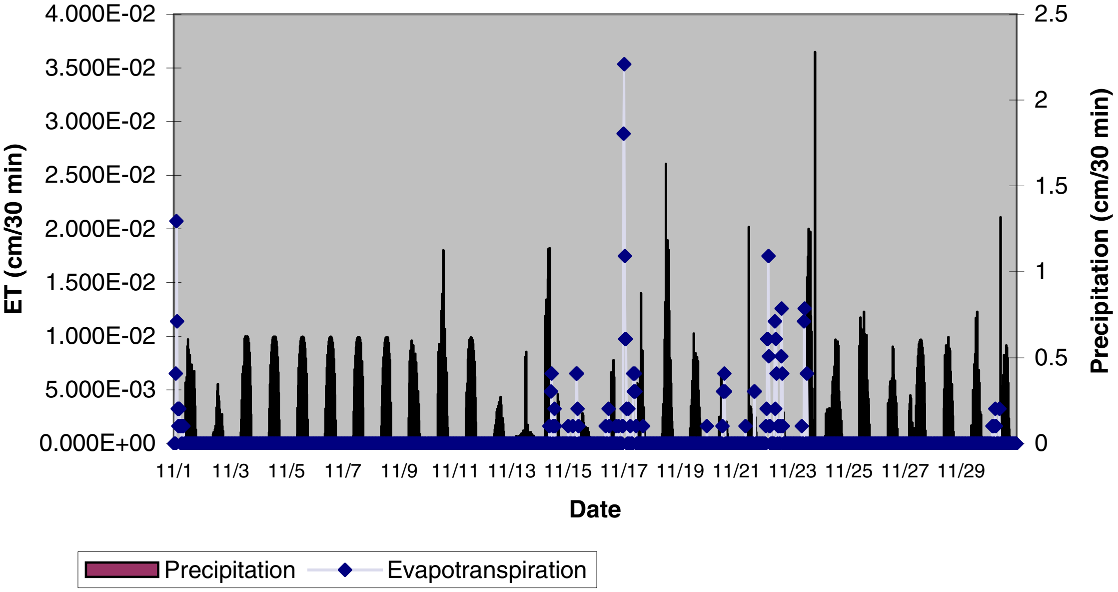
Internal drainage sinkholes are some of the most mature karst features on the Recharge Zone of the Barton Springs segment, and show relatively high efficiency for transferring a given rainfall volume per catchment area into recharge. This efficiency is much higher than other studies of the Barton Springs segment have previously recognized. In this regard, the results of the current study are proposed as more accurate due to the advances in evapotranspiration monitoring and the finer scale of examination. The reasons internal drainage sinkholes are relatively efficient compared to other types of recharge features may be the combination of a number of factors:

1) In well-developed bowls of mature sinkholes within internal drainage microbasins, nearly all of the runoff generated within the catchment area can be stored if not immediately transmitted through its drain. Very little, if any surface runoff ever contributes to downstream creeks. In contrast many creek-bottom swallets typically experience flows that exceed its recharge capacity, such that considerable runoff generated in its catchment is rejected by the feature and flows downstream. In addition, creek-bottom swallets may experience recharge rejection due to their greater proximity to the water table.

2) Through surface piracy as well as bowl and drain enlargement through dissolution, mature sinkholes transmit surface water relatively rapidly below the surface to depth where the water is not subject to significant evaporation and transpiration.

3) The majority of recharge occurs during and shortly after rain events when humidity is relatively high and evapotranspiration is relatively low (see Figure 3).

Figure 3. Evapotranspiration and Rainfall Nov. 2004



Over long periods of time, the change in storage within the soil becomes less significant in comparison with cumulative volumes of rainfall or recharge. Consequently, there can be significant error associated with estimating the total soil water storage of a site, but over long periods the effect these errors becomes insignificant. Over the scale of an individual rain event, the soil moisture content of the soil is very significant in determining whether the field capacity of the soil is exceeded and runoff to the cave will occur. For the purposes of this study, once water descended below the soil it was assumed to be recharge. Some water storage is expected in the epikarst and vadose zone. However, it is unquantifiable by this methodology, and over long periods of measurements this change in storage also becomes insignificant.

The percent of discrete recharge is expected to vary directly with the estimated catchment area. If the actual catchment area is actually half as large as estimated, then the discrete recharge for that basin is twice as much. However, the amount per unit area or percent of total recharge for the microbasin is not subject to possible error in estimating the size of the catchment area. How does one know that the estimated catchment area is reasonable? One check is to look at flow to the cave after storm events when the soils are already saturated. With the catchment areas used in this study, the volume of some flows reaching the cave is about 40% of the immediately preceding rainfall.

The one year and 30 month water balance reference period had total rainfall amounts of 30% and 20%, respectively, above average conditions. Flow data from this study indicates that the discrete recharge component would be expected to be higher during periods of higher rainfall when the soils are already saturated. Therefore, it is possible that under average rainfall conditions the percent of discrete recharge may be less. The total recharge occurring in internal drainage microbasins are not expected to vary greatly under average conditions, although longer period of measurement will examine any shifts in recharge patterns due to varying rainfall patterns. It is also important to recognize the pattern of rainfall and recharge in Central Texas is not evenly distributed, and properly functioning upland internal drainage basins play an important role in capturing flows from storms that would otherwise runoff or evaporate, and thereby maximizing recharge to the aquifer.

Known internal drainage basins comprise about 10% of the 98 square km (38 square mile) area within the Manchaca and Sunset Valley subsegments that feed Barton Springs. Assuming these internal drainage basins all recharge 42% of the rainfall as a function of their catchment area, then these basins contributed 400 l/s (14.3 ft3/s) over the test year, which compares to about 5% of the average 2050 l/s (73 cfs) Barton Springs flow reported by the USGS over the 348-day test period.

Refinement of the water balance and hydrologic types will be possible through the continuation of this study with longer period of records and continued site investigations of other microbasins. Other investigations are underway to quantify recharge sources to the Barton Springs segment through geochemical water balances, direct measurement of creek-bottom recharge, ring infiltration of smaller closed depressions, and hydrograph separation.

Conclusions

Large catchment internal drainage microbasins characteristically have concave solution formed bowls with a bowl volume proportional to the size of the catchment area, its recharge significance, and karst maturity. The bowl volume provides quantitative measurement of surface solution processes associated with a karst feature, and therefore is an excellent indicator of its recharge significance. Generally, karst features primarily formed by collapse (generally characterized by convex cross section) without subsequent dissolution as result of random pirating of additional drainage, have relatively small catchment areas and are less significant as natural recharge sources. Nevertheless, collapse sinkholes are equally likely to have strong hydraulic connection with the aquifer. Collapsed karst features may become significant through diversion of surface water into the feature.

Internal drainage microbasins, ponded internal drainage microbasins, and manmade depressions that intercept surface drainages make up at least 10%, 2%, and 1% respectively of the Recharge Zone of the Barton Springs segment. These areas are similar in that they rarely, if ever, contribute to local downstream drainages. The results of at least one year of monitoring two large internal drainage basins indicated that about 58% of the rainfall evaporates, about 8% enters the cave as discrete recharge, and about 34%

diffusely recharges the aquifer through the soil or other lesser recharge features. Since the test sinkhole microbasin recharged an estimated 42% of its rainfall, preliminary results suggest that internal drainage microbasins are relatively efficient recharge areas, significantly more than the 0.09 to 3.63% of rainfall previous anticipated for the intervening areas between the major creeks. It is estimated that mapped internal drainage basins contributed about 5% of Barton Springs flow during a year test period. More critical examination of all recharge sources to Barton Springs, through a variety of methods, are recommended.

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