Karst and Recharge in the Barton Springs Segment of the Edwards Aquifer:

Field Trip to the City of Austin's Water Quality Protection Lands

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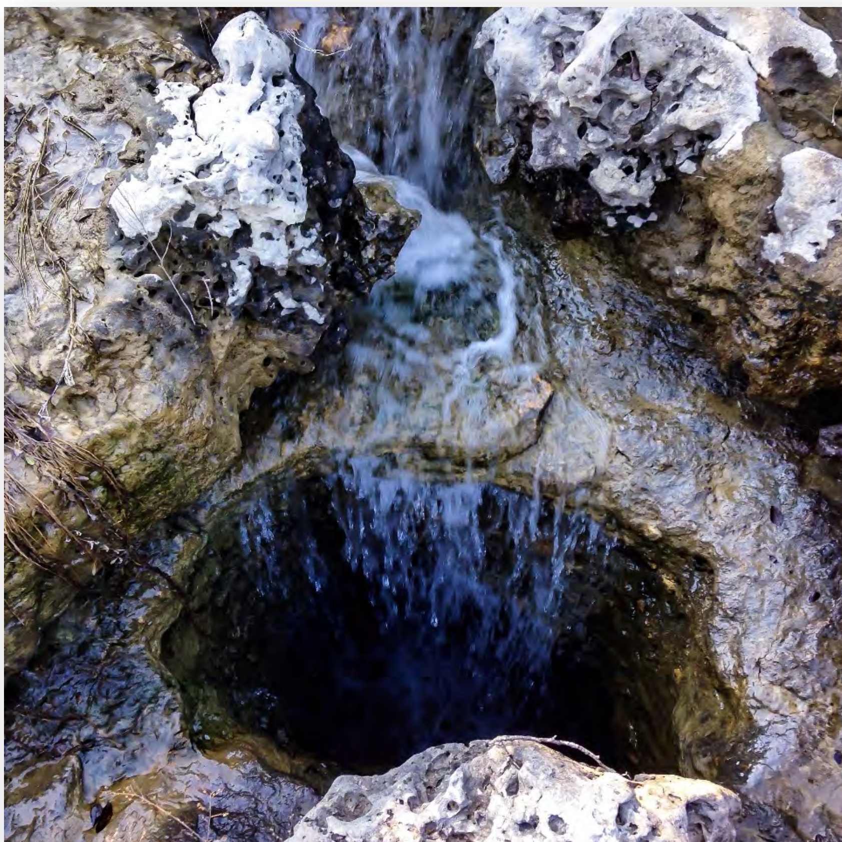

AGS Field Trip Guidebook 35

Austin Geological Society
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Peter Sprouse and Geoff Hoese rappelling and mapping the 130-feet deep Hoskins Hole.

Note that the properties in this guidebook require proper authorization to access. Anyone interested in visiting these sites must contact the City of Austin Wildlands Conservation Division.

Cover: Photograph of a feature within Little Bear Creek. The City has Water Quality Protection Lands (WQPLs) that encompass much of Little Bear Creek.

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Introduction

David Johns and Nico Hauwert

This field trip will address the issues and controversies of upland recharge, geologic assessments, karst feature excavation, wastewater application over the recharge zone, and land acquisition. During this trip we will visit several properties that are part of the Water Quality Protection Lands (WQPL) program of the Austin Water Utility of the City of Austin (COA) (Figures 1 and 2). These properties were purchased specifically for water quality and quantity protection. As of 2015, the City of Austin has acquired about 25% of the Barton Springs Recharge Zone as Water Quality Protection Lands and an additional 6% is protected as Balcones Canyonlands Preserves and Parkland.

In addition, there is a large number of added benefits to WQPLs such as endangered species protection, preservation of wildlife habitat, preservation of scenic vistas, conservation of family ranches (about 17 WQPLs properties are conservation easements), limiting water demand in a water scarce region, preservation of dark skies (anyone remember the stars?), and protection of Native American archeological sites. Specifically in Part I we will visit the Dahlstrom Ranch (a conservation easement), one of the largest intact ranches in the eastern part of the Hill Country, and then in Parts II and III we will visit two properties owned by the COA (Onion Creek and Hudson Ranch).

On this field trip we will have the opportunity to observe outstanding natural karst features, including whirlpool swallets, deep cave shafts, and internal drainage basin sinkholes that are not readily available to visit. We will have the opportunity to observe how ranchers have historically incorporated natural karst features as stock ponds and waste disposal. We also have a unique opportunity to see how various geologists evaluated and interpreted karst features. The trip will examine a wide range of opinions from geologists on the role of upland karst features and how to properly evaluate them for geological assessments. From the example sites visited on this trip, geologists can observe the critical role that excavation plays in the proper evaluation of features in site assessments.

Acknowledgments

The leaders would like to thank the following entities and individuals for supporting and contributing to this guidebook. The City of Austin, Barton Springs/Edwards Aquifer Conservation District, Jack Dahlstrom, Frank Davis and Hanna Morgan of Hill Country Conservancy, Patricia Dickerson (AGS Field Trip Chair), Mustafa Saribudak (AGS Treasurer), Rebecca Smyth (AGS President-Elect and BEG Van driver), Bureau of Economic Geology for use of a van, Rosemary Hatch (COA) for her GIS maps, Alan Cherepon for volunteering to drive a field trip van, Alan Andrews (BSEACD, chase vehicle driver). Brian Hunt (BSEACD) compiled, formatted, and was the primary editor of the guidebook with the field trip leaders. Dana Wilson and Alan Andrews (BSEACD) provided some review and editing. A special thank you to Charlotte Sullivan for her additional editing efforts.

Recharge into Crippled Crawfish Cave before the BMPs were installed. Photo by Brian Hunt.

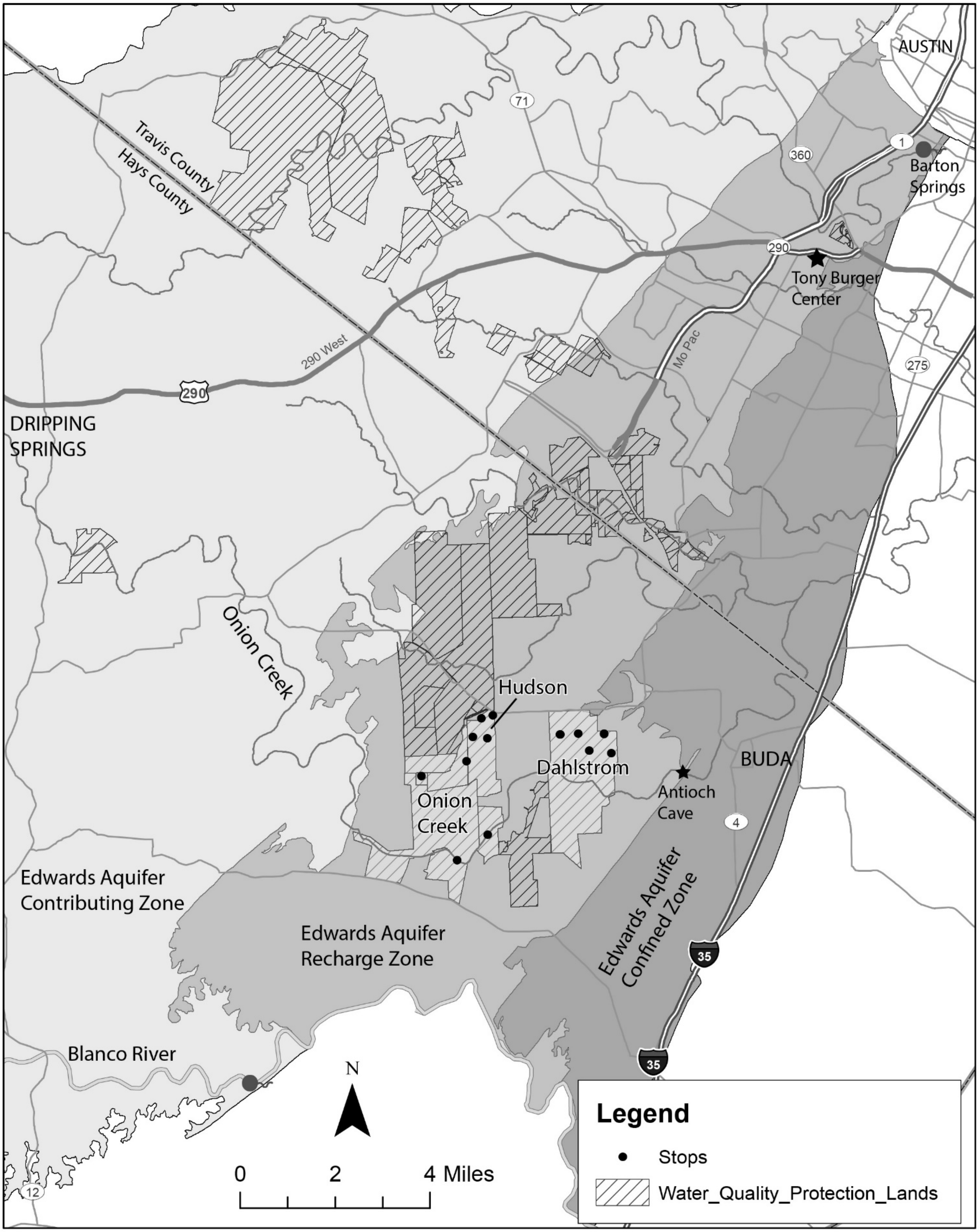


Figure 1. Location map of the region showing the Edwards Aquifer recharge zone, Water Quality Protection Lands and other major landmarks.

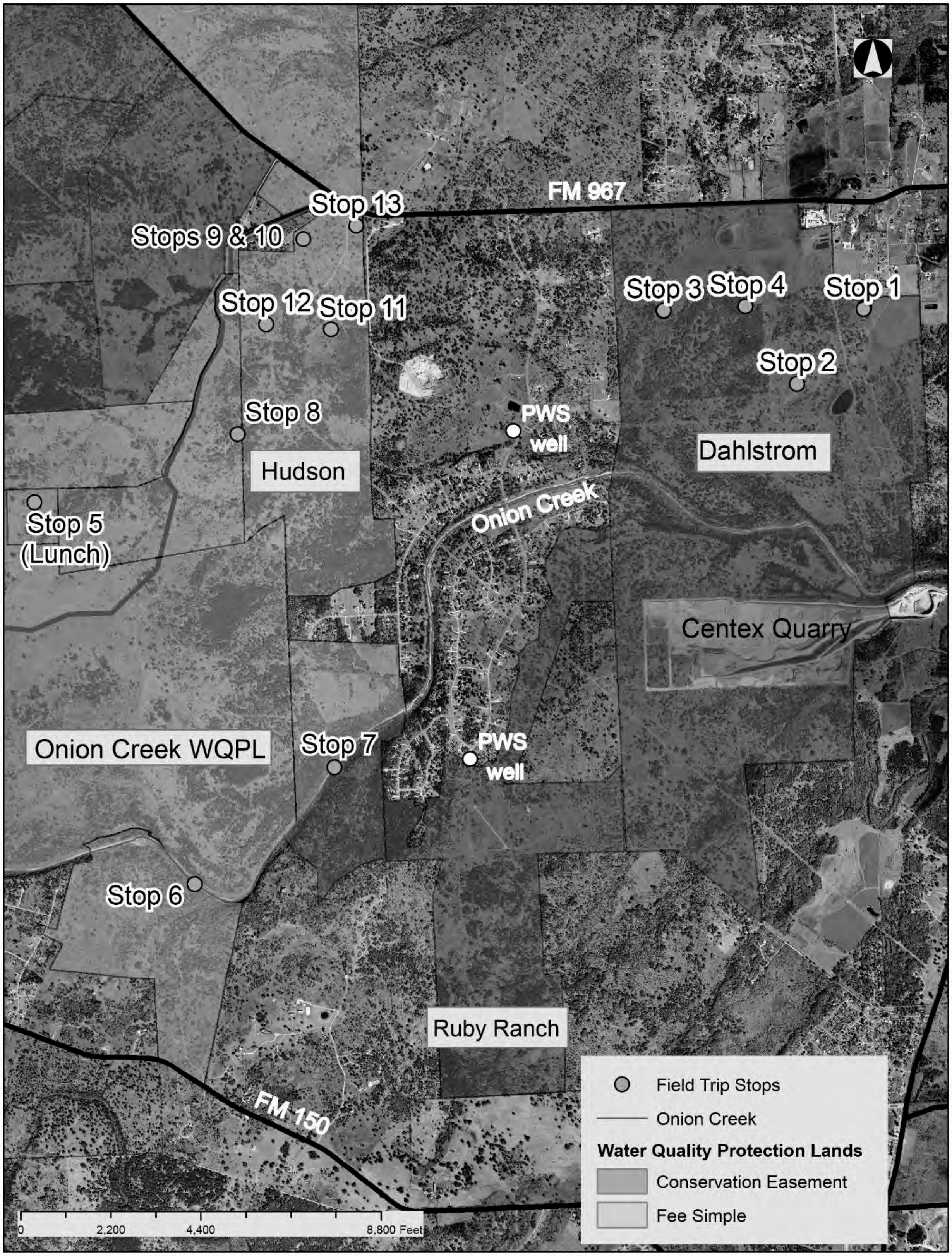
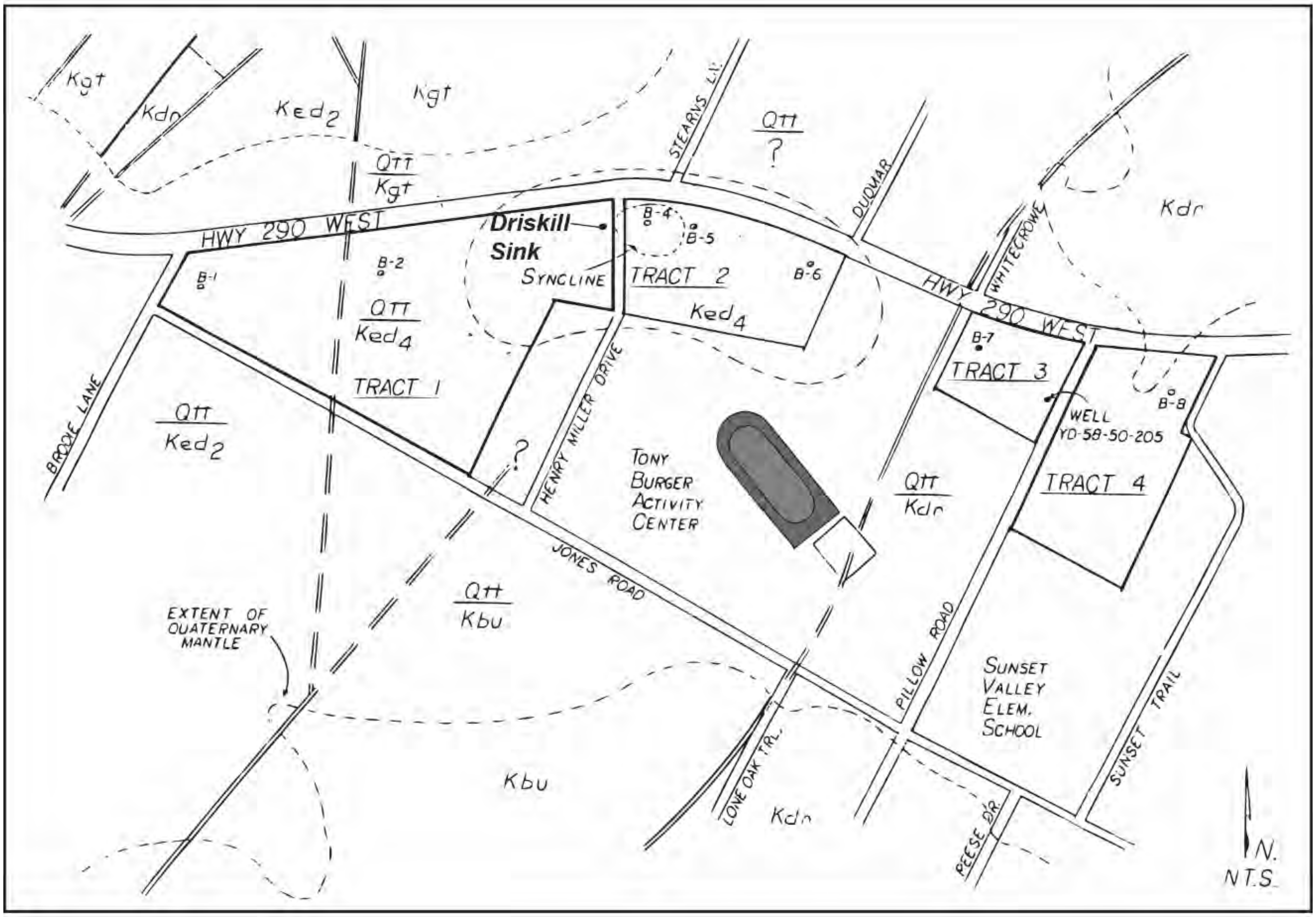


Figure 2. Location map of the three properties and stops in the Field Trip.

Toney Burger Center (Driskill Cave)

The starting site for this field trip has its own geological relevance. Dr. Woodruff (1984) observed the locally derived Saint Elmo Terrace deposits across this area, and hypothesized that the portion of Barton Creek above Mopac Expressway bridge originally was an upper tributary of Williamson Creek. He envisioned piracy of flow in a creek swallet from a paleo channel of Williamson Creek into subsurface cave toward a paleo Barton Springs. The sheer cliffs along downstream portions of Barton Creek represent collapse of overlying rock above the cave, similar to the geomorphology and origin of the steep walled creek downstream of Hamilton Pool in southwest Travis County. Airman's Cave, which has an entrance next to Barton Creek one mile downstream of Loop 360 extends through the subsurface 4,000 feet toward the Toney Burger Center. We think this could be the physical manifestation of the conduit Dr. Woodruff envisioned. In the median of Highway 290 is a small wooded area containing a large bowl sinkhole and 30 foot cave shaft known as Driskill Cave. From the size of its extensive bowl volume Driskill Cave historically contained a large catchment area, and may have been the swallet responsible for pirating flow from Williamson Creek to the paleo Barton Springs.

Nico Hauwert at the entrance to Driscoll Cave, the drain for the Sinkhole where the Toney Burger Center is located. The entrance is now located between the Highway 71 (290 W) and elevated frontage road ramp. Photo taken 1994.



Geologic and karst feature map modified from Snowden, 1988. Note the location of Driskill Sink—the drain of a much larger sinkhole. This map was created before the current highway system.

Note about Surface Geology on the Field Trip

The Dahlstrom, Onion Creek, and Hudson Water Quality Protection Lands contain outcrops of the Cretaceous Edwards and Washita Groups. Table 1 is a chart of the hydrostratigraphic units exposed and their characteristics. The surface geology of the Barton Springs Segment was mapped by John Hansen, Nico Hauwert and verified by Ted Small (Small et al., 1995) as a continuation of US Geological Survey mapping from the San Antonio area using the hydrostratigraphic units proposed by Pete Rose (1972). Site specific access to the Dahlstrom and Hudson tracts from 2007 to 2009 allowed site scaled mapping by Nico Hauwert.

Table 1. From CoA 2009, modified from Hauwert, 2009 and Small et al., 1996.

Hydrogeologic subdivision		Group	Formation	Member	Full Thickness (m)	Lithology	Field Identification	General Hydrogeologic Properties
Quaternary		Alluvium			<10	gravel	loosely or unconsolidated limestone or shale	high permeability
		Colorado River Terrace Deposits			<10	gravel	loosely or poorly consolidated with quartz cobbles	high permeability
Upper Cretaceous	Overlying Confining Units	Taylor	Sprinkle		120	calcareous clay	dark clay	low permeability
		Austin			119	chalk	*Inoceramus subquadratus*, *Inoceramus undulatoplicatus*, *Exogyra ponderosa*, *Phyrygia aucella* and occasional igneous deposits	gen. low permeability, conduits possible where faulted or weathered on surface
		Eagle Ford		South Bosque Shale Bouldin Flags Cloice Shale Pepper Shale	12 - 14	calcareous sandy shale	*Fish fossils,Acanthoceras sp.,Eucalycoceras bentonianum,Neocardioceras,Romaniceras,Coilopoceras,Prionotropia,Alectryonia lugubris*	general low permeability
		Washita	Buda		11 - 18	nodular to massive porcelaneous limestone	Orange pelloids in massive beds, *Budaiceras*, ammonites, *Exogyra clarki*, *Pecten roemeri*, *Codiopsis texana* Whitney, and *Mantelliceras*	commonly feeds shallow wells and small springs
			Del Rio		15 - 18	clay	*Ilymatogyra arietina,* pyrite, gypsum seams	low permeability clay
Lower Cretaceous	Edwards Aquifer		Georgetown		12 - 18	nodular to massive fossiliferous limestone	*Waconella wacoensis*, *Arctostrea carinata*, *Texigryphaea washitaensis*, *Neithea texana*, echinoids, and ammonites.	vertical fissure development
		Edwards	Person	Cyclic and Marine undiv.	0 - 21	massive limestone	chert and caprinids	cavernous
				Leached and Collapsed undivided	21 - < 7	wackestone, mudstone, and grainstone with well-sorted matrix	*Toucasia*, *Chondrodonta*, and sparse miliolid foraminifera	horizontal and vertical extensive cave development
				Regional Dense	4.5 - 10	well-sorted lt tan fissile mudstone	*Pleuromya knowltoni*, rarely *Ceratostreon texanum,* iron-oxide stains	local aquitard frequently breached with vertical fissures
			Kainer	Grainstone	14 - 18	lt gray-white massive grainstone	Miliolid foraminifera, *Chondrodonta*, caprinids, turitella, mudcracks, and bedded chert	Small corkscrew passages and rooms. Serves as competent roof over Kirschberg Mbr
				Kirschberg	12 - 23	crystalline limestone and dolomite pulverulite	Terra rosa. *Cladophyllia, toucasia, caprinid-bearing siliceous remnants*	extensive cave development esp. in pulverulitic beds
				Dolomitic	~ 43	Highly bedded gen. with poorly-sorted matrix	*Toucasia, Caprinid, Dictyoconus walnutensis.* Nodular chert	significant cave development primarily along fissures
				Basal Nodular	16 - 18	fossiliferous, nodular limestone	*Texigryphaea* packestone intermediate miliolid grainstones and burrowed mudstone, echinoids, lower *Ceratostreon Texanum* packstone	Vertical pits and fissures. Produces many minor springs.
	Underlying units	Trinity	Glen Rose		150 - 250	Alternating massive limestone/dolomite and marl layers	dinosaur tracks, plant fossils, celestite nodules, *Trigonia*, *Pecten*, *Alectryonia carinata*, *Orbitolina texana* foraminifera, various echinoids	Little cave development documented here although supports abundant springs/wells.

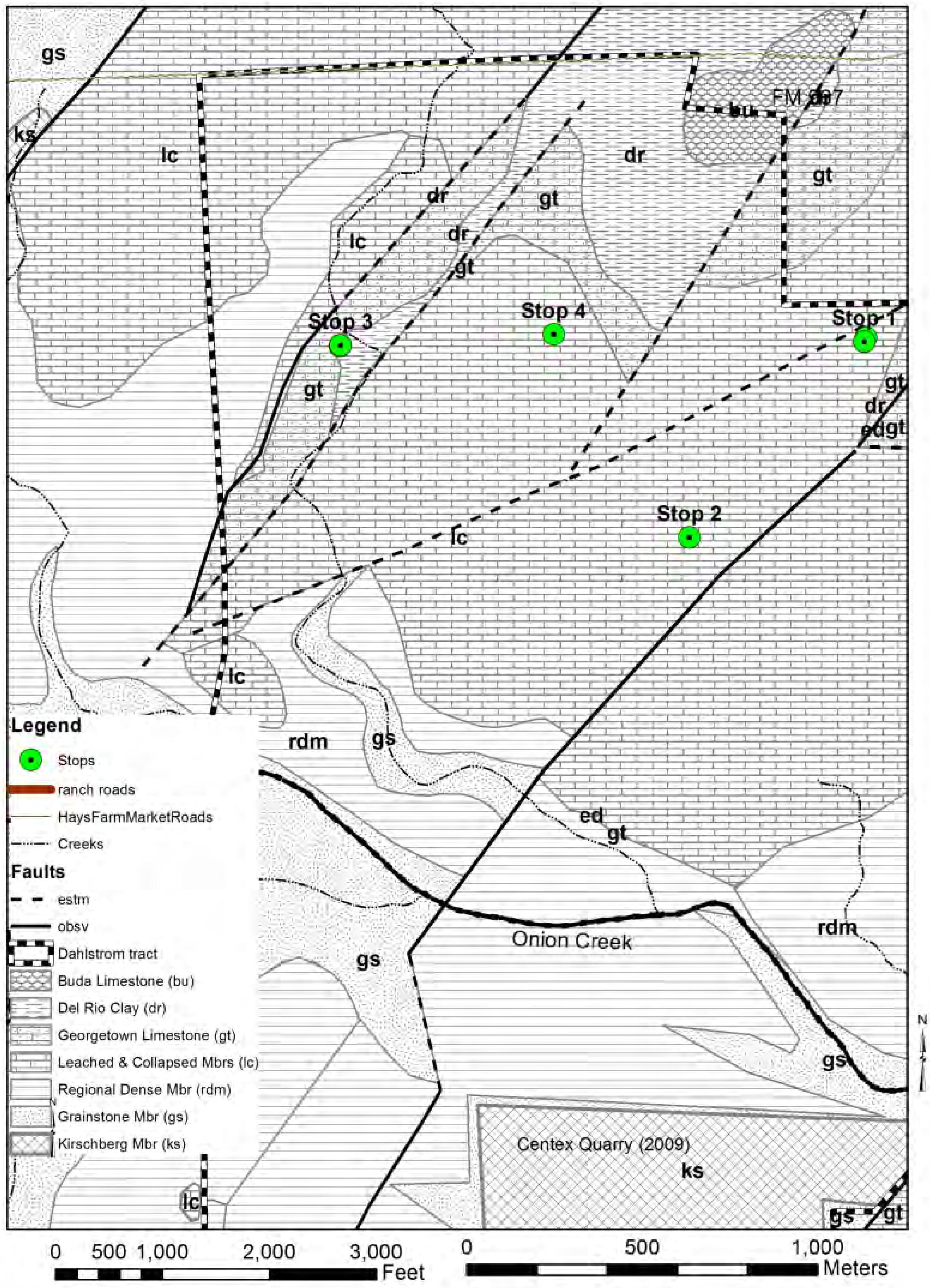
Part I: Dahlstrom Ranch WQPL Easement

Dahlstrom Ranch is one of the largest single land holdings in the Barton Springs Zone. Its 2254 acres includes about one mile of Onion Creek frontage and a large number of upland karst features. The Conservation Easement (CE) was purchased in 2008 as a partnership between Hays County, The Hill Country Conservancy, the USDA National Resources Conservation Service, and the City of Austin. Purchase of the CE allows for public access to a portion of the ranch and protection of several archeological sites as well as continued domestic and exotic wild game hunting on the ranch. A provision of the CE allows for potential use of the quarry to enhance recharge to the aquifer by capturing flood flows from adjacent Onion Creek.

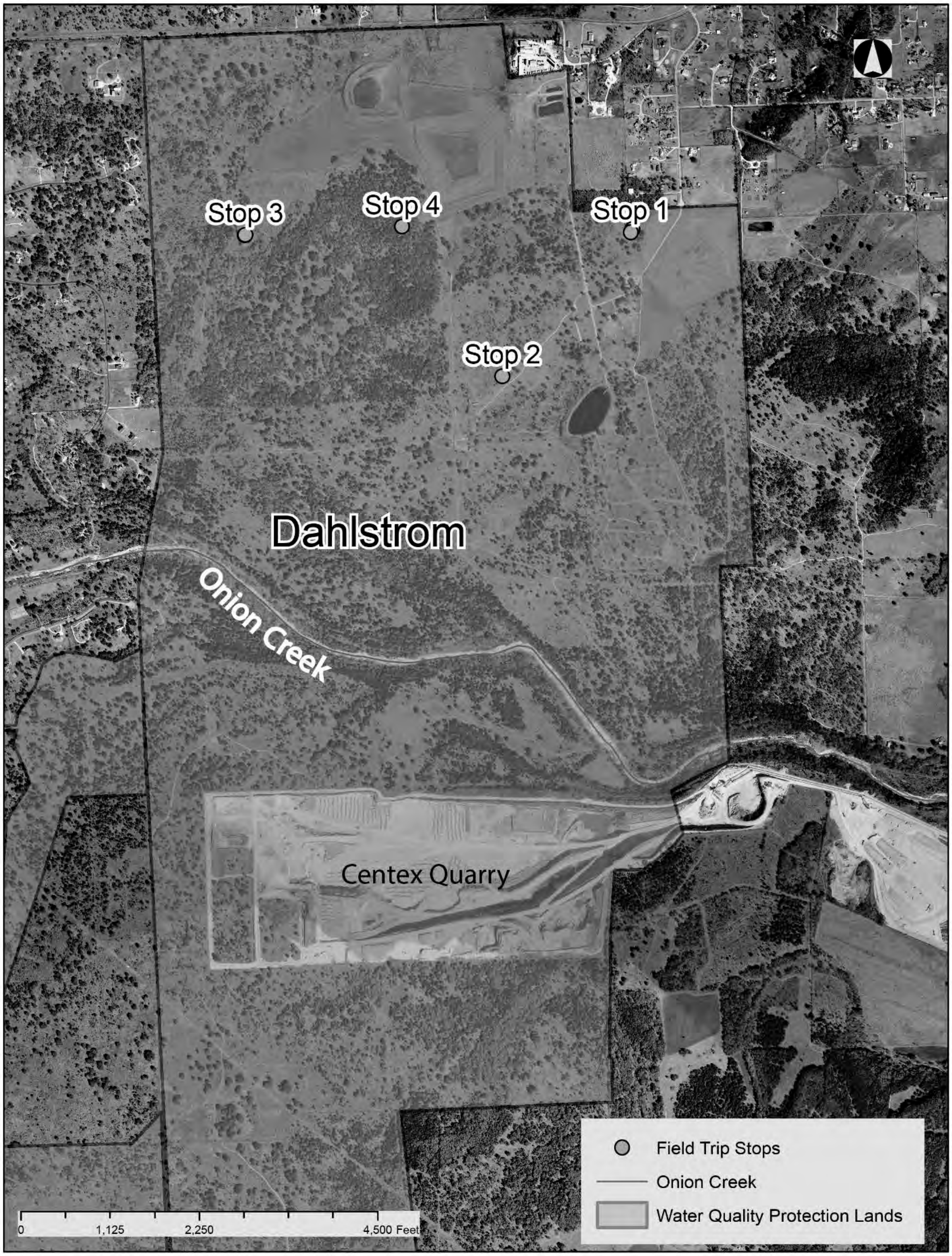
Surface Geology

The Del Rio Clay and Georgetown Limestone of the Washita Group, as well as the Leached and Collapsed and Regional Dense Members of the Person Formation are primarily exposed on the north side of the Dahlstrom WQPL that we will visit. The Marine and Cyclic members of the Edwards Group have not been definitively documented in this area and further north, and are interpreted to be very thin or else eroded below the unconformable contact with the overlying Georgetown Limestone.

Bill Russell examines Prickly Pear Sink on the Dahlstrom Ranch in November 2008.



Geologic map of the Dahlstrom Ranch. Geology from Hauwert modified from Small et al., 1996.



Dahlstrom Ranch location map.

Stop 1: Redberry Sink and Possumhaw Cave. Large internal drainage sinkhole and cave

Redberry Sink displays a well-defined concave rim, characteristic of a solution sinkhole, as well as a convex cross section that characterizes a collapsed sinkhole. Likely, it initiated as a collapse sinkhole through the collapse of a shallow roof, and began capturing increasingly larger surface catchment areas. The cave is developed within the uppermost Leached and Collapsed Members of the Edwards Group near the contact with the overlying Georgetown Formation, which outcrops about 600 feet northwest of the cave entrance. The cave has been mapped to a lateral extent of about 30 feet and depth of about 12 feet by Sprouse (2012, Figures 1-1 and 1-2), though doubtless could be extended with additional fill removal.

Recharge studies utilizing eddy variance evapotranspiration tower and flumes within the Barton Springs Segment suggests that, on average for internal drainage sinkhole basins like this, of the rainfall that falls within its catchment areas 68% evaporates or transpires, 28% recharges through the soils in the catchment area, and about 3% of rainfall flows into the cave entrance (Figure 1-1; see paper in this guidebook). About 90% of all upland intervening autogenic recharge infiltrates through the permeable soils, macropores, and karst features on the slopes. There is no indication from these studies that infiltration on slopes of internal drainage basins differ significantly outside of those basins. In other words, recharge through soils, macropores, and smaller karst features should be consistent across the recharge zone.


Figure 1-1. (Left) Redberry sink before restoration. (Right) Redberry sink or Possumhaw Cave after restoration on January 22, 2015. Photo by Hanna Morgan, Hill Country Conservancy.

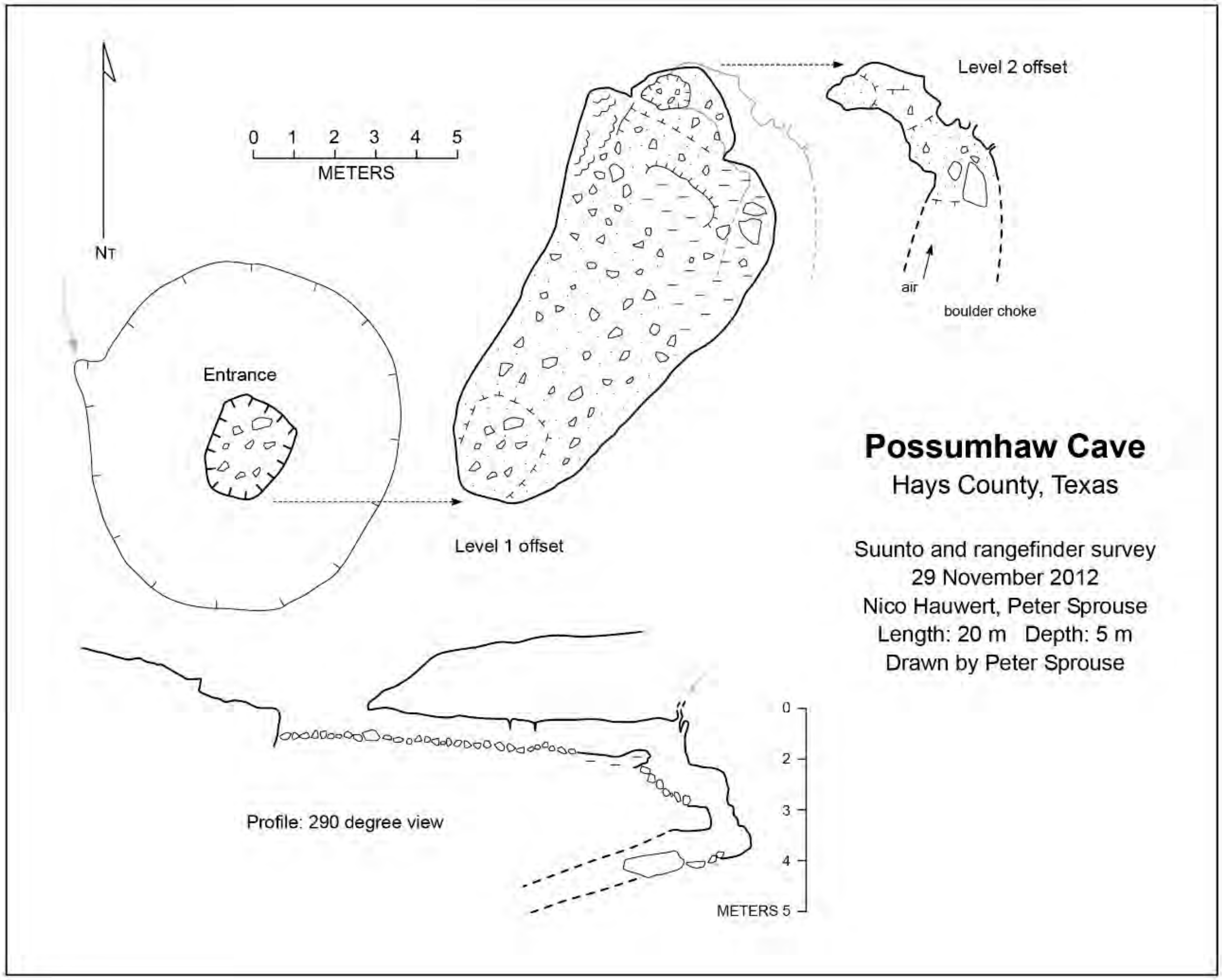


Figure 1-2. Cave map for Redberry Sink and Possumhaw Cave.

Stop 2: Trash Sink/Rim Rock Sink

Trash Sink was used for trash disposal (Figure 2-1) and is classed as an open internal drainage basin. Across the road and north of Trash Sink is Prickly Pear Cave, one of the more extensive caves discovered on the Dahlstrom Tract, descending about 30 feet (Figure 2-2).

Figure 2-1. Photo of Trash Sink

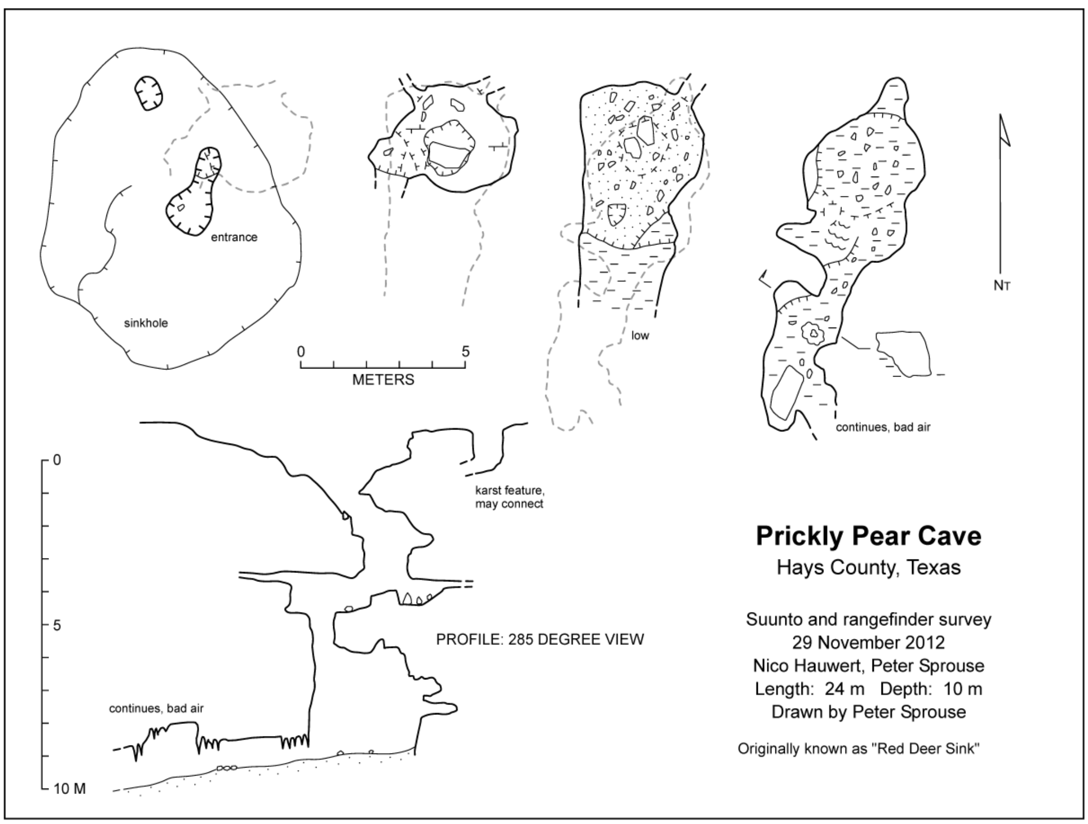


Figure 2-2. Cave map of Prickly Pear Cave.

Nico's Notes: Trash, Caves and Sinkholes: an unfortunate association

Filling caves and sinkholes with trash and fill is an extremely common practice, as each ranch with caves historically had one or more caves designated for trash fill. On historical aerial photographs these can often be recognized as the termination of an internal ranch road. Trash and fill sinkholes can be recognized in the field as locations where trash and rock piles extend into the subsurface grade. If it is a karst area, generally the pertinent question is not if a trash-filled sink or cave is present, but determining where it is. Because filling in caves and sinks was such a widespread practice, concerted long-term effort and funding is necessary to restore caves at a time when they are likely to be overlooked and impacted by development.

Each year the City of Austin and other groups participate in restoring caves filled with trash, although many more filled cave sites still remain. For example, from 1993 to 1999, Mark Sanders of Austin Parks and Recreation led annual cleanups of Midnight Cave that removed 157 cubic yards of trash, including pesticide dip glass bottles, metal cans still containing acetone and other solvents. In 1995 and 1996, about 60 cubic yards were removed from Wildflower Cave. Mark Sanders also led a cleanup of Siebert Cave along Barton Creek Greenbelt, removing roughly 22 cubic yards of trash. From 2012 to present, City of Austin Watershed Protection Dept. initiated cleanup and restoration of filled caves in South Austin including LaCrosse Cave, Wildflower Cave, Bowie High School Cave, and Wade Cave. Together with Zara Environmental, LLC, Water Protection removed fill and restored five caves on the Blowing Sink tract including Brownlee cave, Wyoka Cave, Sinky Dinky, Sink in the Woods, and Winter Woods Cave. These efforts are relatively small steps toward alleviating the effects of a widespread practice leading to the filling of a majority of natural recharge features.

Trash-filled caves or sinks have been present on essentially every historical ranch, and most are still present. Some sinks examined during the field trip had been filled with trash as late as 1995. Excavation of features is a critically underutilized tool for characterizing karst features for geological assessments.

Figure 2-3 Caver Geoff Hoese examines Midnight Cave in 1993 prior to cleanups that continued through 1999. Photograph by Nico Hauwert, standing on a sloping pile of trash across the 50ft long room.

Stop 3: Horseshoe Sink. Large sinkhole modified into stock pond

Horseshoe Sink was named for the horseshoe-shaped bend in the creek tributary. A man-made berm surrounds all but the northwest and west sides of the sink as an apparent attempt to capture water for a stock pond. The berms are apparent on 1958 aerial photos. The pond and sink catchment area is about 420 acres in size and a portion of runoff from this catchment area surpasses the recharge capacity of this sink and flows downstream. Strategies to increase or maintain recharge to Horseshoe Sink include maintaining the open aperture by 1) periodically removing sediment and debris accumulations, 2) maintaining the man-made berm around the feature, 3) berming the bypass channel flowing east, and 4) maintaining high quality creek flow.

Tan Del Rio Clay bearing fossils of *Illymatogyra arientina* appears to be in place at the surface 3 feet overlaying the uppermost Georgetown Formation (Figure 3-1). The rock surfaces dip noticeably to the east within the sink. The fissure likely penetrates through the entire roughly 45-foot- thick Georgetown Formation into the underlying Edwards Group, based on its ability to infiltrate creek flows. A fault with about 30 to 50 feet of displacement is mapped about 100 feet west of Horseshoe Sink. The fault may hydraulically connect large recharge-capacity swallets on Onion Creek with wells further north of FM967.

Figure 3-1. (top) Julie Jenkins stands in Horseshoe Sink. (Bottom) Horseshoe Sink on Dec 13, 2007. A single aperture into the Georgetown Limestone was open at that time. Since 2013, five similar apertures have opened after flood events.

Nico’s Notes: Sinkholes and Stock Ponds

During the drought of the 1950’s there appear to have been widespread efforts to convert sinkholes into water-storage stock ponds. While this practice may have locally made more water available for livestock and fishing ponds, plugging sinkholes on a large scale may have significantly reduced the natural ability of the Edwards Aquifer to efficiently infiltrate rainfall.

Current ranch owner Jack Dahlstrom reported that the large stock pond containing Horseshoe Sink originally held water, but a hunter in a nearby blind heard roaring one day and the stock pond began draining through a vortex. At one point the aperture was covered with concrete to preserve the stock pond function, although the seal failed. He reports that the flow rarely passed further downstream along a bypass channel now that the fissure has opened. On December 13, 2007 an aperture 1-ft wide by 3-feet long and 12-feet deep was measured by Nico Hauwert (Figure 3-1). Since that time numerous apertures have opened in the stock pond, presumably around major floods. While catastrophic collapse of sinkholes is rare in the Edwards, a similar catastrophic collapse can occur when such features are top-loaded with water. For example in January 2012 a catastrophic collapse occurred in a water-quality retention pond in the Shops of Arbor Trails shopping mall at South Mopac and William Cannon Drive. The retention pond sinkhole abruptly opened during a rain where about 10 feet of stormwater filled the pond. The sinkhole collapse completely drained the stormwater pond (Hunt et al., 2013). Because sinkholes were commonly plugged in an attempt to convert them to retain water, stock ponds on the Edwards Aquifer should be carefully examined during the course of geologic assessments to insure they are properly characterized. TCEQ Instructions to Geologists (2004) specifies that simply because a sinkhole is currently ponding does not imply it has low potential for transmission to the subsurface.

In their Instructions to geologists, TCEQ (2004) notes:

> *“Soil filling in a sinkhole, solution cavity, solution-enlarged fracture, or cave does not indicate that rapid infiltration cannot occur at the feature. Long-term maintenance of a cavity or depression is strong evidence that focused flow moves water out the drain in the floor of the depression with sufficient velocity to move soil. The drain may be in the subsurface beneath soil or limestone rubble and connected to the surface via drainage systems in the epikarst, or it may be exposed in the floor of the sinkhole. Soil in the floor of the cavity or sinkhole may be in temporary storage between the time it was moved into the feature and the time it will be moved through the drain. However, existence of a well-formed soil profile or gray or red colors in fine grained fills are evidence that the soil has a long residence time and may be used as evidence that the feature is relict or inactive and has a low infiltration rate.”*

Large internal drainage sinkhole basins constitute about 10% of the recharge zone area and were commonly intentionally plugged to convert them into stock ponds since the 1950s. These sinkholes may periodically reopen, particularly around heavy flood events. Mature large catchment areas solution sinkholes typically have concave, gradually sloping sides and commonly contain siliceous remnants, and are most commonly developed within the Kirschberg, Leached, Collapsed, and Dolomitic members. Collapsed sinkholes that are not significantly reshaped by later dissolution typically have convex or vertical cross sections and are commonly encountered within the Grainstone member. Vertical shafts are commonly developed across the Regional Dense, Dolomitic, and Basal Nodular members.

Stop 4. Hobbit Hole (optional)

Hobbit Hole is the most extensive cave on the Dahlstrom tract explored to date, extending almost 60 feet deep and 110 feet long. The cave is developed within the Leached and Collapsed members of the Edwards Group, and the contact with the overlying Georgetown Limestone is exposed a few feet above and northwest of the entrance.

Figure 4-1. Hobbit Hole. Photo from Bill Russell and Julie Jenkins.

Nico's Notes: Some Distinguishing Characteristics between Sinkholes and Other Features

- Quarries typically have vertical walls and target specific beds, such as the Regional Dense Member, whose nodular clay-rich beds are not prone for sinkhole dissolution (except as vertical shafts) but were quarried for road base.
- Ranchers, particularly in the 1950s, did not mine rock to a gradual slope for the purposes of creating a stock pond, particularly when large internal drainage basin sinkholes are commonly found across the karst terrain. Sinkholes have smooth dissolved walls. Solution sinkholes have bowl cross sections while collapsed sinkholes are vertical or underhanging (convex cross section).
- Non-sinkhole stock ponds are constructed by berming of well-defined drainages.
- Filled sinkholes are typically indicated where soil depths are unusually thick. Soil compositions are typically clay or silt vertisols, possibly mixed with ranch trash. Paleochannels similarly may have relatively deep soils, but typically contain coarser alluvium, such as sand and gravel.
- Sinkholes commonly contain less soluble siliceous remnants as a result of dissolution of overlying rock.
- Sinkhole morphology typically includes an aperture drain.

Part II. Onion Creek WQPL

The 1739 acre Rutherford piece of the Onion Creek WQPL unit was purchased fee-simple in 2000 featuring about 2.5 miles of Onion Creek frontage. A primary attraction for acquisition of this ranch was data from creek flow measurements that indicated a large volume of creek water was lost across the ranch representing a significant portion of recharge for the aquifer. A large number of karst features have since been identified and excavated in the creek channel. This ranch also has magnificent views from the central uplands. The ranch was once slated for development and made it as far as having a Water Pollution Abatement Plan submitted to TCEQ for review and approval.

Stop 5. Onion Creek WQPL Ranch House

Presentations of most papers in this guidebook will be given at the house during lunch.

View looking west across the Onion Creek WQPLs. The Ranch House and lunch stop is barely visible on the right-side horizon of the photograph.

Location map of the Onion Creek Water Quality Protection Lands and stops.

Stop 6. Crooked Oak Cave Swallet

Crooked Oak Cave (Figures 6-1 and 6-2) is located in the channel of Onion Creek on the former Hoskins Ranch. It and other later discovered creek swallets in this stretch of Onion Creek were not identified in an environmental assessment for a Water Pollution Abatement Plan (WPAP) submitted to the Texas Commission on Environmental Quality for the proposed Sky Ranch development. Crooked Oak Cave was discovered by TCEQ geologist Heather Beatty while verifying the submitted assessment. After the City of Austin acquired Onion Creek Water Quality Protection Land in 1999, former historic owner Mr. Hoskins reported that in the past a whirlpool would sometimes form over this cave. On March 18, 2001, Nico Hauwert measured 0.5 ft^3/s of flow entering the submerged entrance. Extensive gravel fill inside the cave appears to restrict its potential recharge capacity, consequently extensive hand excavation and grating of the entrance was undertaken by AWU/Wildlands staff (See Thuesen's paper).

Figure 6-1. On August 12, 2000, under Barton Springs drought discharge of 28 ft^3/s, twenty five pounds of eosine was injected into Crooked Oak Cave. The dye was initially detected 19 miles away at Barton Springs 23 days later. 13% of the dye was recovered from Barton Springs.

Figure 6-2. Brian Cowen (Zara Environmental) discusses Crooked Oak Cave (cave gate shown in foreground) in Onion Creek. Photo by Brian Hunt.

Stop 7. Crippled Crawfish Swallet (optional)

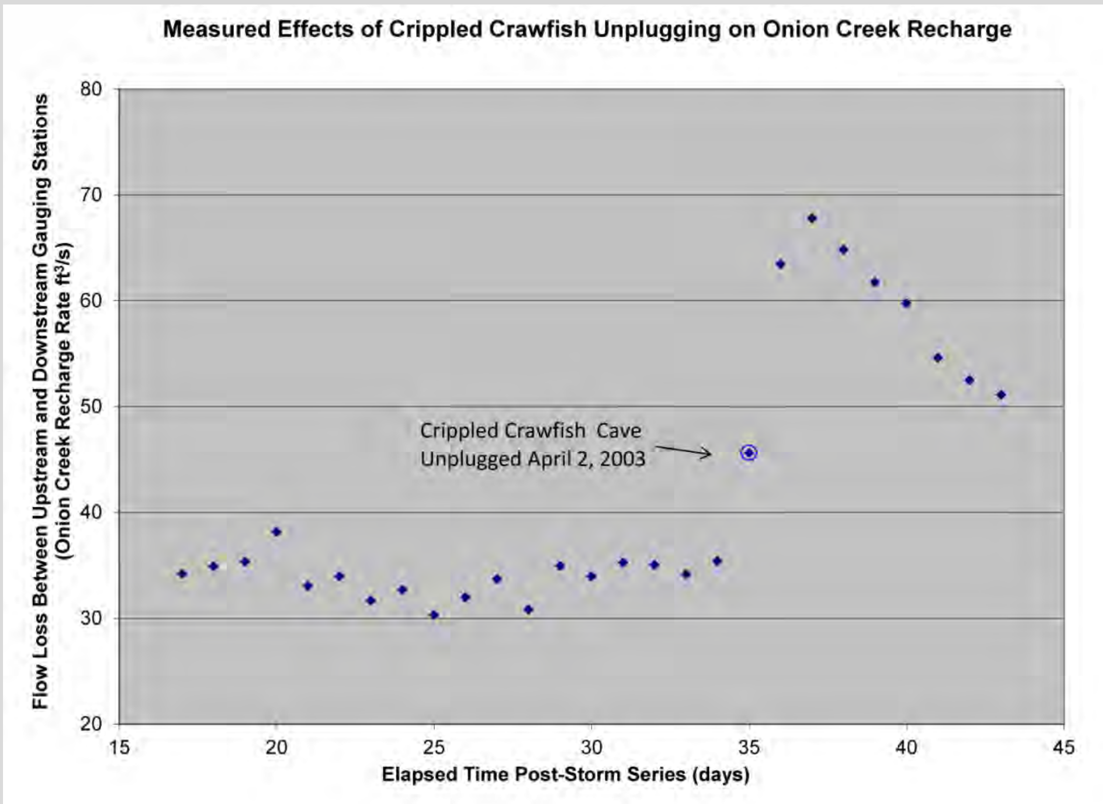
Crippled Crawfish Cave was reported to the Barton Springs/Edwards Aquifer Conservation District staff in the early 1990s by landowner John Orr. It was mapped in 1991 by Doug Allen and Peter Sprouse to extend beneath the opposite creek bank, 200 feet long and 32 feet deep. Since discovery, a whirlpool is frequently associated with the cave when Onion Creek flows over it.

Thirty-five pounds of eosine injected into Crippled Crawfish on May 4, 2005 required 2.4 days to flow 18 miles (29 km) to Barton Springs, under a discharge rate of 103 ft^3/s (high flow conditions). The ratio of advection to dispersion (Peclet number) was calculated to be 21,000 and 7% of the dye was calculated recovered. The Peclet number quantifies the rapid initial arrival at its distant discharge spring; the transport is overwhelmingly through conduits.

Figure 7-1. Cave gate over Crippled Crawfish Swallet. Note whirlpool in lower right of photograph. Photo by BSEACD.

Nico's Note: Swallets and Recharge

Swallets are karst features in the creek channel where flow loss occurs. Flow loss measured across the recharge zone portion of Onion Creek varies from about 20ft^3/s to 100ft^3/s, possibly reaching up to 250 ft^3/s during floods. Flow measurements along the major creeks on the recharge zone indicate that flow loss on each major creek can be attributed to a handful of swallet locations. Each swallet has limited recharge capacity. If the swallet becomes plugged, its recharge capacity is further limited. The chart below illustrates the effects on recharge to the unplugging of a single swallet (Crippled Crawfish). The chart shows that recharge nearly doubled from about 35 cfs to near 70 cfs of recharge. Recharge was calculated as the difference in flow between the upstream FM150 USGS gauging station at Driftwood, and downstream FM967 USGS gauging station at Buda.



Like upland sinkholes, creek swallets tend to plug temporarily with vegetation, gravel and silt under natural conditions. However, their recharge capacity can be enhanced with maintenance and excavation. These plugs appear to be temporary, as swallets in rural creeks are still common and known swallets have not disappeared. Downstream of disturbed and developed areas swallets tend to plug with fine-grained silt and clay that may create longer term, possibly permanent plugs unless excavated. The developer of proposed Sky Ranch asked geologist Nico Hauwert to map the creek swallet locations so they could be plugged because water front was more marketable than dry creeks. While the comment was possibly intended in jest, for a number of reasons people have intentionally and unintentionally plugged creek swallets. Just south of this site on the mouth of Halifax Creek on the Blanco River, a major swallet was reportedly plugged in the 1800s in order to maintain flow to a downstream mill near Kyle. In April 2011 in Austin, an adjacent property owner was discovered attempting to fill a major creek swallet, Dry Fork Sink, on the Kincheon Branch of Williamson Creek. Public ownership or easements of creeks coupled with mapping of swallets and regular maintenance can greatly enhance the recharge to the Edwards Aquifer.

Stop 8. Hoskins Hole (Optional)

Hoskins Hole is a cave shaft 130 feet deep on the Onion Creek Water Quality Protection Land (Figures 8-1 and 8-2). Hoskins Hole was used as the trash dump for the Hoskins Ranch after the first nearby (location unknown) cave was reported filled. Volunteer efforts led by Peter Sprouse, UT grotto, and city staff cleaned Hoskins Hole. Dye injected in Hoskins Hole in 2005 prior to the cleanup efforts was recovered from trash debris and fill (Figure 8-1).

This cave is probably a paleophreatic zone shaft, carrying recharge from a source such as a paleochannel of Onion Creek to an ancient water table, although the current water table is not expected to be too much deeper than the current base of the lower shaft. The Regional Dense Member of the Edwards Group is exposed in the abandoned quarry across the local hill from Hoskins Hole. Vertical shafts are commonly associated with relatively lower permeable beds (White, 1988; Veni, 1992, Hauwert, 2009) as convergent groundwater flows perch above it in the Leached and Collapsed members, and then drop through fissures in the Regional Dense Member, enlarging them into shafts. The momentum of phreatic flows pouring down fissures can potentially result in deeper shafts penetrating deeper rock units. A second possibility is that chemically aggressive hypogene flows from the Trinity Aquifer rose up to a paleo water table, and that the cave developed in the vadose zone (Schindel et al., 2008).

Figures 8-1. (Left) Volunteers pull buckets of trash from the lower second shaft of Hoskins Hole in 2007. Photo by Peter Sprouse. (Right) Austin Water Utility cave biologist Mark Sanders crouches over piles of can trash. Mark led or participated in nearly all of the cave cleanups and cave restorations in the Austin area. Photo by Peter Sprouse.

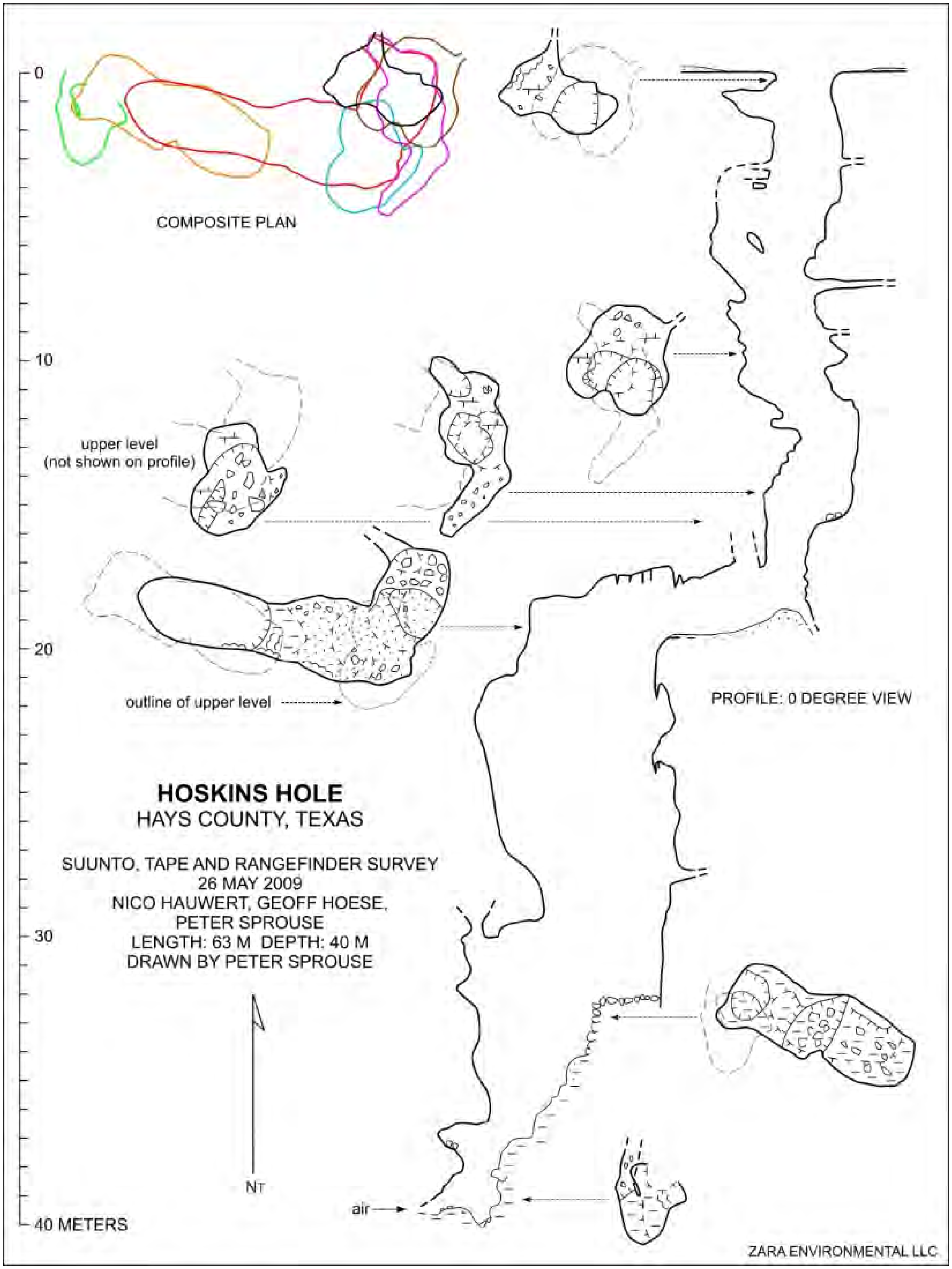


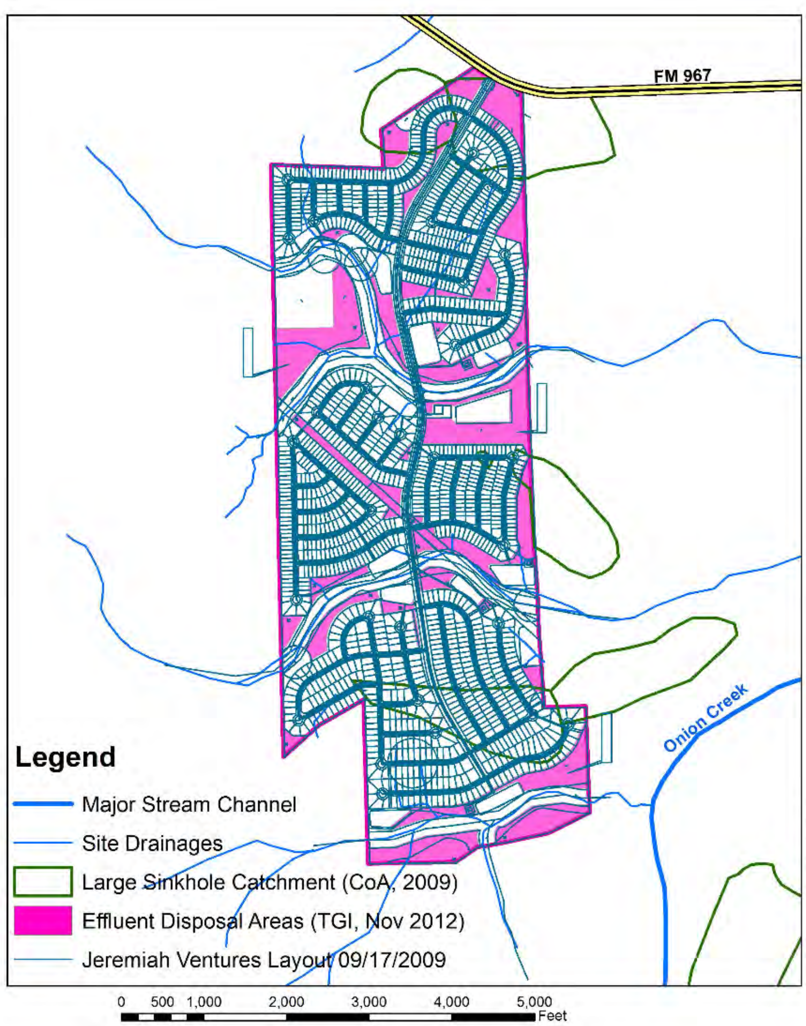
Figure 8-2. Cave map of Hoskins Hole showing natural potential for rapid percolation to the water table.

Part III. Hudson Ranch Water Quality Protection Lands

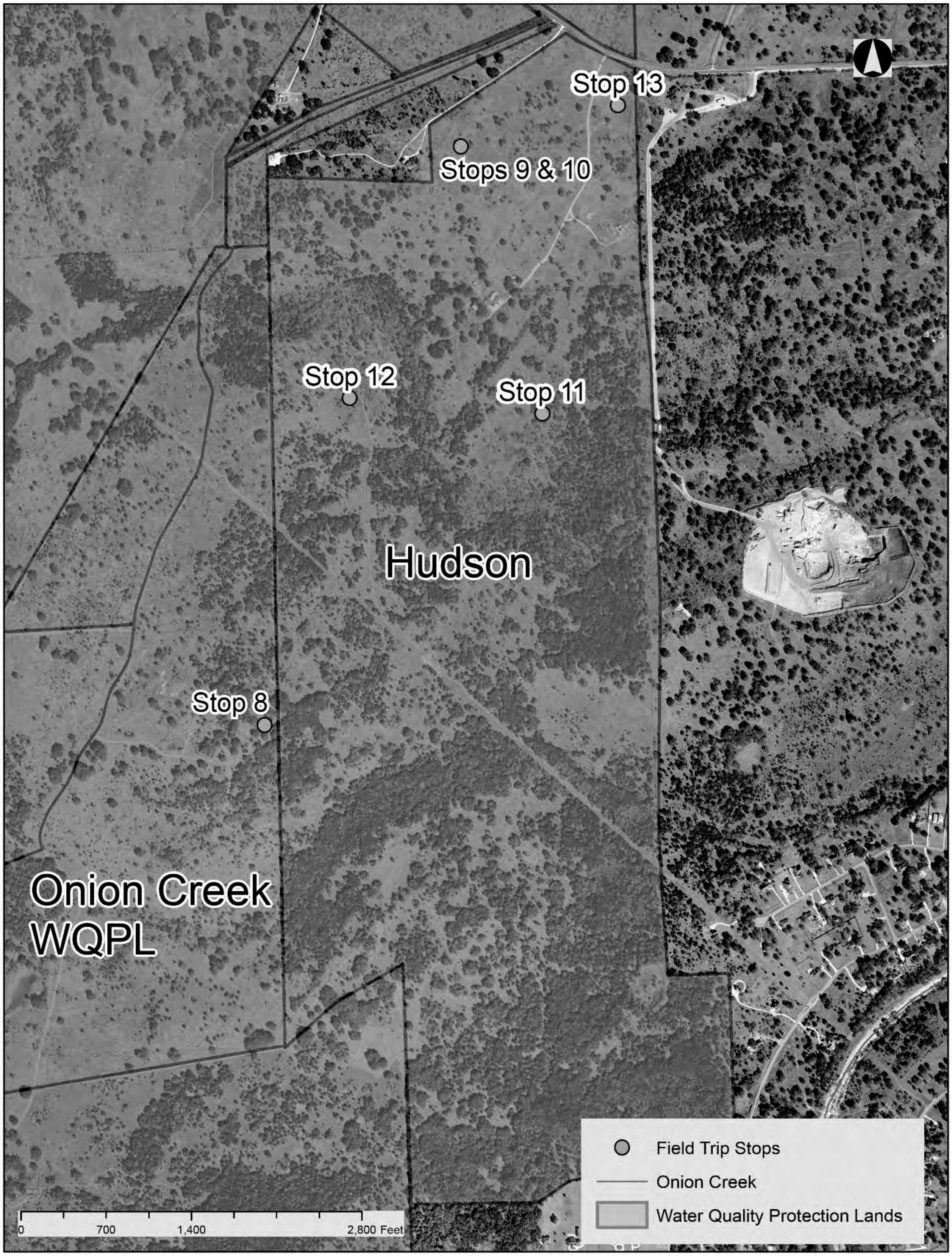
Hudson Ranch is the 608-acre site of a proposed Jeremiah Ventures development that proposed wastewater irrigation systems on the Edwards Aquifer recharge zone. By utilizing the irrigation of treated effluent, more than 1,377 homes could be built on the tract as opposed to a much smaller number utilizing septic tanks, for which Hays County regulations require lower density of residences. As part of a federally designated sole source aquifer, hundreds of domestic water wells are relied upon in local neighborhoods and some larger public water supply wells including Ruby Ranch, Hays Country Oaks, and City of Hays. Geoscientists testified on behalf of the development that because of the soil characteristics, lack of upland recharge sources, and thick vadose zone, that effluent would not likely reach the water table. Ultimately, after conducting two court-ordered assessments of the tract, the City of Austin was sufficiently concerned about the proposed development and its proposed wastewater disposal system that it purchased the property in December 2013 as a Water-Quality Protection Land preserve.

In 2012, staff from City of Austin Watershed Protection manually removed trash from two sinks on the Hudson Tract, as part of an environmental assessment to evaluate a proposed development utilizing wastewater irrigation over the Edwards Aquifer. The City of Austin Water Utility Department which owns and manages Water Quality Protection Lands removed roughly 300 cubic yards of the excavated trash from the two sinks.

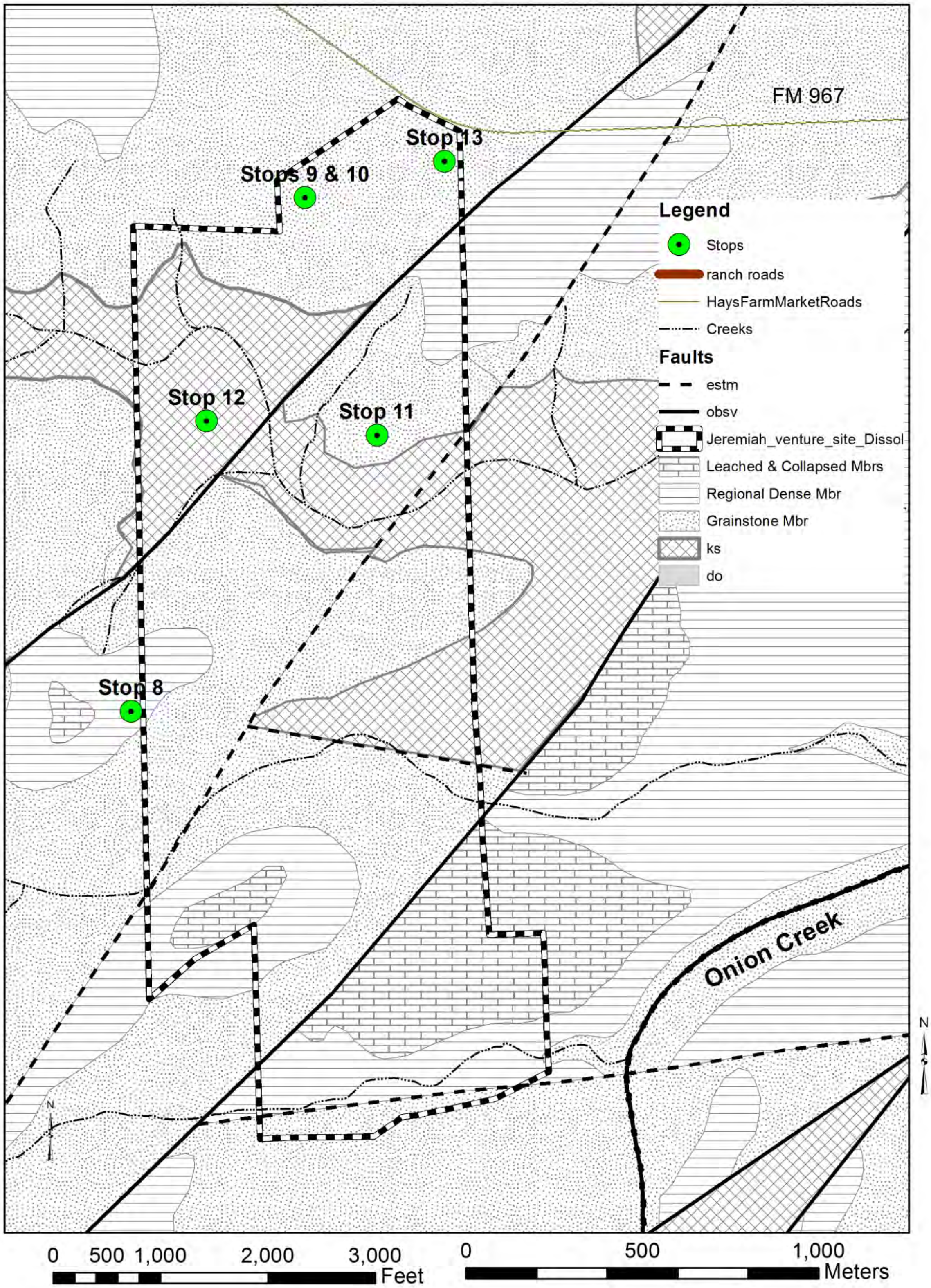
On the Hudson tract we will examine a few of the features that the City of Austin believed were most significant, and explain why; compare how various geologists characterized the features; and the trip participants can then examine the features to make their own conclusions.



Map of the proposed Jeremiah Venture development and effluent disposal areas for the Hudson Ranch.



Location map of the Hudson Ranch Water Quality Protection Lands and stops.



Geologic map of the Hudson Tract. Geology from City of Austin (2009; modified after Small et al., 1996).

A Comparison of Karst Feature Evaluations: The Hudson (aka Jeremiah Venture) Example

The first released environmental assessment of the Hudson Tract by Cuesta (2006) identified 31 features, 2 sinkholes, 3 additional possible sinkholes, and no caves. Because of the outstanding karst on either side of the Hudson tract and based on nearby groundwater tracing results and proposed intensive use of effluent storage and irrigation, the City of Austin requested access to the site for evaluation. A court order allowed access for 8 days in 2009 for a phase I assessment and for seven days in late August 2013 to further evaluate a select number of features for a phase II assessment.

Because of the potential sensitivity of the site and planned revival of large scale effluent land application, a number of geologists examined the features on the site. Dr. Charles Woodruff (2010) and Michael Thornhill (2010/2012) evaluated the features previously identified by Boettner (2006) and City of Austin (2009), but did not conduct separate surveys of the site. The opinions and rating of features by different geologists provides a rare opportunity to evaluate how geologists evaluate features for geologic assessments and the wide range on perspective for their significance.

Note that for the purposes of conducting geologic assessments on the Edwards Aquifer, TCEQ-0585 Instructions to Geologists (2004, p. 3) states:

"if initial assessment leaves significant uncertainty regarding the characteristics of a feature, the geologist is required by the rules to err on the side of being overly protective and rank the feature as sensitive where potential for hydraulic interconnectedness exists and rapid infiltration may occur."

The 2009 phase I assessment (City of Austin, 2009), based on 8 days of court-mandated access and court-specified 100-feet wide transects reported encountering 170 features, 140 of which were rated sensitive on TCEQ rating of greater than 40. The features reported included 7 caves, 3 large internal drainage basin sinkholes, and five features believed to be most likely filled sinkholes or caves. After the fieldwork was completed an additional cave, at least 60 feet long, was reported to by the property owner to geologist Mike Thornhill.

Phase 1. The methodology used by City of Austin and Barton Springs/Edwards Aquifer Conservation District played an important role in discovering and evaluating most features across the entire 608 acres within the 8 days allocated. Three teams were formed with specific functions, utilizing staff from the City of Austin, Barton Springs/Edwards Aquifer Conservation District, and Zara Environmental LLC. The teams together frequently utilized about 15-20 staff and include:

Transect team. Individuals walked the site in 100 ft wide transects, utilizing compasses of global positioning units to follow numbered east to west transect lines. Encountered features were flagged and numbered based on transect number and letter sequence. More features would have likely be encountered with 50-feet wide transects.

Geologist team. Geologists trained in characterizing karst features often walked between the transects, evaluating features as they were encountered by the transection team, locating them with Trimble XRS or XT GPS within 3 feet accuracy. Select members of the geologist team also characterized exposures of hydrostratigraphic units and created GPS control points. Where abrupt changes in hydrostratigraphic units were observed, possible faults were mapped by repeat observations of discontinuities in a linear trend. Features requiring more extensive excavation were deferred to the cave team.

Cave Team. A team of cave specialists evaluated likely caves and sinkholes by hand excavation. For large filled sinkholes, a backhoe is generally preferred if prior authorization from TCEQ is obtained, but in this case was forbidden by the property owner.

Technology. The City of Austin and Barton Springs/Edwards aquifer Conservation District utilized Trimble XT or XRS global positioning units to locate features an transect lines with 3 feet accuracy. ESRI ARCGIS software was used to map the features and overlay coverages. Aerial photographs of the site were examined including

1958 and 1984 coverages that were georeferenced. Topographic maps including Mountain City 1968 USGS quadrangle map. LIDAR coverages used in the assessment are described in a separate article by David Johns in this guidebook.

By 2010, Woodruff, Thornhill, and Hauwert concurred that at least 9 caves were present on the site. There remained considerable disagreement however regarding the 3 large internal drainage sinkhole basins, at least 5 filled sinkholes, and many other features mapped by CoA (2009).

A Phase 2 assessment was authorized by the administrative court for 7 days in August 2013 and involved hand excavation of three features that were verified to be 2 large trash-filled sinkholes and 1 additional cave. The City of Austin's staff believed that the proposed effluent holding pond and irrigation areas were underlain by caves and sinkholes that were not recognized in the land application disposal planning process. In addition to preservation of water quality, the tract allows opportunity for public education and opportunity for geologists to examine the site assessment methodology.

For further examination, the geological assessments for the Hudson tract can be downloaded from: ftp://ftp.ci.austin.tx.us/wre/AGS/.

Stop 9. Tire Sink. Excavated Trash-filled Sinkhole

This area was proposed for wastewater irrigation. Prior to excavation in 2013, the first three geologists concluded this feature was a trash-filled sinkhole. Two other geologists believed it was a man-made feature. All five geologists saw a surface catchment area of less than 1.6 acres, one finding a catchment area as low as 0.09 acres (62 feet square). To further investigate this feature, the City of Austin requested court-ordered access for Phase II examination of this feature.

Tire Sink has not yet been entirely excavated and no additional excavation has been conducted since the City of Austin acquired the Hudson tract as water quality protection land in December 2013.

Considering that the projects proposed effluent fields were shifted on the site based on the geologic assessments, how significant is the limited catchment in evaluating the sensitivity of the sinkhole in a case where effluent irrigation was proposed in the catchment area?

Figure 9-1 Tire Sink as encountered in 2013 prior to excavation. Note partially buried PVC pipe and top of upright tire exposed (far right edge near bottom). Photo by Scott Hiers, City of Austin.

Table 9-1 Feature Classification Comparison

Feature #	Geologist	Year	Type	Diameter (fee)	Catchment (acres)	Sensitivity TCEQ rating
F2	A	2005	Man-made depression possible sinkhole	35x15	<1	25
F4	B	2006	sinkhole	10 x 40	<1.6	35
7A	C	2009	sinkhole	70x80 (30x30)	<1.6	54
19	D	2010	no sinkhole/sinkhole, altered (cut and fill)		0.09	<40*
19	E	2012	man-made depression		0.09	15

*standard TCEQ rating not used but assume "NS" implies less that TCEQ minimum sensitivity score

Figure 9-2 Trash is encountered as feature is manually excavated by City of Austin in 2013. The excavated trash was typical of ranch disposal sites, including pesticides, solvents, batteries and other toxic waste. Dates from the trash ranged from 1993 to 1995 and included pesticide sprayers and bottles, including Green Light brand 50% malathion, Hotshot flying insect killer, and Pennzoil oil bottles. Roughly 70 cubic yards of trash, soil, and rock was excavated from Tire Sink by hand over four days in late August 2013.

Figure 9-3. The smooth walls of the sinkhole were exposed, demonstrating the feature was actually a trash filled sinkhole. In this case, excavation allows a more definitive evaluation of the sinkhole in addition to removing potentially toxic waste materials.

Stop 10. Cell Tower Depression

This feature is located just north of Tire Sink. There was considerable disagreement among geologists assessing this feature whether it was a sinkhole or a man-made excavation. There was also considerable range in the catchment area delineation between 0.93 (200 feet squared) acres to 27 acres, although some geologists limited their evaluation to only the Hudson portion of the catchment areas. Three out of 5 geologists rated it as sensitive, with scores from 40 to 55.

Table 10-1 Feature Classification Comparison

Feature #	Geologist	Year	Type	Diameter (feet)	Catchment (acres)	Sensitivity TCEQ rating
F1	A	2005	sinkhole	260+x120+	2-3	50
F3	B	2006	sinkhole	100x150	<1.6	40
4A	C	2009	sinkhole	340x500	27	55
6	D	2010	non karst closed depression		0.93	<40*
6	E	2012	non karst closed depression		0.93	25

*standard TCEQ rating not used but assume "NS" implies less that TCEQ minimum sensitivity score

Stop 11. Ants in the Pants Cave, 28C (Optional)

A small sinkhole/karst depression not observed in prior assessments turned out to be a cave after excavation. It demonstrates how minor soil-filled depressions can indicate winnowing of fine-grained material into an underlying cave. The cave is 25 feet deep and 59 feet long, but has not been seriously explored. The lack of solution bowl and underhanging cross section indicate the cave is primarily a collapsed sinkhole with minor sheet flow surface recharge. Similar collapsed caves are extremely common where the Grainstone Member serves as a competent roof over the underlying Kirschberg Member. Subsurface voids are common types of macropores over the Edwards Aquifer.

This feature was identified in 2009, during the assessment described above in detail. BSEACD staff noticed a minor soil-filled depression with a small open aperture blowing air. Zara staff excavated the feature.

Figure 11-1. Small depression (flagged) was noted to blow air and was excavated. Photo by Brian Hunt (BSEACD).

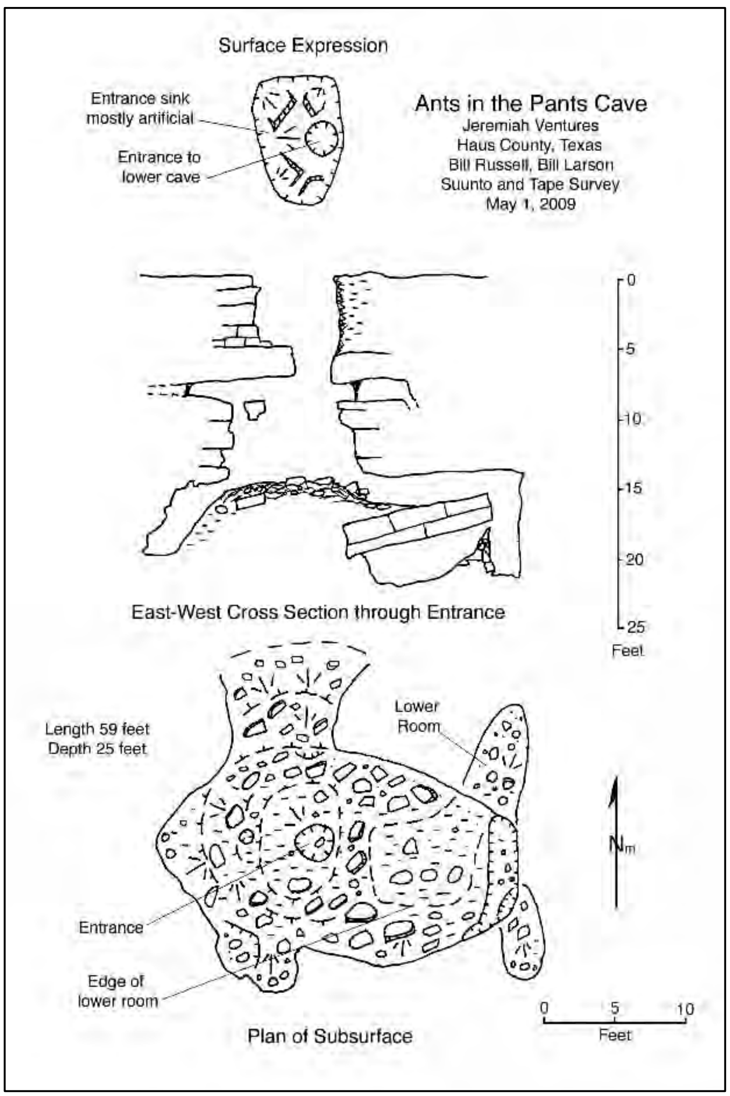


Figure 11-2. Ants in the Pants Cave Map. There is likely extension of the cave that hasn't been mapped. Cave drips can provide valuable sites for monitoring the attenuation of infiltrated runoff or effluent irrigation.

Table 11-1 Feature Classification Comparison

Feature #	Geologist	Year	Type	Diameter (feet)	Catchment (acres)	Sensitivity TCEQ rating
---	A	2005	not discovered			
---	B	2006	not discovered			
28C	C	2009	Cave	25x15	1.4	65
81	D	2010	Cave			<40*
81	E	2012	Cave	31	0.17	55

*standard TCEQ rating not used but assume "NS" implies less that TCEQ minimum sensitivity score

Nico's Notes on features like Ants in Your Pants

- Collapsed sinkholes are extremely common where the lower Grainstone Member is exposed on the surface. This is because the Grainstone Member serves as a very competent roof over the highly soluable Kirschberg Member, where most of the horizontal cave extent develops.
- This feature demonstrates that voids common throughout the Edwards Aquifer can serve as macropores through the soil, yet are often not obvious from the surface without closer examination and, most importantly, excavation.
- This feature would be best initially described as a "small sinkhole" according to TCEQ or "karst depression" by City of Austin, although only thorough excavation is its actual nature revealed as a cave. While most karst depressions are likely immature solution sinkholes, some may pipe soil into underlying voids, as in this case.
- Lindley (2005) measured/studied the infiltration in small sinkholes similar to the initial appearance of Ants in the Pants Cave, using a large diameter ring infiltrometer and found a wide range of values, however, there were no significant differences with background soil test areas.
- Although recharge through soil covered areas are generally characterized as diffuse (Hauwert and Sharp 2014), runoff does not evenly infiltrate the soil as a front. During rain events it can be observed that excess runoff focuses in minor drainages on upland recharge areas that may focus infiltration in specific locations.

Stop 12. Proposed Effluent Pond sink 26C (Optional)

For a single day on August 29, 2013, CoA staff partially excavated feature 73/26C, but were not allowed back on the property the next day. Shallow excavation showed red sediment resembling terra rossa soils that gave an impression that the soil was an ancient soil that had been in place for a long time. However, beneath the red sediment trash was encountered.

This site was proposed for the effluent holding pond for the proposed Jeremiah Ventures development. Feature 26C was first identified as a likely filled sinkhole solely based on partially buried relocated boulders in a circular pattern and lack of bedrock exposure by the City of Austin (2009) as shown in the photo below. Further investigation was conducted using historical aerial photographs. A 1958 aerial showed a 110 feet long dark oval circle that could be a sinkhole. A 1984 aerial showed a road terminating at the feature (Figure 12-2).

Figure 12-1. Feature 26C as it appeared in 2009. Note large exotic boulders extending deep into the subsurface, indicating a filled depression.

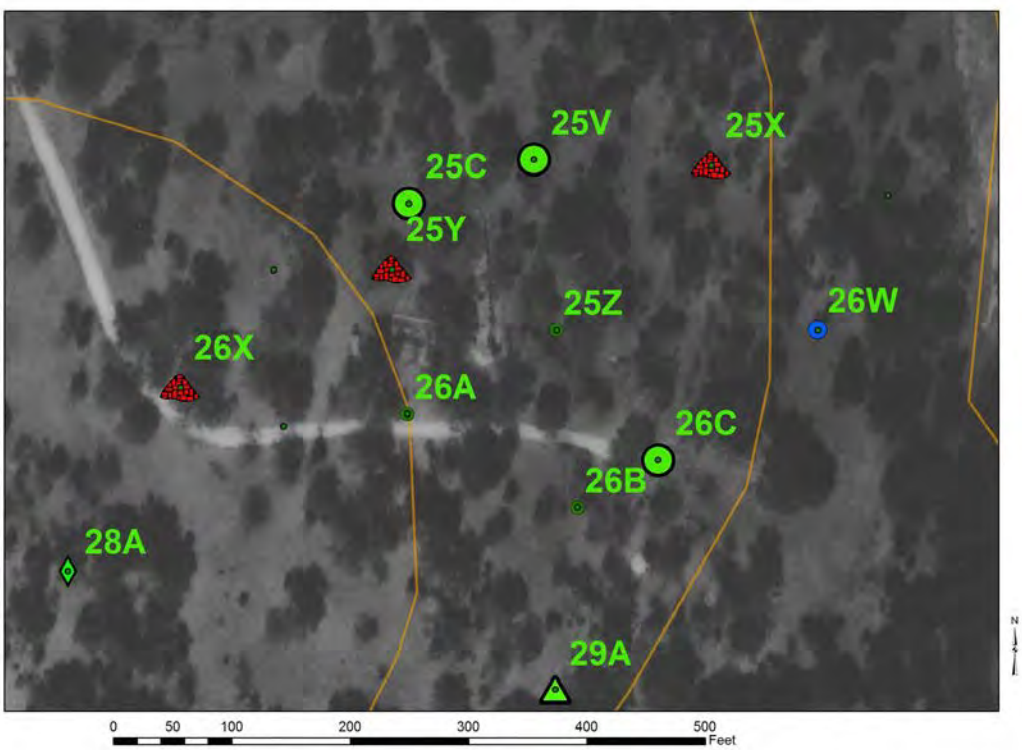


Figure12-2. 1984 aerial photograph of the area around Effluent Pond Sink showing other features and the topographic contour lines. The photograph shows a well-defined road terminating at the site of 26C. The yellow lines are topographic contour lines showing slope to the west.

Figure 12-3. Trash was encountered below red soil. The trash consisted of fuel cans, wrappers for paper plates and Sparkle ice, one of which was dated 1988

Nico's Notes: What to make of Effluent Pond Sink (feature 26C)

- As with 7A Tire Sink, the presence of large partly covered boulders, trash, and rock piles that have subsurface extent, are common in filled sinkholes.
- Historical aerial photos show a road terminating at 26C, consistent with regular use of a sinkhole depression for dumping trash on ranchlands.
- In this case the presence of red soil or clay, resembling ancient terra rossa soils was not a good indicator of ancient residual soils that have been in place for thousands of years. Trash less than 26 years old was found below the red sediment. Likely these soils are common on the nearby surface and washed in or were used to fill in a hydraulically active sinkhole or cave.
- The partially excavated rim was about 30 feet in diameter. Only through excavation can the nature of filled- in features be determined.
- If sufficient excavation is not incorporated into the evaluation, filled features should be assumed to be sinkholes assumed to be sensitive, which are extremely common across the Edwards Aquifer.
- Nearly all of the geologists who conducted karst assessments of this site did not recognize the unexcavated feature as a sinkhole.
- The proposed placement of an effluent holding pond over this and likely other nearby filled sinkholes would be an extremely poor choice considering history of other similar sinkhole collapses in ponds, the abundance of nearby water wells, the history of pathogenic outbreaks in Central Texas when these types of practices were common, and close hydraulic connection with Barton Springs as indicated by nearby tracer tests.

Stop 13. Entrance Sink (Optional)

The feature was initially assessed as a man-made closed depression. Note while some sediment excavation is evident from the pile south of the feature, some berming was also done. Aerial photos from 1958 show this feature. The bedrock surface slopes down to the feature in some areas. The feature has abundant siliceous remnants. The effort required to mine the bedrock surface to a gentle slope over a quarter mile in the 1950s would be considerable, considering the abundance of natural sinkholes across the landscape. Consequently it seems unlikely that this feature is a man-made closed depression. Note the range in estimated catchment areas, from 1-2 acres up to 38 acres. Note that the feature size (sinkhole rim) alone is estimated to be between 1.8 to 4.1 acres in size by the geologists, so a catchment area smaller than the rim is not possible. The surface topography for this site is shown on a paper by David Johns in this guidebook.

Figure 13-1 Large stock pond near the entrance to Hudson WQPL. It is present in 1957 aerial photographs.

Table 13-1 Feature Classification Comparison

Feature #	Geologist	Year	Type	Diameter (feet)	Catchment (acres)
F-5	A	2005	Man-made depression	350x220	>1.6
F2	B	2006	Man-made depression	300x400	1-2
4M	C	2009	sinkhole	480x370	38*
10	D	2010	sinkhole		9.98
10	E	2012	sinkhole		9.98

*historically was larger but catchment area dissected by FM 967

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Restoring Land and Managing Karst to Protect Water Quality and Quantity at Barton Springs, Austin, Texas

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Wildlands Conservation Division / Water Quality Protection Lands Program

Abstract

The Water Quality Protection Lands program was established in 1998 based on a bond proposal passed to protect Barton Springs in the heart of Austin, Texas. Barton Springs is a popular swimming area for citizens and is also home to at least one federally endangered species of salamander. The initial bond called for 15,000 acres of land to be protected. Land acquisition has benefitted from additional bonds since then as well the use of grants to raise the total acreage to over 26,500 acres at present. Additional cost saving measures such as the use of conservation easements have allowed these dollars to be stretched further. Science has helped guide the acquisition of land into more productive geographic areas (based on recharge) and helped direct the management of these lands to further benefit water quality and quantity. Land management focuses on ecological restoration of vegetation back to native prairie and savanna ecosystems which provide optimal water yield from the land based upon the inverse relationship between woody cover and water yield. These restoration actions combined with proper karst management protects both water quality and water quantity recharging through these lands.

Introduction

The Barton Springs segment of the Edwards Aquifer is a segment of the much larger Edwards Aquifer approximately 155 miles in areal extent (Hunt et al 2005) and is located in Travis and Hays Counties, Texas. The aquifer primarily discharges at Barton Springs, which is a collection of four main springs located near downtown Austin, Texas (BSEACD 2003). The springs are home to the federally endangered Barton Springs salamander (*Eurycea sosorum*) and the rare Austin blind salamander (*Eurycea waterlooensis*), which is a candidate for Federal listing as endangered (BSEACD 2003). At the same time, Barton Springs provides base flow for the Colorado River and is a popular swimming destination for citizens as well as a rallying point for many environmental issues in Austin. During the early 1990s, at the crescendo of issues surrounding development and the protection of Barton Springs a call came to protect Barton Springs by additional regulations, including the Save Our Springs (SOS) Ordinance (Dunn 2007, Smith 2012,). Several years after the SOS ordinance was passed, bonds were proposed to further protect Barton Springs as part of the City of Austin's water supply by purchasing sensitive land over the recharge and contributing zones in fee title or conservation easement.

Protecting the Land

In May of 1998 the citizens of Austin voted to support $65 million in bonds that would acquire land "including fee title and easements in the Barton Springs contributing and recharge zones to provide for the conservation and to maintain the safety and quality of a part of the City's water supply" (City of Austin 1998). Additional bonds, grants and other funds since then have raised the entire contribution toward this goal of land acquisition to approximately $145,000,000. The Water Quality Protection Lands program was created to manage these lands and currently protects over 26,500 acres.

Fee Simple versus Conservation Easement

The Water Quality Protection Lands (WQPL) Program owns land in two different ways. The first is through any land owned by a private individual, also referred to as fee simple land ownership. In this case the land is owned outright with all rights and obligations intact. On such fee simple lands the City can conduct land management and outreach, provide public access, and perform other activities as needed. Such land also requires the use of City funds to conduct operations and maintenance related to managing and protecting the land, including installing and maintaining fences, vehicle trails, gates and other sundry activities. This land can still be condemned by higher levels of government (county, state, or federal government).

The other mechanism for land ownership is the conservation easement agreement. Under this scenario the City purchases the development rights and other rights that govern the allowed activities on the land in perpetuity. These are always made with willing buyers as are all real estate transactions related to the WQPL Program. One of the major limiting factors on private property rights required by these conservation easements is the amount of impervious cover allowed on the land (usually between 1 to 2 percent of the net site area). In addition, such easements also have provisions restricting the use of certain pesticides; limits on stocking rates of livestock; a requirement to manage brush on the property; and other restrictions.

Such conservation easements cost the City about 50 percent of the real value of the land. Further, such lands require no outlay of City funds for operations and maintenance of the land, as these are borne by the private landowner. However, each easement is visited annually by WQPL staff to confirm compliance with the easement and provide technical assistance as requested. Occasional legal assistance is also needed to administer this work.

Currently, the WQPL protects 10,731 hectares with 3,941 hectares held in fee simple and 6,790 hectares protected by conservation easements. These purchases have resulted in protecting over 22 percent of the Barton Springs recharge zone and seven percent of the Barton Springs contributing zone. Figure 1 shows the location and type of land holdings and their locations relative to the contributing or recharge zones.

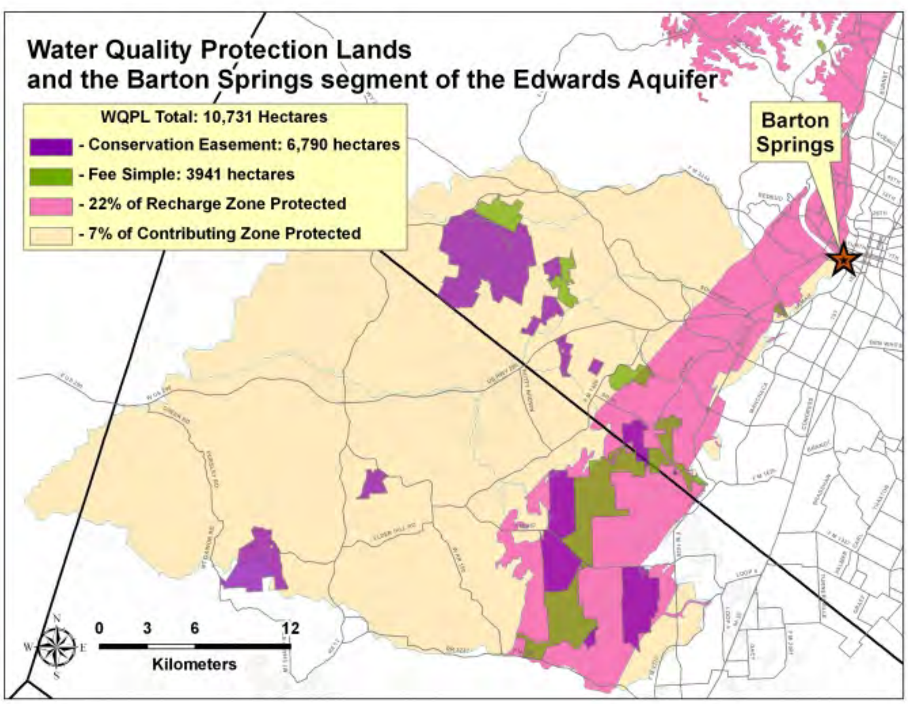

Figure 1. Map of land protected by the Water Quality Protection Lands program as of October 2012

Karst Science Enabling Counterintuitive Purchases

The purchase of these lands includes a variety of factors that determine the acquisition priority of each potential property. Most relevant of these for this paper, but by no means the only priority, is the karst science that has led to relatively counterintuitive acquisitions of property far from Barton Springs.

As shown in Figure 2, the Onion Creek watershed has five different watersheds separating it where Barton Springs discharges prior to reaching the Colorado River. The WQPL Program has made significant purchases in this watershed.

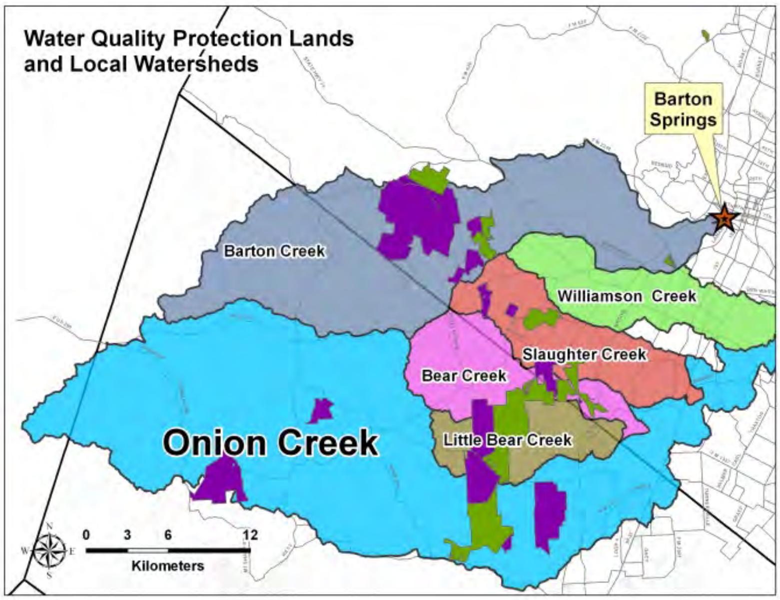

Figure 2.
Map of watersheds in the area protected by the Water Quality Protection lands.

The previous assumption that the most proximal creek to Barton Springs must provide the most significant amount of recharge to Barton Springs has been disproven (Hauwert 2009). Dye traces have indicated a significant flow path from Onion Creek, which is located near the southern groundwater divide (BSEACD 2003, Hauwert et al 2004a, Hauwert et al 2004b, Hunt et al 2005,) that separates water feeding the Barton Springs segment of the Edwards Aquifer to the north and the San Antonio segment of the Edwards Aquifer to the south. Studies by the City of Austin's Watershed Protection Department and the Barton Springs Edwards Aquifer Conservation District have indicated the flow rate can be remarkably rapid from this southern boundary of the recharge zone, travelling up to 11.9 km per day to reach Barton Springs under high flow conditions (Hunt et al 2006). This suggests a major groundwater flow route. In addition, relative to other local watersheds, Onion Creek provides by far the greatest volume of water to the Barton Springs aquifer (Hunt et al 2005), with an estimated 33 percent of the total discharge of Barton Springs originating in Onion Creek (Hauwert 2012). This has led to some significant land purchases almost 31km from Barton Springs and near the furthest extent of the recharge zone for Barton Springs.

Land Management

Owning or otherwise protecting land, including conservation easements, provides the greatest measure of protection from impacts such as potential pollutant sources, and further allows the natural conditions that feed Barton Springs to continue unimpeded into the future. However, simply purchasing the land or rights cannot curtail the transition or succession of land into ecological states that may produce lower water yields than other ecological states. For example, in the central Texas area, grassland and savanna can quickly transition into dense woody canopy following invasion by brush species (Fowler and Simmons 2008). Previously such invasions have been reversed over the evolutionary history of the area by the frequent occurrence of natural wildfires, which have been prevented in the post-settlement era (Bray 1904, Smeins and Fuhlendorf 1997).

The concept of an inverse relationship between woody canopy cover and water yield has been demonstrated in the literature from around the world (Thurow 1998, Wu et al 2001, Le Maitre et al 2002, Davie and Fahey 2005, Hamilton 2008, Mark and Dickinson 2008). Further, various studies from Texas have shown additional water yield following brush management (Thurow and Hester 1997, Dugas and Wright 1998, Huang et al 2006, Saleh et al 2009, Banta and Slattery 2011). This has not been without controversy (Wilcox et al 2005, Wilcox et al 2008, Wilcox and Huang 2010), but ultimately the conditions that are most ideal for brush management from a water yield standpoint are well represented on the recharge zone lands protected by the WQPL Program: that is, a shallow soil overlaying a highly fractured subsurface where water can quickly be transported underground (Wilcox et al 2006).

The WQPL Program conducts ecological restoration activities on land held in fee simple to restore the ecosystems back to or maintain their native ecological states of grasslands and savannas (Lady Bird Johnson Wildflower Center 2001, 2010). These are the same ecosystems that the literature has demonstrated yield the greatest quantity of water. Work conducted in this regard utilizes a number of tools to manage brush and encourage grass restoration, including mechanical thinning, prescribed fire, and native grass seeding. The work is conducted to be as low impact as possible to avoid erosion and other negative consequences on the land.

Balancing water quality and water quantity can be challenging and at times counterproductive, but again the literature has indicated improved water quality under grassland settings compared to other ecological states (Banta and Slattery 2011). In the case discussed herein, the restoration of native grasslands and savanna ecosystems in the recharge and contributing zones has the potential to further protect or even improve water quantity and water quality at Barton Springs.

Karst Management

Once the land is protected and opportunities for optimizing the quantity and quality of water are implemented by land management, the last integral action is to protect the function of karst features. Locating and identifying karst features is an important first step, but this also has to be followed up with prioritizing features in terms of potential to transmit water. Logically, features located in streams beds, such as swallets, would rank above typical upland features in terms of absolute recharge (Hauwert et al 2005), but these upland features should not be discounted. For example the WQPL has at least two upland features with internal drainage basins approaching 24 hectares each. Such internal drainage basins can recharge up to 42 percent of the rain that falls within such a basin (Hauwert et al 2005). A swallet by comparison may have a drainage basin measured in square kilometers. That said, a swallet is unlikely to be able to transmit this total volume due to orifice size and capacity (Hauwert 2009)

Streams over the recharge zone in central Texas are frequently ephemeral in nature and under such conditions may not see appreciable flows for several years. Yet the management of karst features in streams frequently has the highest potential for recharging the largest volume of water over the longest time and accordingly receives the bulk of attention on the WQPL. As a case in point, one feature in Onion Creek (Figure 3) has been estimated to take in up to 425 l/s of water while the creek is flowing (Hauwert 2012).

Swallets can have their function impaired by their success in capturing water as this process also brings in substantial volumes of organic matter, sediment, and rocks included in the bed load of the streams in which they are located. Over time this debris can plug swallets and negatively impact their function. Over geologic time, such features are likely to close and open in some measure of equilibrium. However, in managing such areas to positively impact the quality and quantity of water reaching a spring on a human time scale, steps must be taken to keep the existing swallets in proper functioning condition rather than waiting for formation of new swallets. This is even more of an acute need when additional demands are made on an aquifer without any offsetting decreases in usage or increases in recharge.

Figure 3.
Photo of a swallet recharging on Onion Creek.

The WQPL Program uses a variety of simple techniques to manage such features to maintain their function. Once a swallet is located, it is evaluated to help determine its importance. If it has the potential to provide significant recharge, a grate will be installed above it to help prevent debris from collecting within the swallet.

Further refinement of these grates has resulted in fine debris covers attached externally to these grates. Such debris covers are structurally weak, but are supported by the initial grate and removable without affecting the underlying grate (Figure 4). This has the benefit of blinding quickly with floating organic debris collecting on the fine grates under flood flows. The blinding of the grate then keeps the sediment associated with the initial flood pulses from passing through the grate. Although this prevents a large volume of water from reaching the feature, this initial part of the flood flow is frequently of low quality, and it is better that it does not recharge. The grates can then be cleaned manually once the peak of the flow has passed and allow the cleaner portion of the stream flow to be captured (Figure 5). This helps prevent the plugging of features deep within the swallet, and maintenance of the grates on the surface is usually sufficient to keep the swallets in proper functioning conditions. Prior to the use of these grates it was necessary to wait for a dry period to enter the caves and remove any debris plugs from deeper inside the feature.

Once grated, some swallets can then be excavated to remove accumulated sediment with very little accumulation of new sediment. This can allow the unencumbered passage of water with less re-suspension or movement of old sediment. Few terrestrial organisms survive the periodic and occasionally long lasting inundations, but contractors doing such excavations are required to have U.S. Fish and Wildlife Service permits for working with endangered karst invertebrates.

Figure 4.
Example of swallet grate with fine debris cover.

Figure 5.
Example of swallet grate with fine debris cover after storm event and prior to manual cleaning.

In one example of this type of excavation, a former landowner who was raised on the property, likely around the 1950s or 1960s, reported a frequent whirlpool originating at a known swallet. No whirlpool had been reported or identified in recent time at this location and dye tracing showed it had a much longer travel time to Barton Springs than did a nearby feature also on Onion Creek (BSEACD 2003), albeit under a different flow regime. It seems likely that 50 years of flood-born sediment might be preventing this feature from functioning properly. However, it is hoped that removing this subsurface sediment in combination with the addition of grates will return this swallet to proper functioning condition. The project is ongoing but over 38 meters^3 of sediment and debris have been removed.

Upland features require much less attention, as they are frequently less prone to becoming plugged by debris, and functioning condition is more easily maintained in these features by vegetation management that helps reduce erosion into the features. Frequently, upland features may also be home to karst invertebrates that may be endangered and may require the cave be protected as a refuge for such organisms versus being managed as a recharge feature.

Conclusions

The Water Quality Protection Lands were established to help protect a portion of the City's water supply, namely Barton Springs. The methods of this protection began with the purchase of land and the protection of additional land with conservation easements leading to the protection of over 10,730 hectares.
The WQPL Program went further and is implementing a land management plan to manage the land owned in fee simple to optimize the quality and quantity of water leaving the lands and recharging into the Barton Springs segment of the Edwards Aquifer. Techniques including those associated with ecological restoration are used to restore or maintain the vegetation as native grasslands and savannas, which have been shown to yield greater water than more woody landscapes. Finally, to ensure that water recharging off these lands can continue to benefit Barton Springs, karst features, and especially swallets, are managed and restored to proper functioning condition and protected from sedimentation that could impede or obstruct recharge.

Acknowledgments

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Continuous Discharge Data from Barton Springs and Rainfall Since 1978

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Barton Springs (also known as Parthenia Spring) along with its sister springs of Eliza Spring (Zenobia or Concession Spring) Old Mill (Sunken Garden Spring) and Upper Barton Spring are the primary natural discharge points for the Barton Springs segment of the Edwards Aquifer. Located in Zilker Park in central Austin, discharge from the main spring feeds Barton Springs Pool. The pool is visited by thousands of patrons annually and is home for two endangered species of aquatic salamanders; the Barton Springs salamander (*Eurycea sosorum*) and the Austin Blind salamander (*Eurycea waterlooensis)*.

This paper will summarize and discuss Barton Springs discharge since 1978 when daily discharge measurements began at the springs, as well as changes in Austin rainfall. A discussion on temporal trends in rainfall, spring discharge, and creek flows can be found in Hunt and others (2012).

The U.S. Geological Survey, under a cooperative program with the City of Austin, has been measuring and reporting discharge from Barton Springs continuously since March 1978. This discharge measurement does not include discharge from Upper Barton Spring or other small springs that discharge along the channel of Barton Creek upstream of Barton Springs Pool. Additional data from a multi-probe sonde deployed in the spring orifice provides water depth, temperature, pH, dissolved oxygen, specific conductance, and turbidity data on the same web page. These data provide a high resolution (every 15 minutes) assessment of discharging conditions. Prior to 1978, discharge from the springs was based on period manual measurements and presented as monthly averages (Slade et al, 1986). The 1979-2014 data provides a more detailed and more accurate analysis of spring discharge over this period of time.

Over the 36 years since continuous discharge data collection began, the average daily discharge from Barton Spring is 62 cubic feet per second (cfs) (Figure 1). This value does not include pumping, which has also increased since 1978 (Figure 2), and so does not represent total discharge from the entire Barton Springs segment of the Edwards Aquifer. The maximum estimated discharge between 1978 and 2014 was measured at 130 cfs in December 1991 following heavy winter rains and the minimum discharge of 13 cfs was measured during the drought of 2009. Spring discharge data prior to March 1978 consisted of manual measurements of varying frequency. Hunt and others (2012) report that mean spring discharge is 53 cfs (for the period from 1910 to 2009) but between 1917 and 1957, the average discharge at Barton Springs was 41 cfs whereas it was 65 cfs from 1958-2010, close to the 62 cfs average from 1978-2014.

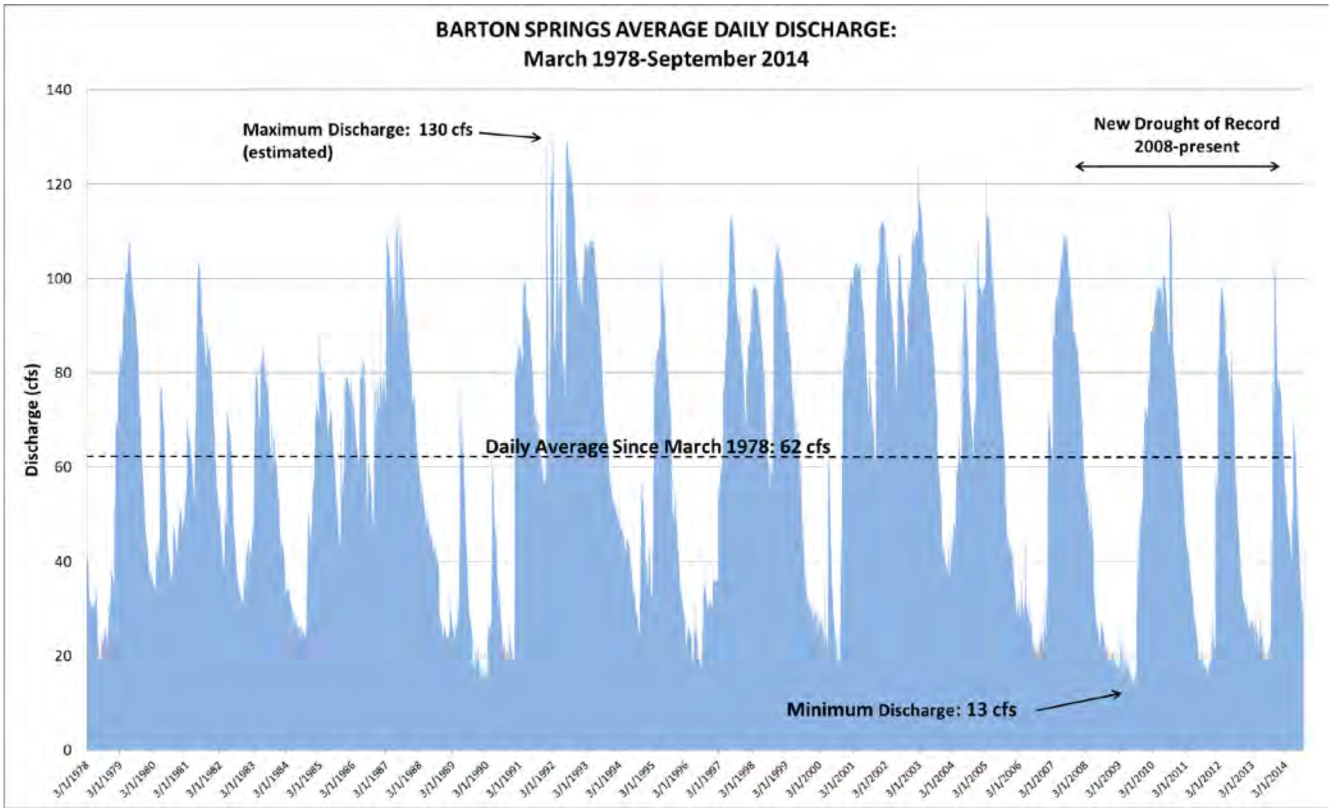

Figure 1. Chart showing Barton Springs average daily discharge from March 1978 through December 2014. Note that the historic minimum discharge of approximately 10 cfs was measured during the drought of the 1950's and the minimum during the current drought is 13 cfs in July 2009.

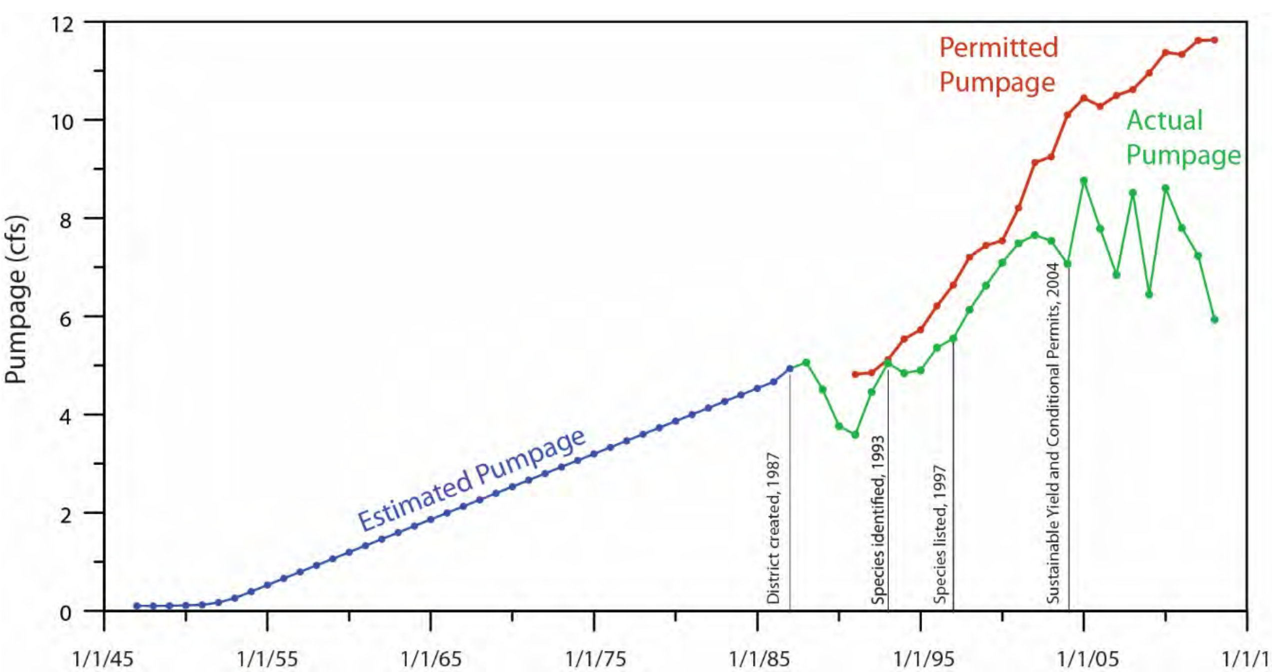

Figure 2. From BSEACD draft Habitat Conservation Plan (2014) showing estimated pumpage prior to 1987 and permitted and actual pumpage from the aquifer after 1987.

Measurement of spring discharge assists in endangered species management at Barton Springs Pool and is an indicator used by the Barton Springs/Edwards Aquifer Conservation District (BSEAD) to help determine drought status (the other indicator is water level in the Lovelady monitoring well). See http://www.bseacd.org/aquifer-science/drought-status/ for more information on the BSEACD drought status.

Average annual rainfall in Austin at Camp Mabry since 1978 is 33.6 inches (Figure 3), which is very similar to the long term average rainfall of 33.5 inches. Over this period of record, maximum rainfall is 52.27 inches in 2004 and minimum is 16.07 inches in 2008. There are two years with rainfall total greater than 50 inches (1991 and 2004) and three years with rainfall totals below 20 inches (1988, 2008 and 2011). Three of the five lowest years of rainfall since 1978 are in the last ten years whereas only one of the five highest is in the last ten years. The LCRA (2015) reports that the current drought, beginning in 2008, is the worst on record for the Highland Lakes. The organization has accordingly reduced the amount of available water in the Colorado basin during drought.

Hunt and others (2012) report that long-term precipitation has increased in some areas, such as Dripping Springs and Blanco, areas that contribute recharge to Barton Springs, even though long-term average rainfall in Austin has stayed relatively constant. This appears to account for the more recent increases in average spring discharges although Hunt and others (2012) note that average low springs flows are decreasing as a result of pumping and lower base flow in contributing creeks.

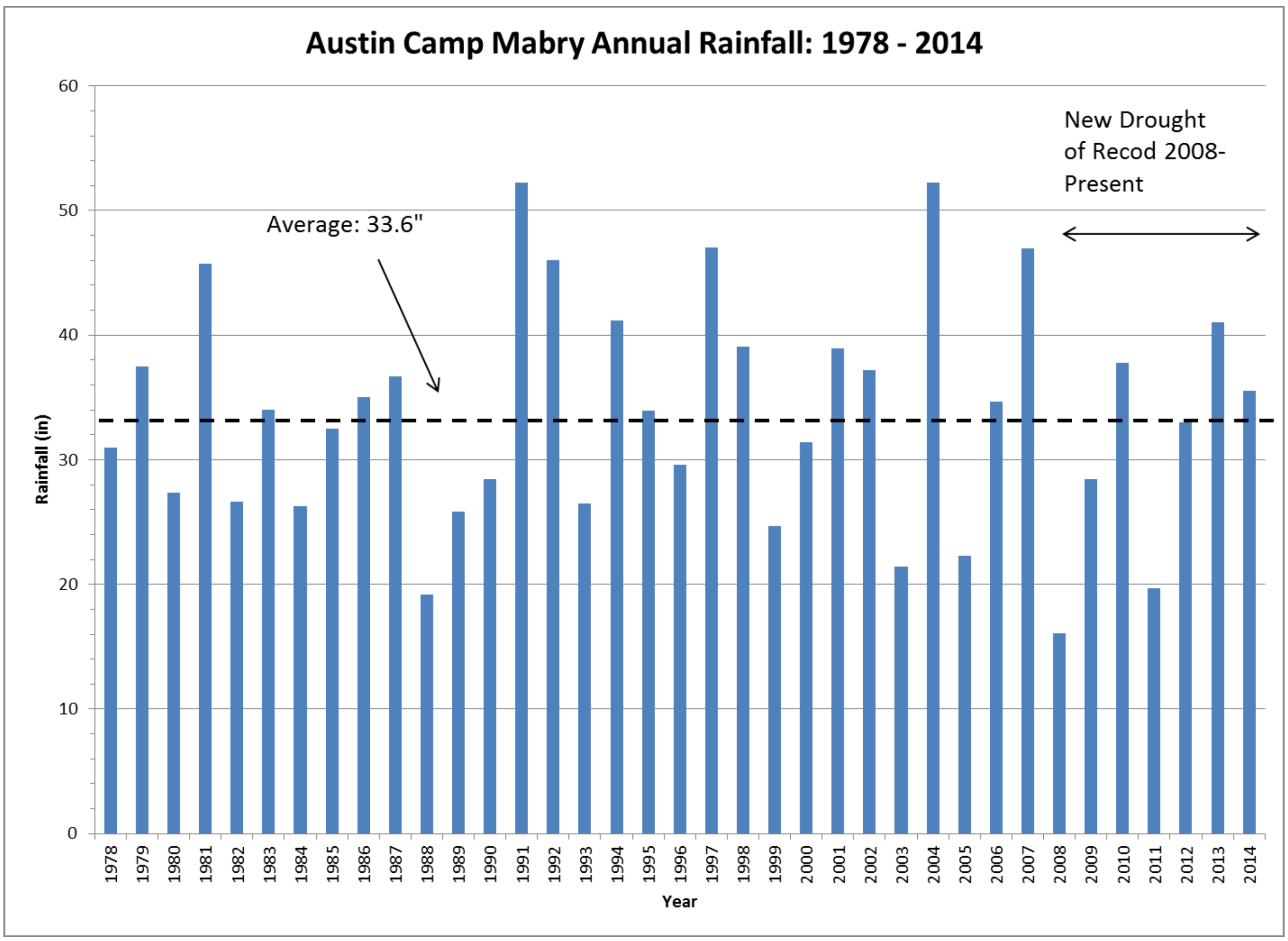

Figure 3. Average annual rainfall at Camp Mabry from 1978 to 2014.

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Using LIDAR for Karst Investigations in Remote Areas of the Barton Springs Segment of the Edwards Aquifer

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LIDAR as defined by Wikipedia (2015) is: "Lidar (also written LIDAR, LiDAR or LADAR) is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. Although thought by some to be an acronym of Light Detection And Ranging (NOAA), the term LIDAR was actually created as a portmanteau of "light" and "radar" (Oxford English Dictionary)(Ring, 1963)." Or for this discussion, "Lidar is popularly used as a technology to make high-resolution maps, with applications in geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, remote sensing, atmospheric physics,(Cracknell, 2007) airborne laser swath mapping (ALSM), laser altimetry, and contour mapping." Wikipedia further says that LIDAR has a "vertical accuracy of below 50 mm" or approximately two inches. For both the northern and southern Edwards Aquifer recharge zone, 2013 LIDAR coverage was gridded to 1 square foot resolution by Watershed Protection Geographic Information System staff. This LIDAR coverage has a data point approximately every 3.84 ft^2. Color-coding of LIDAR data makes startling colorful images akin to spin art paintings that children used to make at county fairs in the 1960's.

Staff from the Watershed Protection Department of the City of Austin use LIDAR topographic data to aid in locating and evaluating potential karst features. The high resolution LIDAR data is particularly useful in remote areas that lack the 2-FT topographic coverage that is available in most urban areas of Austin. Karst surveys on large ranches can be problematic due to the sheer size of the area to be surveyed, vegetation cover, and past land practices can result in filled in or covered karst openings. Subtle topographic relief for some broad upland sinkholes and locally dense vegetation can make identification difficult and mapping the aerial extent equally difficult.

Examples discussed below include delineation of the Flint Ridge surface drainage basin, identification and delineation of karst features on the Ruby Ranch as part of the purchase of a Conservation Easement on the ranch and brief discussion of LIDAR uses on Hudson Ranch and along Onion Creek. Each case includes examining debris patterns from large runoff events to aid defining drainage paths and basin divides.

2013 Investigation of Flint Ridge Cave Surface Catchment

Flint Ridge Cave is an exceptionally large sinkhole and cave located on Water Quality Protection Lands southwest of Austin. The rimmed sinkhole is about 100 ft across and has a surface area draining to the sinkhole of 57.8 acres (Hauwert et al, 2013).

Determining the surface drainage area is challenging due to very subtle topographic relief in the uplands. Poorly defined drainage swales can route runoff and even a few inches of relief can alter the direction runoff flows. In some areas, even small debris dams from sheetflow runoff can locally re-direct runoff into or out of the surface drainage basin.

A traditional topographic survey used by Hauwert (2009) has a density of approximately one point every 8,333 ft^2 whereas the LIDAR coverage in the Flint Ridge area has approximately one point every 3.84 ft^2. The resulting LIDAR topography has much denser data coverage, which results in the ability to detect more subtle topographic changes than the previous manual topographic survey. The LIDAR image illuminates a drainage to Bear Creek that parallels the western edge of the Flint Ridge surface catchment defined by Veni (2000). The drainage becomes more subtle northward where it enters the western lobe of a surface catchment area defined by Hauwert (2009) (labeled "potential catchment" and shown in light brown hatching in Figure 1), which is inside and west of the SW45 SW right-of-way (ROW). Consultants for the Texas Department of Transportation (TxDoT), using similar LIDAR data, have delineated a similar surface catchment for the cave (TxDoT, 2015) (Table 1).

WPD staff examined the western part of the Flint Ridge surface drainage area following the exceptional rain event in October 2013 when over 10 inches of rain fell locally. Deep overland sheetflow during the runoff event bent down grasses even in areas with no defined drainage channel. Figure 2 shows debris dams in the upland created during the runoff event. Topographic relief is so low that field observations suggests that these debris dams might re-direct runoff into or out of the cave surface catchment depending on their location, thus highlighting the value of on-the-ground observations following runoff events.

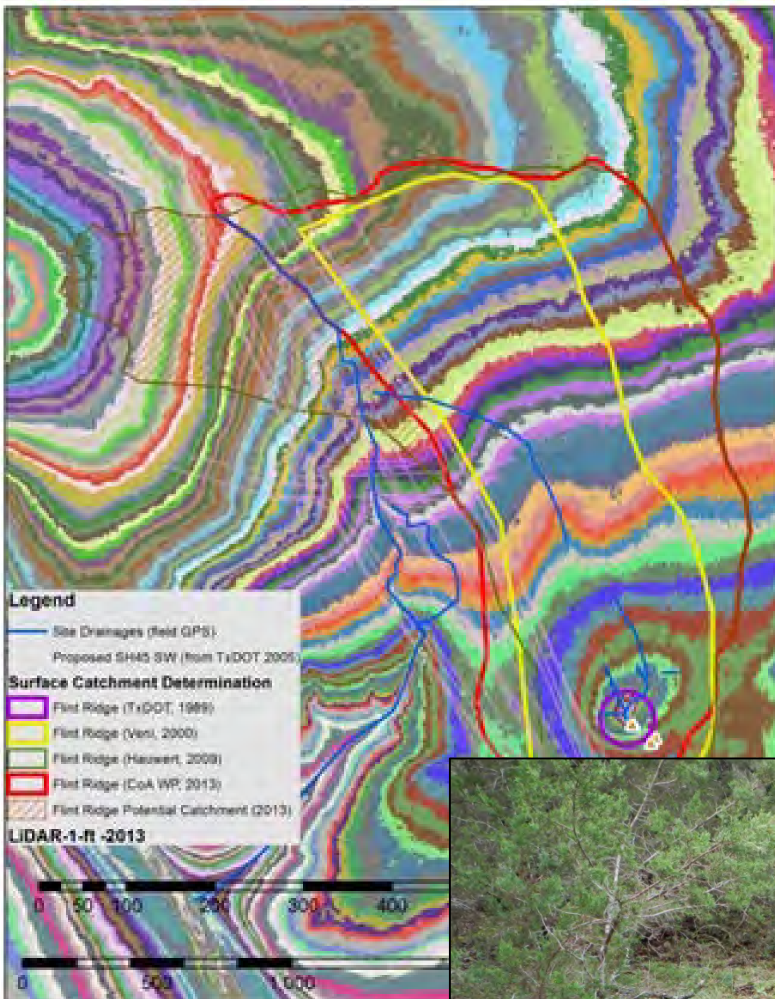

Figure 1. LIDAR image showing the surface drainage basin for Flint Ridge Cave as determined in 2013. Estimates of the basin boundary for other studies are also shown.

Figure 2. Debris dams formed during October 2013 rains near Flint Ridge Cave. In areas of subtle relief, these dams may re-direct water from one drainage path to another.

Table 1. Summary of Surface Catchment Interpretations for Flint Ridge Cave

Description	Area		Source
	(square feet)	(acres)	
Total Surface Catchment	32,370	0.75	TxDoT (1989)
Total Surface Catchment	1,629,144	37.4	Veni (2000)
Total Surface Catchment	3,027,420	69.5	Hauwert (2009)
Primary Surface Catchment	2,517,768	57.8	WP (2013)
Potential Surface Catchment	575,992	13.2	WP (2013)
Unverified Potential Surface Catchment	64,340	1.5	WP (2013)
Total Surface Catchment	2,417,580	55.5	TxDoT (2015)

Ruby Ranch Conservation Easement

COA/WPD staff began assessment of Ruby Ranch in the summer of 2013. Owners of the 747 acre ranch were interested in encumbering the ranch with a Conservation Easement (CE) which would remove nearly all future development rights (i.e. impervious cover) from the property except for development specifically allowed for by the CE. This allows the ranch to continue traditional ranch activities that include cattle raising and hunting. Impervious cover limits allowed in CEs held by the City of Austin typically have total impervious cover of about one percent (compared to 15% allowed by the SOS Water Quality Ordinance, the strictest development ordinance in COA). The Hill Country Conservancy and the Natural Resources Conservation Service of the U.S. Department of Agriculture were partners in the acquisition.

Staff conducted karst survey transects in areas planned for future ranch facilities, utility access corridors and internal ranch roads. LIDAR was initially used to identify potential karst features and later to delineate drainage areas to protected features. LIDAR was particularly useful in in identifying closed depressions. In general, those on the order of 10 feet or more across could be easily identified. Smaller features tended to get lost in the data scatter. Discrete openings to caves or solution conduits could not be delineated with LIDAR.

Based on the karst surveys, 26 karst features were identified that warranted buffers as protection from future development as allowed in the CE. These features range from small solution conduits inches in diameter to large upland collapsed sinkholes hundreds of feet across. Surface catchments were refined based on detailed examination of the surface around the features and observations of debris patterns after runoff events.

A large number of features of interest were identified by LIDAR. Among these were three large upland closed depression sinkholes on the order of hundreds of feet across. A large number of other potential features turned out to be constructed cisterns or shallow bermed depressions adjacent to water wells and used to water cattle. Some features of interest were pseudo-depressions created by road crossings and not related to karst action. Figure 3 shows aerial and LIDAR images of the southern part of Ruby Ranch illustrating large upland sinkholes, sinkholes in the channel of Mustang Branch, and man-made features. Figure 4 shows aerial and LIDAR images of the central part of the ranch showing a large upland sinkhole, a smaller depression and a constructed stock tank. Three large upland sinkholes are described as follows:

Airstrip Sink

Broad upland sink about 300 ft across northeast of the old airstrip. No obvious sinkhole rim. Vegetation change in the sink with thicker grass cover but no open apertures observed. Abundant wetland plants present. Sink contained several separate pools of water within the sink area in November 2013 following October 2013 rains. No high water marks are visible suggesting feature primarily received only direct rainfall with little large-scale water ponding and a small amount of sheet flow from the surrounding area.

Small Ruby Sink

Broad upland sink area about 200 ft across east-to-west and about 250 ft across north-to- south containing several smaller closed depressions. These include a single central low area about 20 ft across, three closed depressions on west side and two on north side. Another closed depression to the southwest about 30 ft across is probably part of same large sink. Slope breaks into the sink are not sharp, and overall grass cover is good. The sink contained several pools of water in November 2013 following heavy October rains, and abundant wetland plants were present in ponded areas.

Big Ruby Sink

This is a broad upland sink on southeast part of ranch and east of Mustang Branch, and is about 300 ft across east-to-west and about 400 ft across north-to-south. Slope break into sink is greater on east side whereas the northwest side is contained with a constructed berm. The north and south ends do not have a pronounced slope break. A constructed berm on north end separates about 100 ft of the sink. A low area in center is 20 ft across, has no vegetation and is oriented closer to east side than west. Overall grass cover in and nearby the sink is good. The land owner has indicated that the sinkhole drains within days after filling but no openings into the subsurface are visible. Only a small pool of water approximately 15 ft across was present 15 days after the October 30-31, 2013 flood. An area of 79.8 acres, mostly to the south and off ranch property, drains to the sink.

Of the three big upland closed depressions, Big Ruby Sink drains quickly and has the largest surface catchment which makes it the most significant of the three. The ponded water and wetlands in Airstrip and Small Ruby Sinks suggests that they recharge water more slowly and they have much smaller surface catchment areas than Big Ruby Sink.

Field Observations Following October 2013 Floods

Exceptionally heavy rain fell over the ranch area in October 2013 offering a unique opportunity to examine surface catchment areas for the karst features and evaluate the drain time of upland features that have no obvious apertures into the subsurface.

Approximately 3-6 inches of rain fell October 12-13 and saturated the ground. Then on October 30-31 (Halloween Flood) 8-9 inches fell on the already saturated ground. These rare events allow for direct observations of recharge. Unofficial estimates of the re-occurrence interval for of the Halloween storm is greater than 100 years. Flood impacts from the Halloween Flood are greater than might normally be expected due to the already saturated ground causing greater runoff. Field observations were made by COA staff about 14 days following the Halloween Flood. Aerial images of this area taken on October 31, 2013 are available on Google Earth (http://www.google.com/earth/). These images offer the unique opportunity to see the closed basins holding water after the epic rain event (Figure 5).

Big Ruby Sink showed evidence of collecting a significant amount of water. Debris lines or high water marks on the sides of the sinkhole indicate it was filled with 5-6 feet of water at the height of runoff following the rain. Debris lines indicate the sink overflowed following the broad topographic low to the north toward Mustang Branch. This area has several relatively small closed depressions and at least one of these depressions contained wetland plants and standing water as of November 22, three weeks after the last heavy rain.

Rough calculations indicate that the sink held approximately 11.5 ac/ft (or 3,760,000 gallons) of water following the Halloween Flood. This is approximately the maximum amount of water the sink can hold. Assuming 9 inches of rain fell across the 79.8 ac catchment area, approximately 60 ac/ft (19,550,000 gallons) of water was deposited over this area, which is much more than the sink could contain. A large volume of water may have infiltrated into the subsurface prior to reaching the sinkhole suggesting that the calculated volume is a minimum value. An examination of debris lines, aerial images and photos provided by the landowner indicate that water was draining from the sink at a rate of about 1 ft/day. This drawdown equates to roughly 940,000 gallons or 2.9 ac/ft of water per day and suggests that this sinkhole, even without an open conduit into the subsurface, would completely drain in about 5 days, which is supported by statements from the land owner. Figure 6 shows the sink full of water 2 days after the Halloween Flood of 2013 and 13 days after the rain, with only a very small pool in the topographic center. This information shows the importance of large upland sinks have in recharging the aquifer; how rapidly they can drain even without open apertures; and the importance of classifying them as sensitive features according to the Texas Commission on Environmental Quality (TCEQ) guidelines.

Upland Sinks on Hudson and the Onion Creek Management Unit

Examination of LIDAR can be a valuable tool prior to conducting on-the-ground surveys for karst features. Figure 7 shows aerial and LIDAR images of Hudson Ranch. Several large topographic lows are visible, some of which may not be immediately evident when viewed from ground level, even though they may be 100's of feet across. Some of the features highlighted from LIDAR were not recognized, not attributed to karst processes, or not considered as significant. Ranch practices often modified these natural low areas into stock tanks for livestock and wildlife, often with poor results. These types of features are commonly described as man-made on assessments. This conclusion overlooks the overall topographic expression of the features, their size and landscape setting. Constructed stock tanks are most commonly located in drainages to collect as much runoff as possible.

Although the ranch is somewhat remote, a developer (i.e. land speculator) created plans for a dense housing development using water supplied by the West Travis County Public Utility Agency. The plans included central wastewater collection with irrigation of treated wastewater effluent over the recharge zone which raised concerns about water quality impacts to the aquifer. COA used voter approved bond money to purchase the ranch in 2013, adding it to the Water Quality Protection Lands program. Additional detail on karst features on the ranch is covered in another paper in this guidebook.

LIDAR is a valuable tool but it does have limitations. Crooked Oak Cave is located in the bed of Onion Creek (Figure 8) but the surface opening (manhole-size) is too small to clearly see with LIDAR even though the feature is capable of recharging a large amount of water. LIDAR simply cannot clearly resolve small solutional openings.

Conclusions

LIDAR imagery is a valuable tool for assessing remote properties. The detailed topographic data have greater density of points than typical topographic data from surveying companies. The data can help identify potential karst features such as closed depressions and sinkholes greater than 10 ft across, although cave or karst solution openings may not be identified. The data help provide good estimates of contributing basin size, which can be further refined with field observations.

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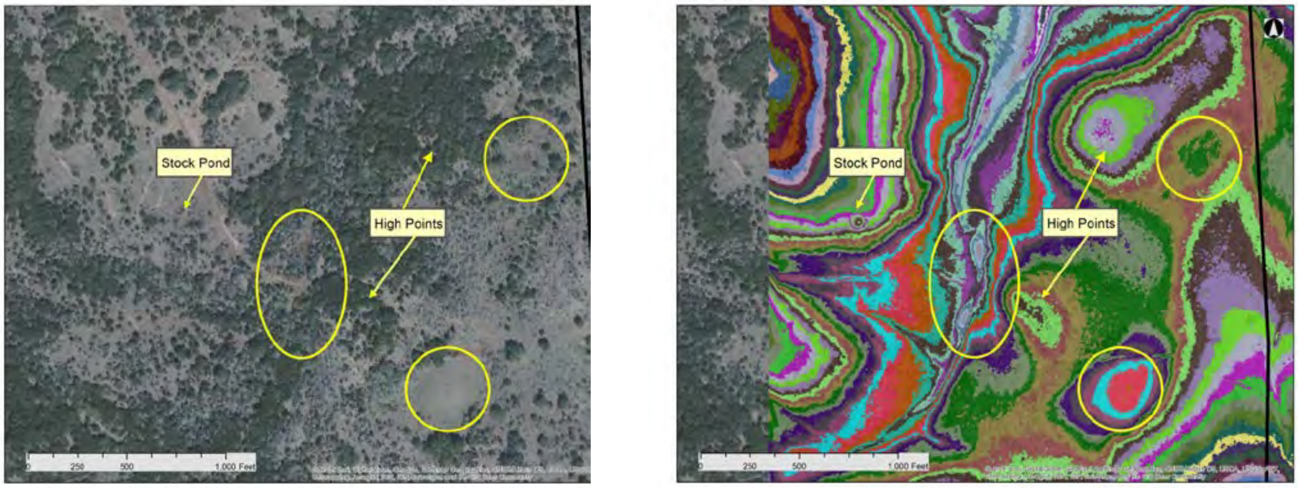
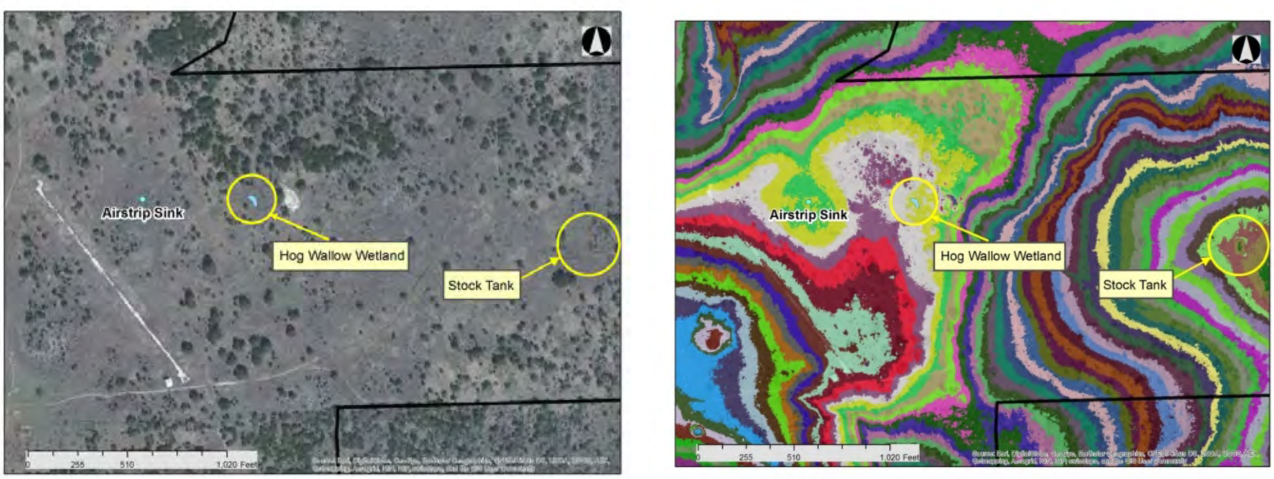


A.

B.

Figure 3. Aerial (A) and LIDAR (B) mages of the southern end of Ruby Ranch showing two large upland closed depressions (right – Small Ruby Sink at top and Big Ruby Sink on bottom), two depressions in the creek channel (center) that likely correspond to sinkholes, and a stock pond that appears on LIDAR as a possible sinkhole but on ground investigation shows an entirely man-made feature.



A.

B.

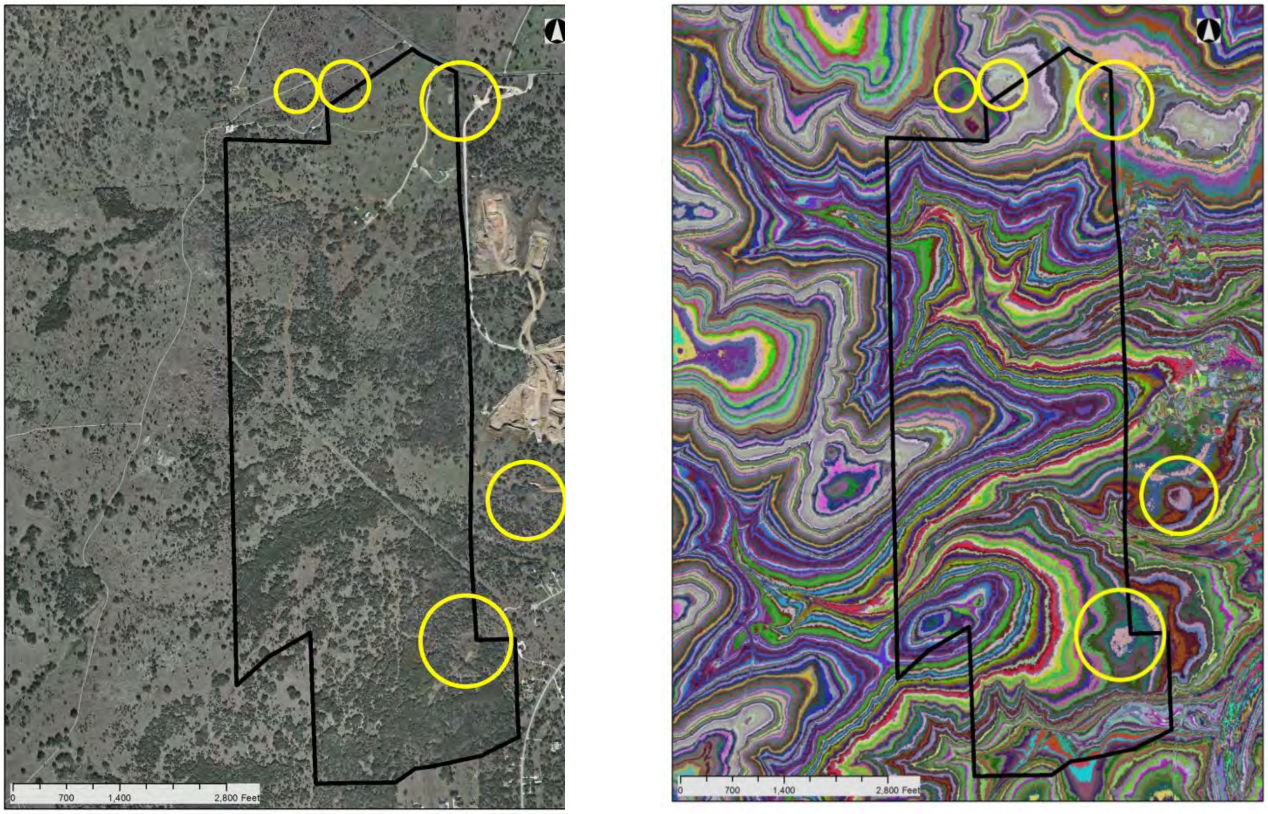
Figure 4. Aerial (A) and LIDAR (B) images of a portion of Ruby Ranch showing a large topographic low called Airstrip Sink, a poorly defined topographic low that holds water after rains (Hog Wallow Wetland), and a constructed stock tank.

Figure 5. Aerial image of the southern portion of Ruby Ranch taken October 31, 2013, the day after epic rains in the area covering roughly the same area shown in Figure 3 and including Big Ruby Sink shown in Figure 6.

B.

A.

Figure 6. Photos of Big Ruby Sink. A. Photo of the sink completely full of water two days after epic rains in the Onion Creek watershed. Photo courtesy of Cecil Ruby. B. Same view point 15 days later with no water present and no open conduits visible. This feature recharged, at a minimum, an estimated 11.5 ac-ft of water during the Halloween Flood in 2013.



A. **B.**

Figure 7. Aerial (A) and LIDAR image (B) of Hudson Ranch. Several large topographic lows are visible (circled) on and adjacent to the ranch. Although they are sometimes dismissed as simply stock tanks, their size, location and topographic characteristics suggests that it is highly unlikely that they are solely man-made.

A. **B.**

Figure 8. Areial (A) and LIDAR (B) mages of Onion Creek showing that LIDAR does not generally delineate realtive small cave openings although larger depressions in the channel are visible and some do correspond with karst features.

Pathogenic Outbreaks in Central Texas

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A pathogenic outbreak is the onset of an acute illness that is associated with water exposure and affects two or more people (Lee 2002). Although pathogens affecting humans can transmitted by wildlife, the waterborne outbreaks are normally associated with anthropogenic sources. Some of the common causes of these outbreaks have been attributed to organized sewage collection system line spills (particularly lift stations) septic tank failure, wastewater treatment plant failures, and animal husbandry pollution. This paper focuses on cases of waterborne pathogenic outbreaks that were documented in the Edwards Aquifer of Central Texas.

Pathogenic outbreaks due to groundwater contamination have been part of society since communities start using wells and springs for their drinking water. In 1854, London witnessed an outbreak of cholera that claimed more than 500 lives. After extensive study, Dr. John Snow concluded that the source was linked to a specific well that was contaminated with sewage water (Snow, 1855). The discoveries resulting from this event revolutionized the field of epidemiology, and water treatment management. A century later in the United States, cases like Crater Lake National Park in Oregon, demonstrated the latent danger that pathogens presented. In that case, a subsurface sewage spill reached a spring source and infected an estimated 2,200 people with the Enterotoxigenic *Escherichia coli*. In 1993, the Milwaukee outbreak of cryptosporidium shook the whole nation. The cases of infection soared to more than 400,000 and resulted in 50 deaths. This is one of the most thoroughly researched incidents due to its magnitude, as well as breakthroughs in analysis for cryptosporidium (MacKenzie, 1994). Corso et al (2003) estimated that the cost of the 400,000 cases was about $95 million dollars. The outbreak was originally thought to have originated from a bovine source, but several studies corroborated that the source had to be human waste. (Sulaiman et al. 1998). This massive outbreak was the combination of a great influx of pathogens and poor performance of the coagulation and filtration process during water treatment.

Between 1971 and 2002, contaminated groundwater pollution was the cause for 28 to 32 percent of all pathogenic outbreaks (AWWA, 2006). One common misconception was that groundwater is naturally attenuated as it moves through layers of rock before reaching the water table (St. Clair, 1979). This idea was nurtured by the lack of comprehension on the flow of groundwater, particularly in karst aquifers (Schindel et al., 1996). A perfect example happened in Walkersville, Maryland. The Maryland Department of Environment designed a 5-year and 10-year time-of-travel protection zone radius around three production wells on the limestone Biscayne Aquifer using a numerical ground water model. Tracers injected near the 5-year time of travel contour actually reached the wells within 17.5 hours (Aley and Field, 1993). The protection zones where restructured according to the dye tracing results. The study averted a disaster in 1999, when 900,000 gallons of sewage were spilled in the area and officials were prepared to immediately seek alternative water sources. One of the best-known tragedies in North America in recent history occurred May 2000 in Walkerton Ontario, Canada. Public supply wells completed in a karst aquifer became contaminated with pathogenic bacteria, resulting in seven fatalities and illnesses in more than 2300 people.

Addressing these issues is critical, due to the serious impact of outbreaks on the affected communities. These impacts include social, economic, and physical damage. Many costs are associated with an outbreak. For example, people that contract a disease from an outbreak spend money on medical help, which typically includes a doctor visit, medicine, and sometimes hospitalization. The disease may result in death or permanent injury. Also, the city has to spend money in the cleaning of the water, as well as investigation and development of better treatment methods. The loss of confidence the public has in its drinking water supply and the entities responsible for protecting it can have long term consequences.

Pathogens

In the analysis and prevention of pathogenic outbreaks, the characteristics of the pathogen are important. Waterborne pathogens include viruses, bacteria, and parasites (Brittle, 2014). Parasites include protozoa and helminths. The transmission of waterborne pathogens is primarily through a fecal-oral pathway. A pathogen infects its host and spreads its microbes through the feces. This characteristic makes pathogens very common in wastewater and animal husbandry. Most waterborne pathogens are capable of infecting both humans and animals.

The occurrence of the different types of pathogens has changed over time with improvements in sanitary technology. From the 1800s to 1960s, bacteria that caused diseases like cholera or typhoid fever were responsible of vast majority of outbreaks. This changed with the introduction of chlorination and filtration of drinking water and development of organized sewage collection systems. These practices raised the quality of water exponentially, but soon viruses and protozoans began appearing in the water. This discovery was most likely due to better detection methods. One of the main outbreaks of pathogens in the 1960s was the Hepatitis A virus. According to the AWWA (2006), Hepatitis A caused 22 percent of the outbreaks during that time period. Since then, protozoans have been the leading cause of outbreaks within the United States.

Cases in Central Texas

In Central Texas, cases like Georgetown, Braun Station, and Brushy Creek have shown the vulnerability of the karstic Edwards Aquifer. Although not used in the 1980s and early 1990s, tracing studies conducted over the Edwards Aquifer since 1996 have shown that groundwater can move rapidly with little attenuation (Hauwert, 2009), as described in another article in this guidebook. This unique characteristic makes the groundwater from the Edwards Aquifer of central Texas very susceptible to contamination by pathogens from sewage spills, animal husbandry run-off, and septic tank leakage. The quality of groundwater is very important to the state of Texas because of how often it is utilized. The TWDB estimates that groundwater provides 60% of the 16.1million acre-feet of total water use state-wide. Because of the growing scarcity of water supplies for a growing population, loss of potable groundwater further restricts the availability of water resources. The Edwards Aquifer was the first federally designated sole source aquifer, which means a large number of people over a relatively large area have no economically viable alternate water source.

Georgetown 1980

One of the largest pathogenic outbreaks in central Texas occurred in Georgetown, Texas on June of 1980. Georgetown is a small city located north of Austin, over the Balcones Fault Zone Northern Segment of the Edwards Aquifer. West of the Interstate I-35 in Georgetown, there is well-developed karst terrain where the Edwards Aquifer outcrops at the surface. The population at the time of the outbreak was approximately 10,000.

Georgetown relied on groundwater for drinking purposes. This water was obtained from seven different wells. As explained by Hejkal (1980), four of the wells were located in the center of the city: one in the park and one north of town at the airport. All of these wells were treated with a chlorination process, which consisted of chlorine injections that were administered to the storage tank. Water was retained for 20 to 30 minutes. The water treatment used at that time was well known for effectively treating bacterial pathogens, but it was not ideal for much smaller sized viruses and protozoans.

The outbreak started in June 1980 after a heavy rainfall event. The symptoms started with gastrointestinal problems in the communities utilizing municipal water derived from water well system, which included an “acute onset of diarrhea, abdominal cramps, nausea and fever” (Hejkal, 1980). Approximately 7,900 people were infected, which was 79% of the population.

The source of the groundwater contamination that caused the gastrointestinal illness has still not been reported. Testing for protozoans was in its infancy in 1980 and too expensive to use on short notice. It is safe to say that a possible protozoan was implicated in the outbreak was cryptosporidium. The characteristics of the outbreak resemble similar outbreaks involving this pathogen. The gastrointestinal cases presented, and the incubation period coincides with the recognized symptoms. Also other pathogens that come directly from humans were detected, which leads to the suspicion that the source came from septic tanks or sewage.

A month later several cases of Hepatitis A virus started to develop within the community. A total of 36 cases of Hepatitis A appeared in July 1980. This time frame corresponds with the incubation period of the virus if it was related to the previous pathogenic outbreak, which is approximately four to six weeks. Hepatitis A is among the smallest of the viruses, and is among the most resistant to treatment. It is transmitted fecal-oral, eventually infecting the liver. This pathogen is not zoonotic, which means that it came from a human waste source.

Hejkal (1980), conducted studies on the different wells, tap water and sewage in Georgetown on June 19, 1980. He concluded that the four central wells were contaminated with Coxsakievirus B3 and B2, and they contained very high concentrations of fecal coliform.

The Georgetown tap water was tested and no significant fecal coliform was detected. According to Hejkel (1980), the test results led state and local officials to think that the water was safe for consumption. Fecal coliform testing has proven effective in detecting bacterial pathogens and is frequently used as an indicator bacteria for other pathogens, but simple chlorination and filtration of the water supply may not eliminate other pathogens that may be present. Furthermore contaminates can move through the aquifer in pulses and may not be present when later testing is conducted. In the 1993 Milwaukee cryptosporidium outbreak, it was storage of ice samples from an ice factory and breakthroughs in laboratory analysis for protozoan that led to the identification of the pathogen. “Disease outbreaks (especially *Giardia* and *Crypstosporidium*) and endemic waterborne disease risk have been reported on water systems that have not violated either 1975 or 1989 maximum contaminant levels for total coliforms.”(Craun, 1997). The failure to identify the pathogen and its source in the well water led to an increase of the cases in the outbreak.

Speculations vary for the major source of contamination. Due to the nature of some pathogens that were found during the outbreak, it can be assumed that the source was human waste. Hepatitis A is not a zoonotic pathogen, meaning its only reservoir is humans. One big influence was the heavy rainfall event that occurred days before the outbreak, and that can percolate contaminates deep into the aquifer (Pronk, 2009). Dye tracing could have delineated the groundwater basin source area to the well, but was not reported to have been conducted. Apparently the source of contamination was corrected or treatment processes were improved as the outbreak is not known to have repeated.

Braun Station 1984

The outbreak in Braun Station, a subdivision west of San Antonio, outbreaks occurred in May and July 1984. At the time of the outbreak Braun Station was a suburban community with a population of approximately 5,900. Braun Station relied on artesian wells from the Edwards aquifer to extract their drinking water. “Potable water was supplied to all house-holds from the same artesian well” (D’Antonio, 1985). Overlying confining units were thought to afford protection for the water supply from contamination and that additional water treatment beyond chlorination was not deemed necessary.

In response to the alarm caused by the May outbreak, the water in Braun Station was tested in June. The initial chlorinated water samples from the households tested negative for fecal coliform. When the raw water in the wells was tested in July, heavy fecal coliform was found.

D’Antonio (1985) performed a telephone survey to estimate the size of the outbreak providing better documentation for the July 1984 outbreak, with many reported cases of diarrhea and vomiting. . His investigation revealed two distinct outbreaks. One occurred in the month of May, and the second in July. Both outbreaks resulted in the same symptoms among those affected. Because the May outbreak was not widely recognized, just six serum samples were collected. Four samples revealed an elevated level of the Norwalk virus. A telephone survey conducted by D'Antonio (1985), on 100 of 1,791 households with possible infections revealed that almost 72% of households presented symptoms.

This study helped health officials and D'Antonio (1985) to respond faster to the second outbreak in July. The investigations by D'Antonio (1985) on the second outbreak revealed that 117 people in 60 households had a gastrointestinal illness. Their ages varied from 1 to 72 years. The most common symptoms among those infected were diarrhea, abdominal cramps, and headaches with some fever. In the lab, oocysts of *Cryptosporidium* were identified on 47 of 79 stools samples examined in July.

Cryptosporidium is a unicellular parasitic protozoa, with a high infectivity rate among humans. *Cryptosporidium* in its infective stage has very thick oocyst wall, making the pathogen resistant to water stressors and some water treatments, including chlorination. *C. Parvum* is the most common cause of the outbreaks. It is a zoonotic pathogen, with young calves being the biggest reservoir. The Braun Station outbreak was the first registered outbreak in the United States where the involvement of *Cryptosporidium* was identified.

The proposed solution to prevent the outbreak from spreading was a mandate to the community to boil their water. This remained in effect until a different source of water was provided. The local well system was replaced by service from the San Antonio municipal water supply. According to Hrudey (2004), several studies including dye tracing revealed that the community sewage system was responsible for the outbreaks, but further specifics were not revealed.

This case was very important for the water treatment industry because it revealed that chlorination treatment was not a reliable method for eliminating all water borne pathogens. Reliance on indicator bacteria tests from chlorinated water samples can yield misleading results in evaluating the safety of a water supply. The failure to provide an accurate initial assessment of the outbreak and its causes resulted in a large total number of outbreak cases. At the time, the resistance of pathogens, such as *Cryptosporidium*, was not well understood. The knowledge/understanding gained from the Braun Station case has proven invaluable in the detection of other outbreaks.

Brushy Creek, 1998

Brushy Creek Municipal Utility District provided water to around 10,000 residents in the outskirts of Round Rock, Texas in 1998. Brushy Creek MUD obtained its water from two different sources. Approximately 60% of the water comes from chlorinated groundwater extracted from five different wells within the Edwards Aquifer. Each well is cement encased and approximately 30 meters deep. The second source of water is surface water. This water receives required treatment, which includes coagulation, flocculation, sedimentation, filtration, and chlorination.

At the time of the outbreak the Brushy Creek MUD area was experiencing very severe drought conditions. On July 13, 1998, lightning struck a City of Austin sewage pump station, causing it to fail and to spill 635,000 liters of raw sewage water. This spilled effluent went into Brushy Creek and readily percolated into the underlying Edwards Aquifer, resulting in another outbreak of *Cryptosporidium*.

The outbreak reports started on July 21, 1998 when Round Rock residents registered complaints about gastrointestinal illness. Approximately 1,100 residents called to report symptoms that included diarrhea, nausea, abdominal cramps, and vomiting. Bergmire-Sweat (1999) reports that of the 500 telephone-survey calls they made, only 189 responded. From this survey they estimated that there were between 1,300 to 1,500 cases. This represented 24% of the 6,000 people who used the Brushy Creek MUD services. According to Bergmire-Sweatt (1999), *Cryptosporidium* was detected in 89 of the 164 stool samples.

The chlorinated water tested negative for fecal coliforms, but immediately after that the state regulator ordered a test of the raw water from the wells. The result was four out of five wells were contaminated with high fecal coliforms. A rapid response from the state regulator reduced the number of cases in the area. It was decided that water supply for the Brushy Creek MUD area should be purchased from the nearby city of Round Rock, and that the wells should be taken out of operation.

This case is a breakthrough in outbreak response. In comparison to other cases like Georgetown and Braun Station, the investigation did not rely simply on a fecal coliform testing of the chlorinated water. The knowledge acquired from previous outbreaks and from further investigation of pathogens like *Cryptosporidium* and *Giardia* greatly reduced the vulnerability of cities relying on the Edwards Aquifer. Still there was a failure to convey the message to their population on a short notice. Officials waited a day to shut down the wells exposing their citizens to contaminated groundwater. Three families sued the City of Austin, the Brushy Creek municipal utility district, and the well operator because they did not sufficiently monitor the lift station, did not notify the citizens soon, enough and confidently stated the water was safe for consumption, even withholding vital information from the affected homeowners (Davenport, 1998).

The decision to shut down the use of the wells and transition to the purchase of surface water can be detrimental in the long term. Texas is expected to have a shortage of water in the near future. The solution should be focused on delineating and protecting water sources as opposed to seeking alternative water supplies for non-potable contaminated supplies. Note that a year before the Brushy Creek spill, successful groundwater tracing was conducted in the upstream headwaters of Brushy Creek and found tracers traveled three miles away in three days (Hauwert and Cowan, 2013). This tracing in the nearby Buttercup Creek neighborhood revealed that it is possible to conduct similar traces to delineate sources to Brushy Creek MUD wells if the foresight is taken to conduct similar tracing studies. Delineation of source areas using tracing is a vital tool for understanding the sensitivity of water supply wells.

Conclusion

The advance in water treatment technology in recent years has been outstanding. We have found solutions ranging from piping sewage in 1850s to membrane filtration and ozonation in recent years. However, we must not forget that pathogens are still present on the water. Large scale pathogenic outbreaks were not reported from Edwards Aquifer groundwater sources after the late 1990's. New water-quality management practices may be preventing the reduction in outbreak occurrence and magnitude. These practices include the discontinuation of permitting for large scale effluent land application over the Edwards Aquifer; TCEQ Edwards Rules and other regulation of organized wastewater system design, construction and monitoring; and improved understanding of groundwater flow and source areas through groundwater tracing. Even though the number of outbreaks has decreased, communities may still be vulnerable to sewage spills, water treatment failures, large flood events, and other circumstances. It is important to acknowledge the past, and use this knowledge to prevent future outbreaks.

Solutions should be focused on understanding the aquifers and groundwater flow, rather than simply seeking a different supply. It is important for a water manager to be able to determine the groundwater travel time from various potential pollution sources and pathways in order to be prepared during an emergency. Dye tracing has been proven a very effective method to determine boundaries of groundwater basins, recharge area for springs and the route of sewage effluent and pollutants (Mull et al, 1988). This tool provides better management practices for environmental agencies and water managers. As shown in the case of Walkersville described earlier, dye tracing was used to understand the flow and create an effective protection zone for wells, which avoided a potential disaster during a subsequent spill.

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New Recharge Studies for Central Texas

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Introduction

Karst terrains are known for well-developed recharge structures such as internal drainage sinkholes and swallets that at times are capable of rapidly infiltrating rainfall beyond evapotranspiration extinction depth (Meinzner, 1923; Jennings, 1985). Hill and Vaughn (1898) observed the entire creek flow of the Nueces River lost at a swallet. USGS geologist DeCook (1957) wrote:

> *"Although data are not at hand to illustrate how much of the precipitation ultimately reaches the Edwards ground water, it is generally believed that it is a relatively high percentage in limestones such as the Edwards as compared with that in other rock types."*

Across the world, studies utilizing a variety of methods consistently measured ranges of 18% to almost 70% of precipitation recharged karst aquifers (Figure 1). It is expected that recharge studies of less permeable substrate resulted in lower values. For example, the Eagle Ford Shale near Waco was measured to recharge 1% of precipitation (Harrison, 1996). The Evangeline and Chicot silts, sands, and clays near Houston recharged about 11% of precipitation (Noble et al., 1996).

Published recharge values (as % of precipitation) for the karstic Edwards Aquifer appears to be anomalously low when compared to other karst aquifers around the world (Figure 1). Are the processes and hydrogeology substantially different, or perhaps this anomaly reflects the tools and approaches used?

The purpose of this paper is to summarize previous water balance studies and to present new water balance studies that utilize different approaches and data sets. Results are then put into context and compared to other studies around the world.

Setting

The Edwards Aquifer is one of the most prolific aquifers in the world. The Barton Springs segment of the Edwards Aquifer is a federally designated sole source aquifer that supplies an estimated 60,000 people. Its major discharge springs, Barton and Cold Springs, are habitat for aquatic salamanders included the federally listed endangered *Eurycea sosorum* and *Eurycea waterlooensis*. The Edwards Aquifer is composed of Cretaceous aged Edwards Group limestone and overlying Georgetown limestone of the Washita Group, is underlain by the Trinity Group limestone and dolomite, and is overlain by confining units of clays, shales, limestone, and chalk of the Washita and Austin Groups.

Recharge to the Barton Springs occurs directly from precipitation falling over the 82 square mile recharge area that may become autogenic recharge:

Precipitation = evapotranspiration (ET) + upland intervening autogenic recharge + runoff

Only about 68 square miles of the recharge area is composed of Edwards Group outcrop, the remainder includes isolated or upslope outcrops of overlying confining units, particularly Del Rio Clay of the Washita Group. A portion of the autogenic recharge infiltrates in the upland intervening area between the major creeks (Slade et al., 1986), while a portion of the autogenic recharge infiltrates with the major creek channels. The major creek channels extend upstream into a 260 square mile Contributing Zone that provides allogenic recharge.

Figure 1. Compilation of various recharge studies from karst areas across the world.

% Recharge of PPT	Location	Aquifer, Basin, or Region	Source
18%	Tunisia	Bargou Aptial Ls	Zebidi, 1963
14-19.5%	Morocco	Plio-Plest.	Bolelli, 1951
15-20%	Barbados	Uplands	Jones et al., 2000
33%	Crimea, Ukraine		Dublyanskii et al., 1984
37%	Israel	Turonian/Cenomanian	Mandel & Shiftan, 1981
23-42%	Tunisia		Tixeront et al., 1951
41%	Syria	Damascus	Burdon, 1960
10-45%	Israel	W. Galilee	Goldschmidt, 1960
45%	Syria	Ghab basin	Voute, 1961
47%	Saudia Arabia		Hoetzl, 1995
16-49%	Tunisia		Tixeront et al., 1951
51%	Greece	Parnassos-Ghiona	Burdon and Papakis, 1961
52%	Greece	Lilaia	Aronis et al, 1961
53%	Israel	Na'aman Spr	Mero, 1958
54%	Mendip Hills, England	Carboniferous Ls	Atkinson, 1977
60%	Guam		Mink and Vacher, 1997
43-67%	Syria	Damascus	Al-Charide, 2012
67%	Guam		Jocson et al., 2002
36-91%	Tunisia	Eocene Ls	Schoeller, 1955

Previous Water Balance Studies

Throughout Central Texas, recharge to the Edwards Aquifer was most frequently measured by utilizing a water balance between gauged stream flow loss (upstream flow minus downstream flow) and gauged discharge (springs and pumpage). Gauging data collected by the US Geological Survey, analyzed and reported by Slade et al. (1986), was analyzed by Woodruff (1984) in the context of precipitation across the recharge and contributing area for the Barton Springs Segment of the Edwards Aquifer. This study reported that only 1% of precipitation recharged directly in upland intervening areas of the recharge zone and that 5% of precipitation recharged in the creek channels, 9% of precipitation ran off into the major creeks and flowed downstream of the recharge zone, and the remaining 85% of precipitation was released to the atmosphere through evapotranspiration. Woodruff (1984) referenced a test plot in San Antonio where even higher values of potential ET were measured. Put into perspective of total recharge the essential concept of 85% of recharge occurring in the major creek channels and only 15% in the intervening upland recharge zone was fairly universally accepted without debate for the next 20 years, and the insignificance attributed to upland intervening autogenic recharge set the stage for development practices of the 1980’s, including diverting urban stormwater into sinkholes, land application of wastewater over the recharge zone, and building over sinkholes and caves, many of which practices were later banned. During the 1980’s and early 1990’s two organized sewage collection systems relying on land application of effluent (Permit 11728-001 for Southwest Travis County MUD#1 in Shady Hollow and Travis Country MUD permit 11294-001) were permitted within the Barton Springs Segment until the early 1990’s. These facilities were later closed and the practice was not repeated in the recharge zone of the Barton Springs segment at this scale. However, the resulting impression that upland recharge is insignificant continues to the present. This is illustrated by the former Jeremiah Ventures development (now Hudson Ranch WQPL) that proposed a large-scale irrigation of effluent on the recharge zone. This tract and topic will be examined in the fieldtrip.

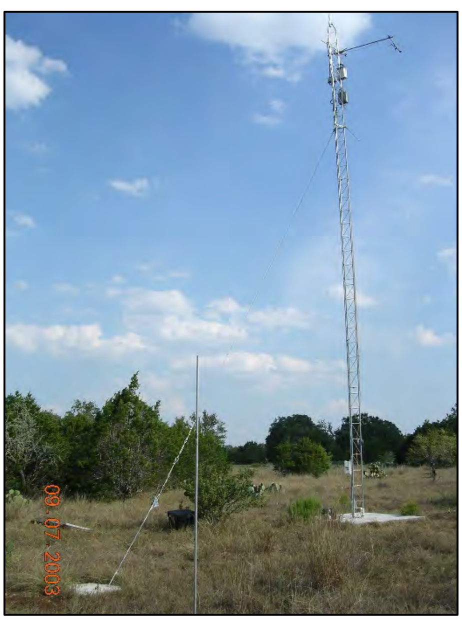
Results of Recent Water Balance Studies

Groundwater Tracing

The area contributing recharge to an aquifer is critical to the calculation of its water balance. Dye tracing is fundamental to groundwater basin delineation in a karst aquifer. Groundwater tracing began in 1996 and clarified fate of recharging surface water as well as providing valuable data on rates and direction of groundwater migration, which in turn, benefits water balance calculations for the aquifer. Successful long-distance tracing from Barton Creek showed that the entire portion of Barton Creek from which Slade et al., 1986 attributed 28% of the recharge budget to Barton Springs, does not actually flow to Barton Springs but instead flows to Cold Springs in Lady Bird Lake. This was verified with additional tracing under high- and low-discharge conditions such that Barton Creek is one of the most directly traced watersheds in the world (see associated tracing article). Calculations show that the groundwater basin assumptions used by Slade 1984; Slade et al., 1986 and Woodruff 1984 for Barton Creek alone accounted for unusually low upland source autogenic recharge values they obtained (Hauwert, 2009). In addition, recent dye studies have shown additional revisions to the groundwater basin. For example, Onion Creek flows to San Marcos Springs under non-drought conditions, and the Blanco River contributes flow to Barton Springs during drought conditions (Smith et al., 2012; Johnson et al., 2012).

Evapotranspiration

In 1998, Texas A&M researcher Dugas (and others, 1998) introduced a method for direct measurement of actual evapotranspiration and runoff components of precipitation at site scale to Central Texas, using new technological advances with a Bowen ratio ET flux tower. Dugas measured ET of 65% precipitation, runoff of 5% precipitation, and calculated that the remaining 30% of precipitation recharged the Trinity Aquifer. Hauwert (2009) presented a 1.4-year water balance from the J17 research site in Travis County that measured very similar values within a large internal drainage sinkhole basin over the Edwards Aquifer (Figure 2). Internal drainage basin sinkholes are analogous to large low sloping (<1 degree) permeable bathtubs with drains represented by terminal caves. The study utilized a 50-foot-tall eddy covariance ET flux tower, rain gauges, soil moisture sensors, and flumes to measure runoff. Precipitation and runoff was also measured in a second nearby large internal drainage sinkhole, Flint Ridge, for comparison.



Eddy covariance tower installed on CoA J17 WQPL as cooperative recharge study with University of Texas Department of Geosciences from 2002 to 2009. Measured parameter included precipitation, runoff, evapotranspiration, and soil moisture.

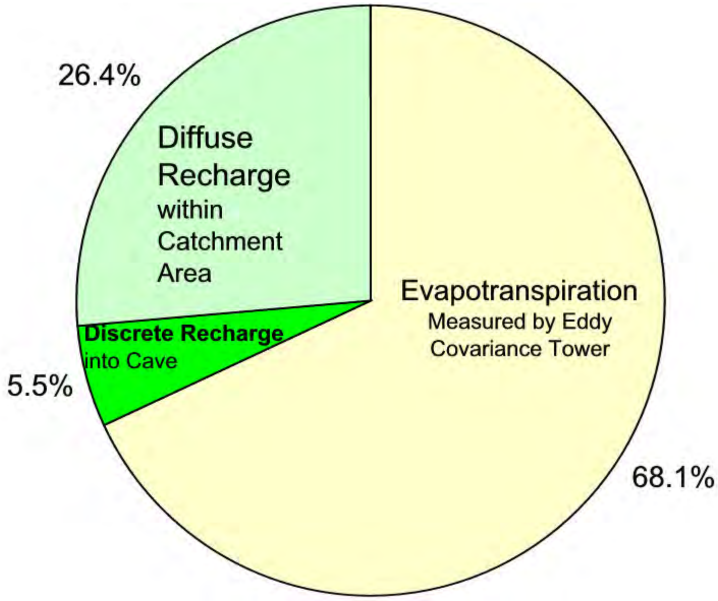


Figure 2. Water balance results from City of Austin J17 WQPL research site in Travis County utilized a 1.4-year water balance interval with 34% higher than a 158-year average precipitation of 33.5 inches calculated by Johns, 2015. (From Hauwert and Sharp, 2014)

This first direct measurement of recharge within microbasins of the Barton Springs Edwards Aquifer provided new information on upland autogenic recharge. These include:

- About 90% of all recharge within the HQ Flat Sink and Flint Ridge catchment basins on average occurred through the generally soil-covered slopes and not through the terminal cave drain. This finding is consistent with observations by Gunn (1983) that most recharge within large catchment New Zealand sinkholes occurred through the permeable soil-covered slopes rather than at the cave drain.

- The discrete runoff that entered the cave drains generated within the 46-acre (0.19 km^2) HQ Flat sinkhole catchment and approximately 60-acre Flint Ridge sinkhole catchment were 3% of precipitation during long-term average rainfall conditions, but exceeded half of precipitation during some events when soil moisture was relatively high from previous rain.

- It is expected that outside of an internal drainage basin, the 3% of precipitation may be representative of runoff from the recharge zone to the creeks.

- ET was relatively low during the rain events when infiltration was taking place.

- Internal drainage basins delineated across the Barton Springs Segment constituted about 10% of the recharge zone area.

For the J17 water balance interval, precipitation was 34% higher than a calculated long term average of 33.5 inches (85 cm) from 1856 to 2014 (David Johns, this guidebook). Furthermore, variability in infiltration, percolation, vegetation, and anthropogenic modifications can be expected from site to site. To examine variability across Central Texas during various rainfall conditions, ET climate tower data from various published reports were averaged on annual time steps (Figure 3).

Because this water balance method directly measures roughly 70% of the precipitation budget components, there is a much higher confidence at site scale than the 9% to roughly 20% of the precipitation budget measured at the aquifer-wide scale using stream flow losses.

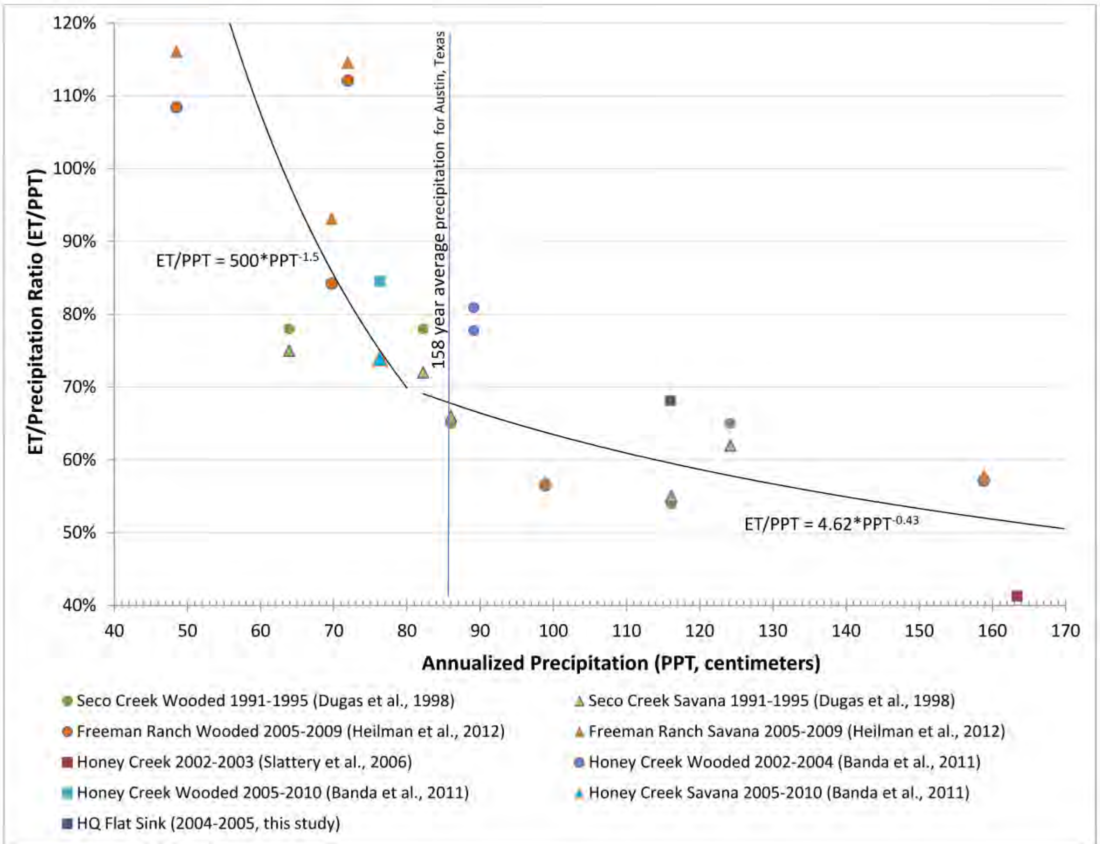


Figure 3. Compilation of annualized evapotranspiration values from Central Texas Bowen ratio and eddy covariance flux towers. The residual between ET values and 100% are primarily recharge values but also include runoff and any change in soil moisture storage. Values during higher than average precipitation show filling of soil moisture storage while lower than average rainfall values show depletion of soil moisture storage. (Modified from Hauwert and Sharp, 2014).

Stream loss

A stream flow loss water budget using 2003 to 2007 gauging data from upstream and downstream stations on the major creeks, including Little Bear Creek, was presented at the World Lake Conference on November 2, 2011, and is being prepared for publication. In 2003 (with funding from Texas Natural Resource Conservation Commission) the USGS, LCRA, City of Austin, and Barton Springs/Edwards Aquifer Conservation District installed continuous gauging stations on the downstream end of the recharge zone for all major creeks. This provided discharge and recharge data for every major creek for the first time. New sites included Barton Creek just upstream of Barton Springs pool and Little Bear Creek. Over a 1,573-day interval from May 31, 2003 to September 19, 2007, stream flow loss in the major creek sources to Barton Springs was compared to total discharge including USGS-reported Barton Springs discharge, well pumpage, and additional lower Barton Creek discharge (Hauwert, 2015, in preparation). This study excludes Cold Springs groundwater basin since its discharge cannot be directly or indirectly measured with high precision. The interval was selected based on identical starting and ending Barton Springs discharge and also has an average rainfall of 32.5 inches, slightly less than an annual average precipitation total of

33.4 inches (85 cm) from 1856 to 2002 by (David Johns of City of Austin). This period had average total discharge of 76 ft^3/s, close to long-term 1978 to 2012 average of 70 ft^3/s. The results of this study showed:

- The recharge sources comprised 33% Onion Creek, <11% Barton Creek downstream of Loop 360, 7% Slaughter Creek, 6% Bear Creek, 6% Blanco River, 3% Little Bear Creek, 1% Williamson Creek, and the remaining 33% to 44% of recharge is primarily originate from the intervening areas plus urban leakage, Trinity Aquifer leakage, saline water zone leakage, and potentially other sources.

- Further breaking down recharge sources, allogenic recharge from the contributing zone was measured from upstream gauging stations to be 39% to 50% of total discharge.

- The remaining 50% to 61% of the total discharge is derived from autogenic recharge sources and leakages sources such as urban leakage, saline water zone leakage, and Trinity leakage.

- The leakage contributions are more precisely measured by different methods, such as those used by Passarello (2011) of urban leakage (about 4% of total discharge), geochemical measurement of Saline Water Zone contribution (<1% of total discharge) by Hauwert, et al., 2004, and modeling of Trinity Aquifer contribution by Mace et al (2000, not specifically quantified for Barton Springs segment).

- Based on the stream flow loss water budget, of the direct rainfall over a 68-square-mile Edwards outcrop recharge area for Barton Springs 18% of precipitation flowed to the major creeks as runoff and downstream of the recharge zone without recharging, 18% infiltrated on the intervening area as recharge, 8% of precipitation recharged within the major creek channels, and 56% of precipitation was released as evapotranspiration.

Flow loss surveys taken along the length of the major creeks and Blanco River suggest that recharge in each is focused on a handful of swallets in each creek channel that have limited recharge capacity and may become intermittently plugged. Disturbance activity releases fine-grained sediment to the creeks that can have long-term effects of plugging creek swallets.

Upland intervening areas are relatively efficient in infiltrating precipitation, per catchment area because of (1) limited recharge capacity of major creeks (2) rapid infiltration of upland autogenic recharge during precipitation events when evapotranspiration is relatively low, and (3) the presence of internal drainage basins that capture most or all of runoff produced by large storms. Even though major creek channels have large catchment areas and recharge greater volume of water than uplands, their watersheds cannot be entirely protected like the surface catchment areas of upland internal drainage sinkholes.

A comparison of site-specific ET tower water balance with results from the stream flow loss study is shown in Table 1. Half of the total runoff in this calculation is from Onion Creek. During nearly all of the water balance interval the downstream Onion Creek gauging station was at a downstream site that included 15 square miles of overlying confining unit exposure and perennial springflow, which could result in overestimation of runoff and underestimation of evapotranspiration using the stream flow loss method applied.

Table 1. Comparison of Recharge Calculations using J17 research site and aquifer-wide stream flow loss. Note, the site scaled field measurements from multiple stations across Central Texas over multiple years involves considerably less potential error than other methods and is deemed most representative.

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

Chloride Mass Balance

A third recharge measurement involved mass balance of chloride in rainfall with chloride measured in a Barker Ranch Cave drip 20 feet below the surface (Hauwert, 2009). The underlying assumption in chloride mass balance is the rainfall chloride and discharge chloride is representative, that the enrichment in chloride is solely due to evapotranspiration and runoff is insignificant. Depending on whether the rainfall chloride is similar to that measured at the Attwater National Atmospheric Deposition Program station (average 0.64 mg/l chloride) or two local rainfall quality values (average 1.21 mg/l chloride), recharge values of 26% to 49% of precipitation were calculated for Barker Ranch Cave (average 2.46 mg/l chloride). The calculation for recharge using chloride is simply the ratio or precipitation concentrations and the groundwater concentration.

Discussion

Other researchers have recently presented data supporting the new values for upland recharge and evapotranspiration measured for the Barton Springs Segment. USGS study of Bexar County by Ockerman (2002) found that 44% of the recharge to the Edwards Aquifer originated from stream channel losses, and the remaining 56% originated as upland intervening portion of autogenic recharge. These compare to measured major creek channel recharge of 85% by Slade et al., 1986 and 56% to 67% by Hauwert for the Barton Springs Segment. Huang and Wilcox (2005) and Wilcox (2008) also noted large discrepancies between recharge values derived from stream-flow loss and evapotranspiration tower data and concluded that stream flow loss, as applied in Texas, has greatly underestimated upland intervening autogenic recharge. Actual evapotranspiration was estimated county by county across the United States by the USGS, using data from 1971 to 2000 (Sanford and Selnick, 2013). Travis and Hays counties were reported to have ET/precipitation ratios of 70% to 79% (as compared to an average of 68% measured by ET towers over the Edwards and Trinity aquifers). The Edwards Aquifer outcrop would be expected to have lower relative ET than the clay/shale, and marl that outcrop across large portions the counties. While modeling the Northern Segment of the Edwards Aquifer, Jones (2003) had to raise intervening autogenic recharge to 20% to match measured discharge values.

Slade (2014) argues why he believes the 1980s water budget is still valid and is the most accurate measurement of recharge. However, because of the potential error in any single measurement of recharge, it is critical to look for other methods for corroboration (Scanlon et al., 2002).

Conclusion

Recharge studies of the 1980's found low recharge values of less than 1% for upland intervening areas of the Barton Springs Edwards Aquifer, that were based on assumptions regarding groundwater basins underlying Barton Creek, that have since been revised based on dye-tracing studies. Based on the results of new recharge studies, autogenic recharge to the Edwards Aquifer is about 26-28% of precipitation. Upland intervening areas of the Edwards Aquifer are relatively efficient in infiltrating and percolating rainfall relative to its catchment area size. Eight percent of the precipitation over the Recharge Zone ran off the major creek channels to recharge as autogenic creek recharge. The total autogenic recharge and allogenic recharge sources each make up roughly half of the total discharge, coupled with some additional smaller leakage sources. Although runoff is focused to well-defined creeks, creek recharge is limited to a relatively small number of swallets with limited recharge capacity, which may become plugged, and consequently lose flow to downstream runoff if not maintained. The importance of protecting upland recharge sources includes identification and protection of upland karst features through geologic assessments. Although it is not possible to purchase and focus protection efforts on the entire recharge and contributing zones, protection of upland areas, particularly internal drainage basins as well as creeks of the recharge zone are justified. As of 2015, the City of Austin has acquired about 25% of the Barton Springs Recharge Zone as Water Quality Protection Lands and additional 6% is protected as Balcones Canyonlands Preserves and Parkland.

The most important conclusion of this work is that upland recharge values are potentially much higher previous (and some recent) studies have concluded. These have significant implications for the quality and quantity of source water recharging the aquifer and supplying water to wells and Barton Springs. These processes should be frequently evaluated with on-going studies and data collection that use a variety of approaches.

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Update on Groundwater Tracing of the Barton Springs Segment of the Edwards Aquifer, Austin Texas

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City of Austin Watershed Protection Department

Introduction

The Barton Springs Segment of the Edwards Aquifer (Barton Springs Segment) is a relatively small segment of the Edwards Aquifer of Central Texas, compared to the much larger San Antonio Segment and Edwards Plateau (Rose 1972). Early Texas geologists including Roemer (1849), Hill and Vaughn (1897), Taylor and Schoch (1922) and Guyton (1964) described the Edwards Aquifer as a conduit-driven system with rapid groundwater flow. Hill and Vaughn (1897) used the presence of aquatic salamanders to suggest that the aquifer was fairly well connected with conduits and bedding plane fissures. Meizner (1923) recognized that in some karst areas, cave streams exist that functioned as underground streams. Around the 1950's to 1970's, the perception of the karst aquifers nationwide began changing, perhaps in part because of Hubbert's (1940) classic description of porous media led hydrogeologists to believe this case applied to all aquifers (White, 2000; White 2007), or that it was shaped by the desire of early hydrogeologists to distinguish their scientific evaluations from the dousers who conceived groundwater flowing through underground streams in all aquifers (Hauwert, 2009, Appendix A).

Tracing of the Barton Springs segment was attempted by the US Geological Survey (USGS) from Barton Creek on December 31, 1981, but its lack of recovery at Barton Springs was interpreted to imply that the method of tracing used was "unreliable" (Senger and Kreitler, 1984) and would take many years to discharge. Slade et al., 1986 characterized the Barton Springs Edwards Aquifer as having high dispersion such that it would take years for recharge from Onion Creek (Alexander 1990) or a spill from proposed SH45SW (TxDOT, 1989) to discharge from Barton Springs.

At that time it was thought that the rapid change in flow observed at Barton Springs was created by artesian flow conditions and rapid water quality changes observed at Barton Springs had to come from nearby Barton Creek (Slade, 1984). However, dye tracing studies have provided new data and insight that have largely revised the previous (slow flow) conceptual models of the 1980s. The purpose of this paper is to provide and update and summary of the more than 40 dye traces that the author and others have conducted since 1996 to present.

Groundwater Tracing

Quinlan and Ray (1981) championed the application of groundwater tracing for delineating groundwater basins and source areas in Mammoth Cave National Park, Kentucky. In the 1980's a karst hydrogeologist from Tennessee, Albert Ogden, began conducting long distance traces around San Marcos Springs, bringing concepts used across the world for defining groundwater basins. In the early 1990's Quinlan presented his research at a well-attended Austin Geological Society meeting.

Since 1996, groundwater tracing of the Barton Springs Segment has revealed a new conceptual model of groundwater flow characteristics and source areas (Hauwert et al., 2004; Hunt et al., 2004; Smith et al., 2006; Hauwert, 2009; Hauwert, 2012; Johnson et al., 2012). Forty traces were conducted as "watershed phases" from

Barton, Williamson, Slaughter, Bear, Little Bear, Onion, and Blanco watersheds (Table 1). Of the forty traces conducted, 35 traces were recovered, an 88% success rate. The tracing distinguished three separate groundwater basins. The Manchaca and Sunset Valley groundwater basins comprise 82 square miles and discharge with varying mixtures at the four known Barton Springs (Main or Parthenia, Eliza, Old Mill, and Upper Barton Springs; Figure 1). The roughly12 square mile Cold Springs groundwater basin discharges at Cold Springs and other springs discharging nearby into the Colorado River. Each groundwater basin has one or two primary groundwater flow routes where flow is localized. Secondary or tertiary groundwater flow paths typically originate from stream swallets corresponding to stream flow loss or large sinkhole internal drainage basins, resembling veins in their flow contribution to primary flow routes (arteries). Groundwater flow rates of 5-7 miles per day are commonly observed from injections across the segment, but these flow rates diminish significantly during low discharge conditions to 1 mile per day or less. Hydraulic conductivity measured in the aquifer is highest in water-saturated caves associated with primary or secondary groundwater flow routes (Slade et al., 1986; Hauwert, 2009).

Tracing has shown that groundwater flow in the Barton Springs segment actually has a high component of advective (conduit) flow through caves and very low diffusion and dispersion as compared to porous media aquifers which are dominantly dispersion and diffusion. Peclet numbers, the ratio of advection to dispersion, measured from seven traces where sufficient breakthrough concentrations were measured, show that advection is about 1,000 to about 60,000 times dispersion as groundwater flows across the aquifer under average to high discharge conditions (Table 2). The very low dispersion and high advection are also indicated by the relatively rapid arrival of 35 out of 40 traces recovered (Table 1). While in most ways the tracing results were in stark contrast to many beliefs in the literature of the Edwards Aquifer from the 1970s and 1980s, the new results would not be surprising to early geologists as far back as the 1840s or compared to other karst aquifers around the world.

Tracing has revealed that some stream sources, like parts of Barton Creek, closest to the primary discharge site of Barton Springs, are outside its drainage basin (Figure 1), yet distant stream sources such as the Blanco River, may play a sustaining role during low discharge conditions (Figure 2). Groundwater flow from the western side of the Recharge Zone is generally perpendicular to faulting toward down-faulted blocks. In the confined zone and in the Recharge Zone within several miles of the discharge springs, groundwater tends to converge on a few primary groundwater flow routes that generally follow a few select fault trends northeast toward the discharge springs. A Saline-Flow Route is theorized to generally follow the edge of the fresh water and saline zones.

Local tracing from soil-covered areas and recharge features to underlying cave drips have provided a better understanding of transport through the soil and shallow vadose zone (Hauwert and Cowan, 2013). Direct chemical and dye tracing illuminate the influences of hydrostratigraphic unit characteristics, bedding dip, and/or down faulted blocks on vadose flow. Tracing through the soil to underlying cave drips 100 to 300 feet away within 3 to 48 hours suggests the soil and epikarst are relatively permeable and important groundwater reservoirs in contrast to published papers (Woodruff, 1984, Wilding and Dill, 2007, Wilding, 2007) that the Brackett soils over the Edwards Aquifer inhibit downward movement of water and strongly attenuate pollutants.

Tracing is a method to achieve greater understanding of aquifer characteristics that is recognized around the world. Advances in tracer detection techniques have also help advance the science. Tracing continues to be used in and around the Austin and Central Texas area to study local aquifers and groundwater flow.

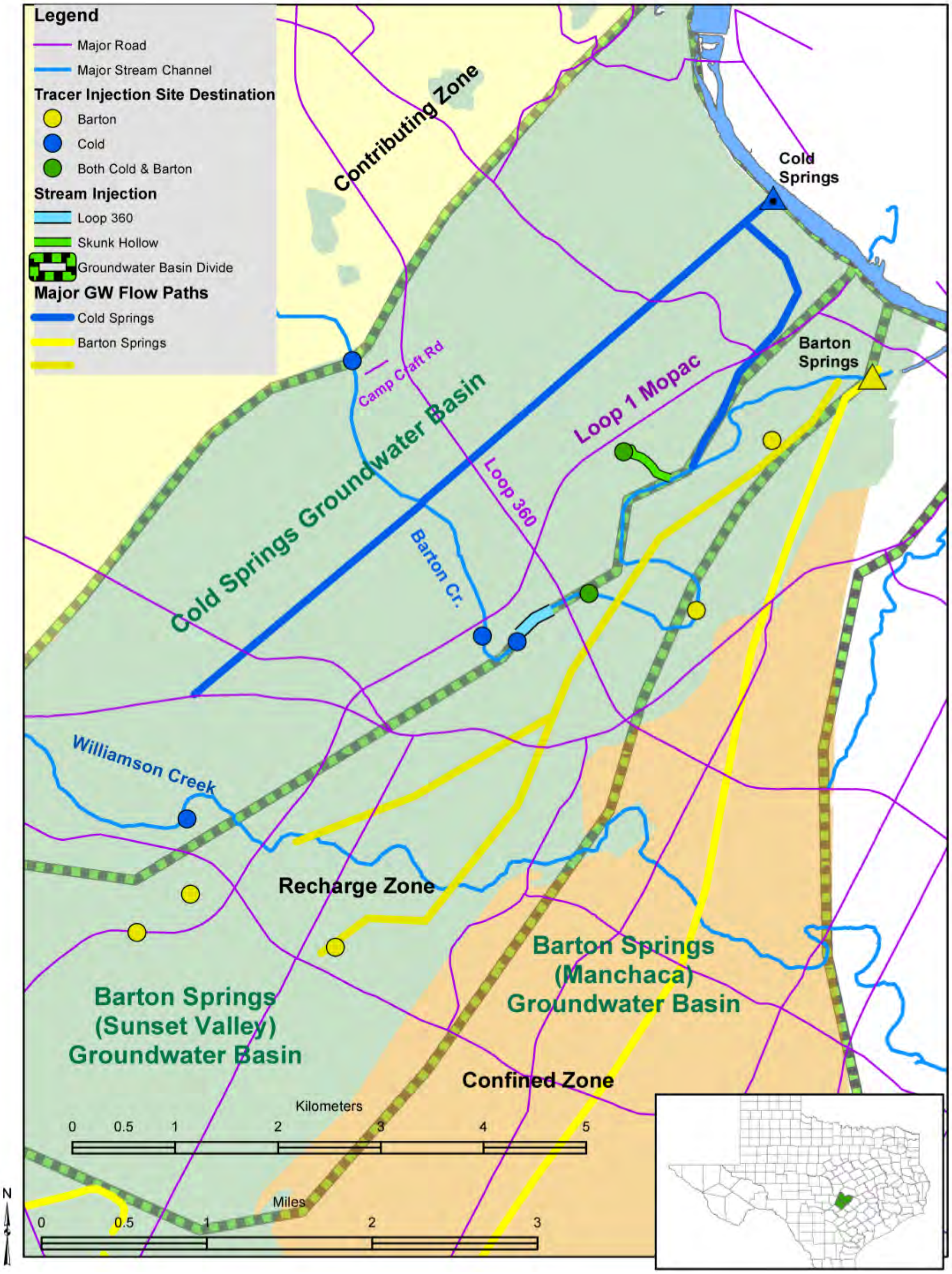

Figure 1. Summary map of groundwater dye tracer injection results used to define groundwater basins near Barton Springs. Note the Barton Creek site just downstream of Loop 1 Mopac was traced twice, under Barton Springs discharge of 18 and 107 ft3/s, which represents very low and very high flow conditions, yielding consistent results. This area is one of the most extensively traced in the world.

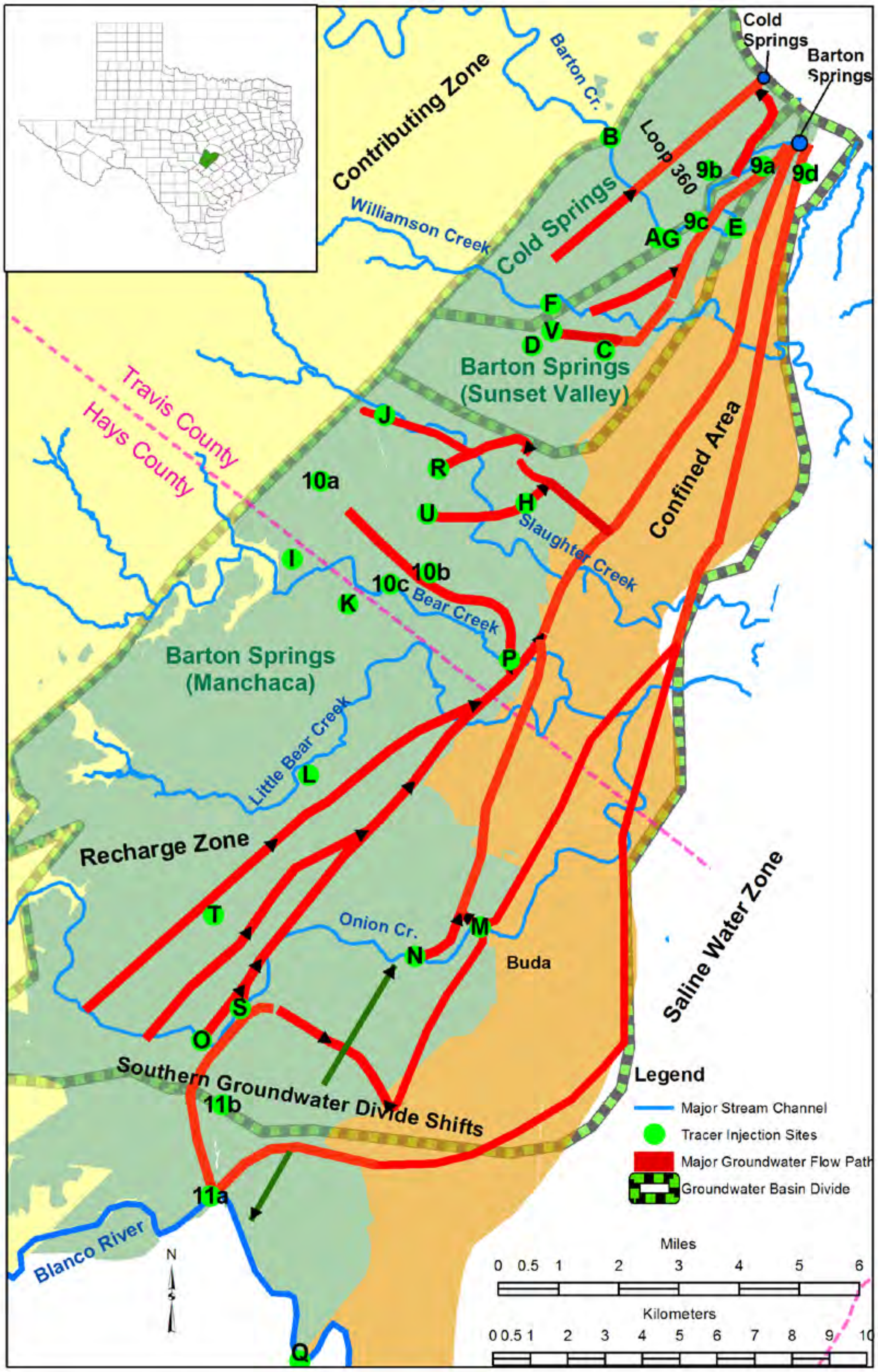

Figure 2. Injection Sites, Primary Groundwater Flow Paths, and Groundwater Divides Defined by Groundwater Tracing from 1996 to 2012 in Aquifer-Wide Traces Conducted by Barton Springs/Edwards Aquifer Conservation District and City of Austin, with EPA 319H Funding Administered through TCEQ and City of Austin Capital Improvement Project.

Table 1. Summary of Aquifer-Wide Groundwater Traces from 1996 to 2012

No.	Name	Inj. Date	BS flow (cfs)	Tracer	Tracer mass (lbs OUL mix)	Mass Recovery	Min Distance to Discharge	Days to first detection	Discharge Site
	PHASE I								
A	Mopac Bridge	8/13/1996	18	RWT	10	59%	3.4	5	Cold
B	Mt Bonnell Fault	8/13/1996	18	Fl	10	---	2.7	6	Cold
	PHASE II								
A'	Mopac Bridge	8/5/1997	107	Eosine	5	77%	3.4	0.79	Cold
C	Dry Fork Sink	6/17/1997	101	Fl	3	4.2%	4.8	<1.25	Barton
F	Brush Country	6/24/1997	110	RWT	10	---	5.3	<8	Cold
V	Arbor Trails	2/3/2012	60	Phloxine B	16.3	---	5.7	<4	Barton
	PHASE III								
H	Brodie Sink	4/27/1999	83	Eosine	7	7.4%	8.6	1-2	Barton
J	Midnight Cave	4/27/1999	83	RWT	5	16.6%	11	7-8	Barton
D	Whirlpool Cave	6/16/1999	68	Eosine	5	0.07%	5.6	3-4	Barton
E	Westhill Drive	6/16/1999	68	SRB	2	7%	2	0.4	Barton
	PHASE IV								
I	Hobbit Hole	9/28/1999	37	Fl	5	0%	not recovered		
K	Spillar Ranch	9/28/1999	37	RWT	10	0.0002%	1.3	22-28	well 58-50-742
L	Dahlstrom Cave	9/28/1999	37	Eosine	10	0.7%	14.9	21	Barton
	PHASE V								
M	Antioch Cave	3/28/2000	26	RWT	20	<0.0001%	3.3	8-22	well 58-58-128
N	Barber Falls	3/29/2000	26	Fl	10	0.04%	15.7	14-16	Barton
P	Marbridge Sink	3/28/2000	26	Eosine	20	<0.001%	11	36-43	Barton
	PHASE VI								
G	Loop 360	6/23/2000	61	Pyranine	5	1.1%	3.3	<2	Cold
Q	Tarbutton Cave	8/3-5/2000	29	Fl	15	0%	not recovered		
O	Crooked Oak	8/12/2000	28	Eosine	25	13%	18.6	23	Barton
R	Recharge Sink	10/6/2000	24	SRB	12	0%	not recovered		
M'	Antioch Cave	11/21/2000	81	RWT	24	<0.001%	recovered only in wells		
	PHASE VII								
M"	Antioch Cave	8/2/2002	98	Fl	25	80%	14	7.1	Barton
S	Crippled Crawfish	8/6/2002	99	Eosine	35	1%	17.5	3.5	Barton
	PHASE VIII								
T	Hoskins Hole	5/4/2005	104	SRB	35	0.0%	Not Recovered		
S'	Crippled Crawfish	5/4/2005	104	Eosine	35	5.2%	17.5	2.4	Barton/San Marcos
U	HQ Flat Cave	5/5/2005	103	RWT	30	41.7%	9.5	4.1	Barton
K'	Spillar Ranch Sink	5/5/2005	103	Fl	20	10.5%	11.5	3.3	Barton
	PHASE IX								
9a	Barton Hills Trib	3/1/2006	31	Fl	10	<0.001%	0.7	NC	Barton
9b	Skunk Hollow	3/3/2006	31	RWT	25	<0.001%	1.9	NC	Cold/Barton
9c	Seismic Wall	3/6/2006	31	Eosine	50	<0.001%	2.8	NC	Cold/Barton
9d	Frech well	3/30/2006	31	SRB		0.0%	not recovered	NC	
	PHASE X								
10a	Hangtree	4/10/2007	96	Eosine	30	<4%	14	3-4	Barton
10b	Sandbur	4/11/2007	96	RWT	45	4%	11	2.7	Barton
10c	Bear Creek Tabor	5/1/2007	96	Fl	5	45%	12	2	Barton
10d	Wildflower Cave	4/9/2007	96	SRB	30	22%	10	2.5	Barton
10d'	Wildflower Cave	5/24/2010	98	SRB	33.5	5%	10	17.7	Barton
	PHASE XI Blanco River								
11b	Bull Pasture	6/10/2008	31	Fl	40	<0.001%	19	106-113	Barton
11a	Halifax Mouth	5/20/2008	38	eosine	0.275	0%		not recov.	insuff mass
11a	Halifax Mouth	6/10/2008	31	eosine	40	<0.001%	21	background	BS/SM
11a	Halifax Mouth	9/12/2008	25	eosine	17.5	<0.001%	21	82-122	BS/SM
11a	Johnson Swallet	2/26/2009	19	eosine	70	<0.001%	21	36-78	BS/SM

Nc= not calculated

Table 2. Calculation of Groundwater Transport Properties from Seven Groundwater Traces. Results from Hauwert, 2009 and Hauwert, 2012.

Injection Site	Injection Date	Barton Springs Flow (USGS) (m3/s)	Distance to Barton Springs (km)	Dye	Mass (kg)	Initial Detection at Barton Springs (days)	Mean Residence Time (days)	Mean Tracer Velocity (km/days)	Time to Peak (days)	Recovery (%)	Peclet number
K	5/5/05	2.94	19	Fl	9.1	3.28	4.35	4.36	4.45	15	3,882
S	5/4/05	2.92	29	E	15.9	2.38	1.97	14.74	2.54	7	21,008
U	5/5/05	2.94	17	RWT	13.6	4.13	5.42	3.1	4.79	27	16,231
E	6/16/99	1.92	2.6	SRB	0.9	0.42	0.85	3.07	0.63	13	1,314
10B	4/11/07	2.72	18	RWT	20.4	2.9	4.7	3.77	2.9	4	60,520
10C	5/1/07	2.72	19	Fl	2.3	2	5	3.86	2.6	45	2,832
10D	4/9/07	2.72	16	SRB	13.6	2.5	8.1	1.99	3	22	4,225

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Recharge Enhancement at Antioch Cave, Onion Creek

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Antioch cave is the largest capacity discrete recharge feature to the Barton Springs Segment of the Edwards aquifer. Some estimates put the amount of recharge the cave is able to accept at over 100 cubic feet per second. The cave is located just over a mile west of Buda, Texas in the bed of Onion Creek at the eastern edge of the Edwards Aquifer recharge zone (Figure 1). Dye tracer studies carried out at the site reveal that during high-flow conditions in the creek, groundwater travels north-northeast and can reach Barton Springs in a matter of 7-8 days, a distance of about 17 miles.

Antioch cave forms a 50-ft vertical shaft that penetrates the Georgetown limestone outcropping in Onion creek and goes into the uppermost units of the Edwards Group limestones, located about 30 ft down from the entrance. At about 40 ft depth, there is a horizontal passage just large enough for a person to crawl into on their stomach. This passage that trends west-northwest (Figures 2 and 3). Approximately 80 feet from the cave shaft, the horizontal passage splits into two branches, a west branch and a north branch that each continue for another 100 ft or so before becoming too narrow to enter.

In 1997 a concrete vault with an automated valve was constructed over the entrance to Antioch Cave as part of an EPA and TCEQ-funded recharge enhancement project in an effort to prevent storm waters from going into the cave, during times when the concentration of sediment, bacteria, and other contaminants is high (Figure 4). The structure was improved (added intake valve and screen, automation) in 2010. Water quality sensors now measure turbidity levels and automatically close the cave vault valve when the most turbid waters from a storm pulse are flowing through the creek, and reopen the valve when water turbidity drops below 50 NTUs. The effect of the valve is twofold in that it improves the quality of water entering the aquifer and also improves the quantity of water over the long-term by preventing the cave entrance from becoming clogged by debris and sediment.

Smith et al. (2010) carried out a study between fall 2009 and summer 2010 and quantified the amount (in pounds) of contaminants prevented from entering the aquifer over the course of 5 storm events. Over the course of the study, 190,480 lbs of total suspended solids, 295 lbs of phosphorous, and 2,346 pounds of nitrates and nitrites were prevented from entering Antioch cave and thus contaminating groundwater supply (Figure 5).

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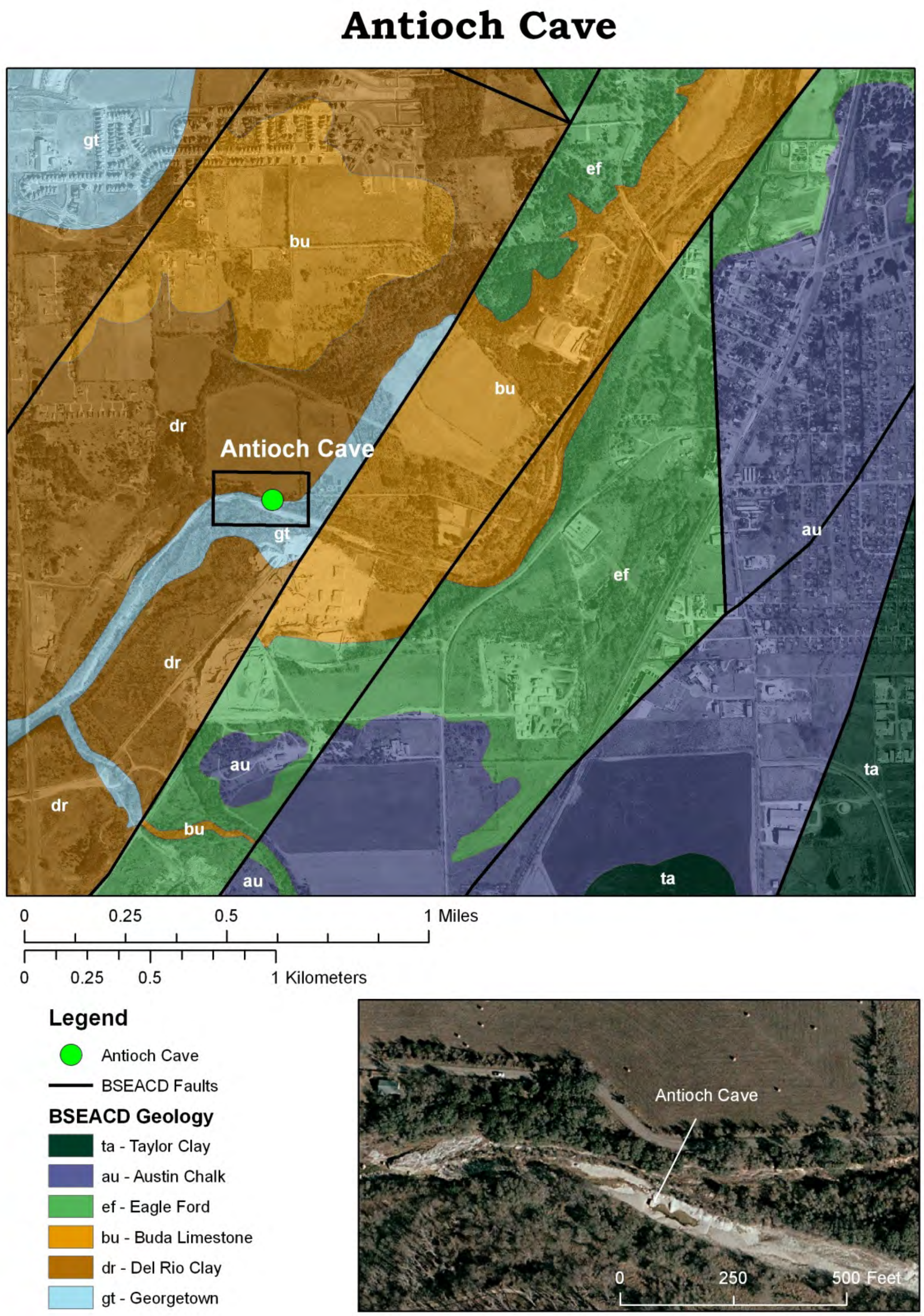


Figure 1. Geologic map of area near Onion creek at Antioch cave. The cave is on property owned by the Barton Springs/Edwards Aquifer Conservation District.

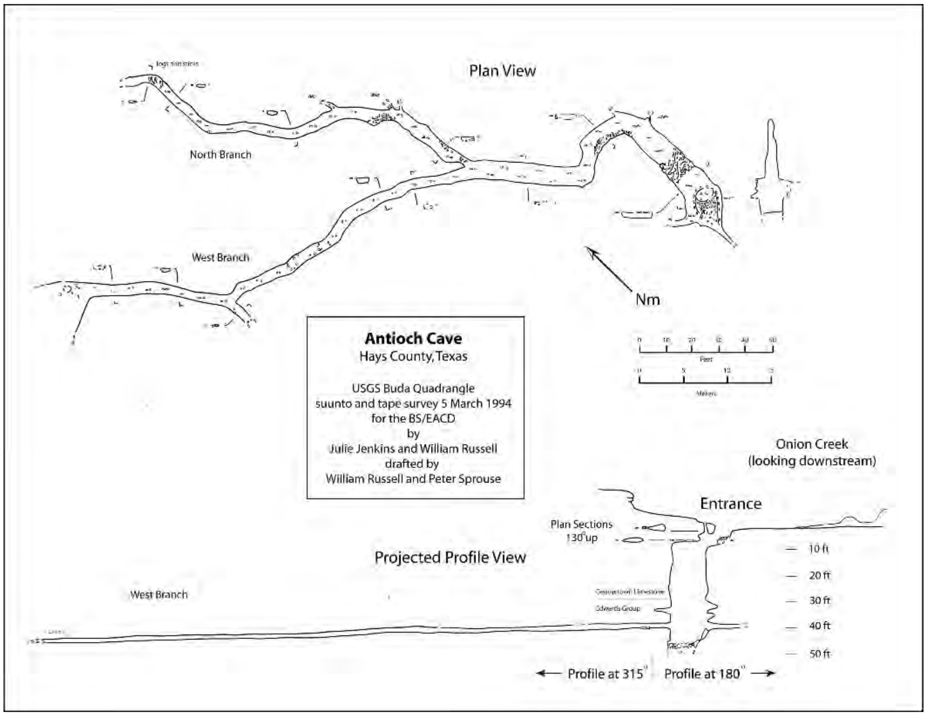
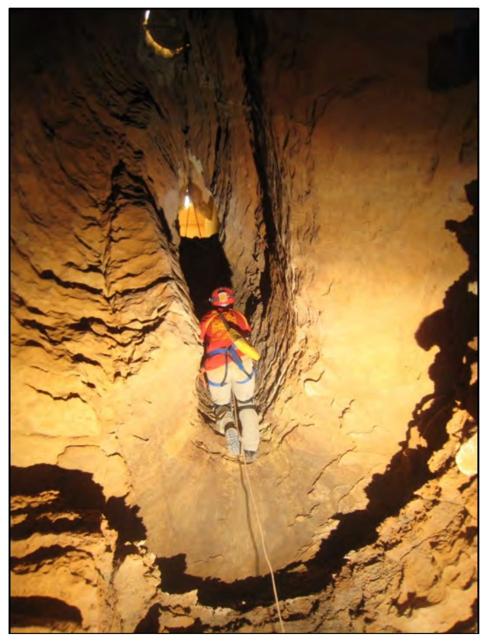


Figure 2. Antioch Cave Map

A.



B.

Figure 3. A) Photograph ca. 1996 showing recharge and the entrance to Antioch Cave before the BMP was constructed. The debris over the entrance and also sedimentation within the cave decrease the amount of recharge entering the cave. Photograph by Ron Fieseler. B) Figure 3. Caver rappelling into entrance pit of Antioch Cave ca. 2010. Vault and air vent are visible above main shaft. Photo by Peter Sprouse.

Figure 4. Onion Creek at Antioch cave vault during low-flow conditions.

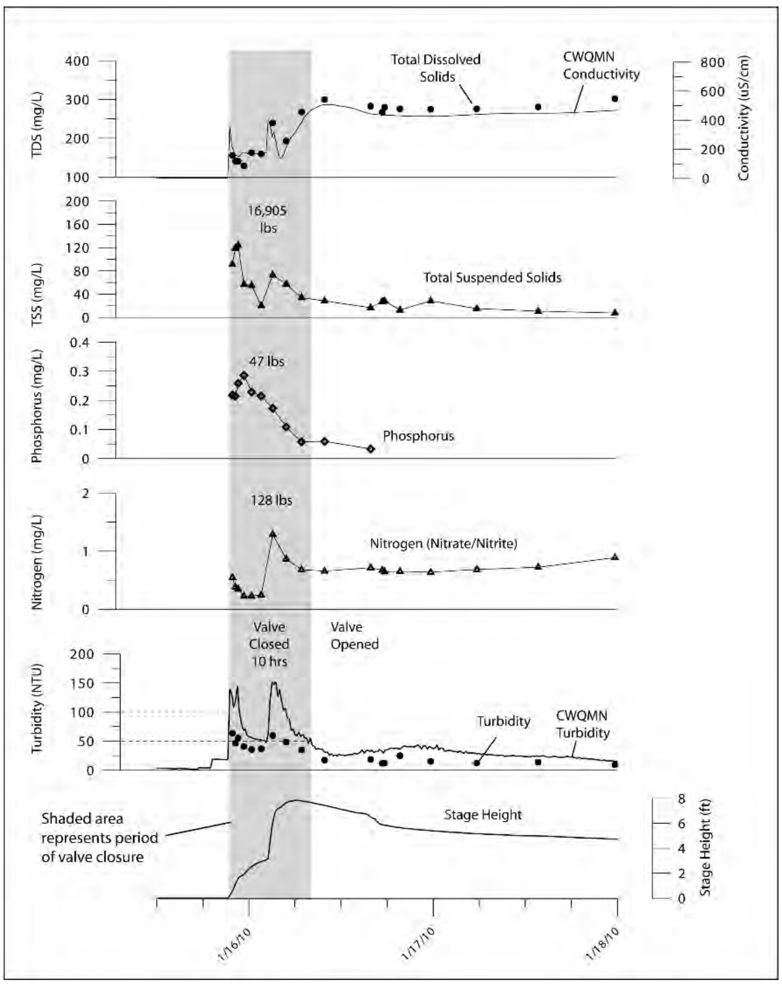


Figure 5. Water Quality and laboratory analytical data for a storm in January 2010, showing Total Dissolved, Total Suspended Solids, Phosphorous, Nitrogen, Turbidity, and Onion Creek stage height at various points during the storm hydrograph and at which times the automatic valve on Antioch Cave was open and closed.

Recharge-discharge water budget based recharge rates for the Barton Springs segment of the Edwards aquifer

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Method to calculate recharge volumes

A method of estimating surface recharge to the Edwards aquifer was first introduced by the U.S. Geological Survey (USGS) and published by Garza (1962). Recharge consists of the infiltration of streamflow plus direct infiltration of runoff in the interstream (recharge) areas. The approach of estimating recharge in each stream basin is presented in the form of a water-balance equation, in which the recharge value within a stream basin is attributed to the difference between gaged streamflow upstream and downstream from the recharge area, plus the estimated runoff in the intervening area. The intervening area is the drainage area within the recharge area between the two streamflow-gaging stations in each stream basin. Runoff from the recharge area is estimated on the basis of unit runoff from the area upstream from the recharge area. Such an assumption is deemed reasonable because the land slopes, soil and vegetation type and extent, and precipitation characteristics generally are similar in both areas. Estimates of monthly recharge during periods of high runoff probably contain major errors (Puente, 1978). Other sources of recharge such as cross formational flow from the Trinity, and urban leakage are not considered significant.

The basic equation for computing monthly recharge is as follows:
$R = Q_u + SI - Q_d$

where R is monthly recharge volume; Q_U is the monthly flow volume at the upstream gaging station; SI is the estimated monthly runoff volume (including infiltration) resulting from precipitation in the intervening (recharge) area; and, Q_d is the monthly flow volume at the downstream gaging station.

For the Barton Springs segment of the Edwards aquifer, streamflow-gaging stations exist upstream and downstream for all, except one, of the six major streams crossing the recharge area. Because of the relatively small contributing area for Little Bear Creek (about 3.3 mi^2), a streamflow station was not installed at the upstream boundary of its recharge area. Therefore, recharge rates can be calculated for each basin and for the total Barton Springs segment of the aquifer. Additionally, based on the streamflow station data and streamflow gain-loss studies that were conducted on each stream, the rate of recharge that occurs on each main streambed for each of the six creeks can be calculated. The interstream recharge (that outside the main channels) thus is calculated as the total recharge minus that in the main channels. Based on the precipitation on the recharge area, the interstream recharge volume thus can be expressed as a percent of precipitation.

Discharge from the Edwards aquifer

Discharge from the aquifer represents five sources--the identification and long-term mean discharge for each source is identified below.

Barton Springs and Withdrawals

The long-term (1917-2013) mean discharge from Barton Springs is 54 ft^3/s. The mean discharge is based on daily-mean gaged discharges from 1978 to 2013 and on 725 instantaneous discharge measurements made from 1917 to 1978. Details for the calculations are presented by Slade et al. (1986, p. 67-72).

A limited discharge of intermittent springflow occurs in the reach of Barton Creek immediately upstream from Barton Springs. Such springflow varies from zero when groundwater levels are below the streambed, to about 5 ft^3/s when local groundwater levels above the streambed. When Barton Springs discharges 54 ft^3/s (its long-term mean), the springflow from the streambed is about 0.8 ft^3/s (Slade, 2014, figure 3, p.18).

Monthly-mean groundwater withdrawals from 1917-2013 were provided by the Barton Springs Edwards Aquifer Conservation District (BSEACD, written commun.). The vast majority of pumpage is metered, thus withdrawal rates are considered to have minimal potential error. Privately-owned wells are not metered but their pumpage volumes are estimated. Based on these data, the 1917-2013 mean total pumpage is 2.7 ft^3/s. Some of the withdrawal volumes likely are lost as leakage from transmission pipes, ineffective irrigation, or effluent discharges, but the vast majority of such losses are considered to have an ultimate fate as evapotranspiration and some portion as recharge (over the recharge zone). Therefore, only a minimal amount of pumpage is deemed to be lost as recharge to the Edwards aquifer, thus gross withdrawal volumes are represented as discharge for the water budget.

Other Discharges

Cold Springs is located on the southern bank of the Colorado River, about a mile northwest of Barton Springs (Slade, 2014, figure 2, p. 15). Its recharge source probably represents Dry Creek, a small creek north of Barton Creek, and part of the flow in Barton Creek. Based on 11 discharge measurements, the mean discharge for Cold Springs is 6.48 ft3/s. Some of the springflow is known to discharge below the normal level of Lady Bird Lake, built in 1960--measurements made during such conditions were excluded from the calculation of the mean springflow value. The discharge for Barton Springs was estimated for each of the measurement dates for Cold Springs. The mean discharge of Barton Springs for the dates of the 11 measurements is 41.5 ft3/s, which is 77 percent of its long-term mean discharge of 54 ft3/s. The assumption was made that the mean measured discharge for Cold Springs (6.48 ft3/s) also is 77 percent of its long-term mean discharge. Based on this assumption, the long-term mean discharge for Cold Springs is estimated to be 8.4 ft3/s (Slade, in review).

A limited amount of outflow is believed to discharge the Edwards aquifer as seeps or springflow into Lady Bird Lake (the Colorado River) adjacent to the northern boundary of the aquifer (figure 1). Prior to the construction of the dam forming the lake, two streamflow gain loss studies conducted by the USGS documented the unaccountable streamflow gains to represent 0.4 ft3/s and 1.0 ft3/s. These gains could result from: groundwater discharge through terrace deposits along the river; groundwater discharge from the north side of the river; or surficial runoff outside the Edwards Aquifer. Also, it is possible that no streamflow gain occurred due to potential error in the streamflow measurements. However, even if both gains represent discharges from the Barton Springs part of the Edwards aquifer, their discharge are minor compared to other discharges from the aquifer. For purposes of documenting such discharges from the aquifer, the assumption is made that the mean discharge from the Colorado River bank is 0.7 ft3/s, the mean value for the two streamflow gain studies. Additional information and references regarding this analysis is reported by Slade (2014, p. 17-18).

Based on the five sources for discharge documented above, the total mean discharge from the aquifer calculates to be 67 ft3/s. The long-term mean recharge rate is assumed to be equivalent to this value.

Water budgets based on U.S. Geological Survey methods

The first recharge-discharge water budget for the Barton Springs segment of the Edwards aquifer was published as a U.S. Geological Survey report by Slade et al. (1986, p. 73-76) and later verified and slightly refined by Slade (2014, p. 18). The budget represents the period December 1, 1979 through July 31, 1982, is based on recharge calculations as described above and on discharges from Barton Springs and withdrawals. Based on the budget, the recharge volume exceeded the discharge volume by 3.3 percent (Slade, 2014, p.18). Interstream recharge as a percent of precipitation on the recharge area calculated to represented 6.6 percent of precipitation (table 1).

Based on the recharge calculation method described earlier, the recharge volume was calculated for a recent long-term period (Slade, in review). The new water budget period represents the six-year period November 1, 2003 through October 31, 2009. The total mean recharge calculates to be 69.1 ft^3/s. Aquifer discharge during the same period is summarized below:

- The mean discharge from Barton Springs during the period is 54.8 ft^3/s.
- The mean withdrawal from the aquifer during the period is 7.8 ft^3/s (BSEACD, 2014, written commun.).
- During the period, a mean springflow of about 0.8 ft^3/s discharged from the reach of Barton Creek immediately upstream from Barton springs (Slade, 2014, p. 17-18).
- Discharge from the aquifer to Lady Bird Lake was assumed to represent 0.7 ft^3/s during the period.
- Finally, the discharge from Cold Springs was assumed to represent its long-term mean value of 8.4 ft^3/s (Slade, in review).

Therefore, the total discharge for the budget period has a mean value of 72.5 ft^3/s, a value that exceeded the calculated recharge by 5 percent. This error is within the margin of error of the data used for the calculations. Interstream recharge as a percent of precipitation on the recharge area calculates to represent 9 percent of precipitation (table 1).

Other recharge-discharge water budgets for the aquifer

Five partial or complete recharge-discharge water budgets have been identified for the Barton Springs segment of the Edwards aquifer (table 1). However, only two of the budgets (Slade et al. 1986 & 2014 and Slade (in review) independently document and compare recharge and discharge volumes.

Budget for 2003 to 2007

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

Hauwert's (2011) approach assumes the difference between the total main channel recharge volume and the total discharge volume (Barton Springs discharge and gross withdrawals) to represent the interstream recharge volume. However, as demonstrated above, main channel recharge volumes as calculated by Hauwert (2011) likely are erroneous, as would be the values for interstream recharge. Additionally, the total recharge volume is not calculated independently from discharge volume and Hauwert could not compare the recharge volume to the total discharge volume for verification of a budget balance.

Budget for 2004 to 2005

Hauwert and Sharp (2014) present a short-duration budget for a small closed basin (0.07 mi^2) within the recharge area but closed to runoff from other portions of the recharge area. Evapotranspiration is measured directly via flux tower instrumentation within the basin. Because the small basin is closed to runoff from the basin, interstream recharge is calculated as the difference between the volume of precipitation on the basin and the volume of evapotranspiration from the basin. Based on these calculations, evapotranspiration represents 68 percent of precipitation and interstream recharge was thus deemed to be 32 percent of precipitation (table 5).

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

Also, the budget represents an extremely "wet" period during which time discharge from Barton Springs plus withdrawals equaled 166 percent of its long-term mean value (table 5). Therefore, for the budget period, recharge as a percent of precipitation would logically be much greater than its long-term mean value, and evapotranspiration would be much less than its long-term mean value. Additionally, the budget period is short--less than 17 months.

Hauwert and Sharp (2014) conclude that "Based on compilation of ET data from other flux towers in Central Texas under a wide variety of annual precipitation conditions, it can be estimated that under average precipitation conditions, 69% of rainfall leaves as ET; 28% of rainfall percolates as autogenic recharge into the Edwards Aquifer." The flux tower study nearest to the Barton Springs watershed was conducted for the Edwards aquifer on the Freeman Ranch near San Marcos (Hays County). However, for the Freeman Ranch study, , ET was found to be 92% of precipitation thus limiting recharge to 8 percent of precipitation (Heilman and others, 2009).

The only ET discussed in the text by Hauwert and Sharp (2014) was conducted by Dugas et al. (1998), however, many problems raise questions that the results of that water-budget study to be of little, if any, relevance to the Barton Spring Edwards aquifer area. For example, the Dugas et al. (1998) study was conducted on the Trinity aquifer rather than on the Edwards aquifer. Additionally, the Dugas study was on the Seco Creek basin in Uvalde county which is of considerable distance from the Barton Springs study area--the annual-mean precipitation in the Uvalde study area is only 22 percent of that in the Barton Springs Edwards aquifer area. Also, ET data were not collected during the Dugas et al. (1998) study for the months of November through February, nor were they subsequently estimated. Finally, Wilcox (2008) states "According to USGS streamflow measurements for the same years as the Dugas et al, 1998 study, Seco Creek streamflow makes up 20% of the water budget; therefore on the basis of the water budget method, evapotranspiration would constitute around 80%, a figure 15% higher than that (65%) derived by Dugas et al, (1998)."

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

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

1. Based on long-term precipitation data from the National Weather Service gage in Austin, the annual-mean precipitation is about 33 inches per year, as documented online at http://www.weather.gov/climate/xmacis.php?wfo=ewx
2. Thirty-three inches of annual-mean precipitation over the 90 square-mile recharge area produces a precipitation volume of 158,400 acre feet per year.
3. Applying 28 percent of that precipitation as interstream recharge produces 44,400 acre feet per year, a value equivalent to 61 ft3/s.

As shown in table 5, Hauwert (2011) concludes that 56 to 67 percent of total recharge occurs on the main channels of the major streams; Slade (1986 & 2014) indicate 75 percent of total recharge to occur on the main channels; and Slade (in review) documents 74 percent of total recharge to occur on the main channels. Based on these reports, interstream recharge (61 ft3/s as referenced above) thus ranges from 25 to 44 percent of total recharge. Therefore, based on Hauwert and Sharp's (2014) interstream recharge rate of 28 percent of precipitation, long-term total mean recharge would represent a range of 139 ft3/s to 244 ft3/s. However, as documented earlier in this report, the long-term (1917-2013) mean discharge (and thus recharge) for the Barton Springs segment of the Edwards aquifer is 67 ft3/s. Accordingly, an interstream recharge rate of 28 percent of precipitation produces recharge values that range from 207 percent to 364 percent of the documented long-term mean recharge value.

This same type of analysis documents that interstream recharge as 15 percent of precipitation, as shown in the Hauwert 2011 budget (table 1), also would produce total long-term recharge volumes much greater than documented.

Because the long-term mean recharge and recharge contributed by the major streambeds is known, the long-term mean interstream recharge to the aquifer can be calculated and expressed as a percent of mean-annual precipitation on the recharge area. Table 1 documents recharge on the main channels as a percent of total recharge. Based on the three studies with such values, 70 percent represents the mean value for main channel recharge as a percent of total recharge. Therefore, 30 percent of total recharge occurs as interstream recharge. As documented earlier, the long-term mean discharge from the aquifer is 67 cubic feet per second, as is the long-term mean recharge. Therefore, interstream recharge calculates to be 20 cubic feet per second or 14,500 acre feet per year. Interstream recharge thus represents 0.25 feet of depth over the recharge area of 90 square miles (57,600 acres). Based on the mean-annual precipitation value of 33 inches (2.75 feet) per year over the recharge area, interstream recharge thus calculates to be 9 percent of precipitation. As table 5 shows, 9 percent of interstream recharge as a percent of precipitation on the recharge area represents a value much less than those produced by Hauwert (2011) and Hauwert and Sharp (2014).

Table 1. Summary of water budgets conducted on the Barton Springs part of the Edwards aquifer. NA--Not applicable; NR--Not reported

Water Budget Study	Portion of recharge area used as basis for budget	Budget Period	Budget duration (years)	Percent recharge exceeds or less than (-) discharge (%)	Mean discharge as percent of long-term mean [1]
Woodruff (1984)	entire area	7/1979 - 12/1982	3.5	NA	110%
Slade (1986 & 2014)	entire area	12/1979 - 7/1982	2.7	3.3% [2]	112%
Hauwert (2011) [3]	most area	5/31/2003 - 9/19/2007	4.3	NR	128%
Hauwert & Sharp (2014) [4]	0.07 mi^2	4/2/2004 - 8/20/2005	1.4	NA	166%
Slade (in review)	entire area	11/1/2003-10/31/2009	6	-5.00%	110%

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

Water Budget Study	Fate of precipitation on recharge area as percent of such precipitation				Percent of total recharge from contributing area
	Interstream recharge	Main channel recharge	Runoff from recharge area	Evapo-transpiration	
Woodruff (1984)	NA	NA	NA	NA	NA
Slade (1986 &2014)	6.60%	NR [6]	NR [6]	NR [7]	NR [6]
Hauwert (2011)	15%	7% [6]	15% [6]	63% [7]	39-50% [6]
Hauwert & Sharp (2014) [4]	32%	0	0	68%	NA
Slade (in review)	9%	4 [8]	17% [9]	70% [9]	64% [9]

[1] Based on 1917-2013 mean discharge of 57 ft3/s for Barton Springs plus withdrawals
[2] Based on Cold Springs mean discharge of 5.5 ft3/s (Slade, 2014 p. 15)
[3] Excludes the "Cold Springs basin" thus represents only 82 mi^2 recharge area rather than 90 mi2
[4] Based on small closed basin (0.07 mi^2) within the 90 square mile recharge area
[5] Recharge loss to Trinity aquifer in contributing area not included--probably about 3 to 4 percent of precipitation on contributing and recharge areas
[6] Data do not exist to calculate values for source (contributing area or recharge area) of main channel recharge, runoff from recharge area, or recharge from contributing area.
[7] Without directly measured ET data at sites representative of recharge area, its value must be calculated as residual of recharge area water budget: ET = precipitation - recharge - runoff. However, 2 components of budget (total recharge within recharge area and runoff from recharge area) are unknown. See footnote 6.
[8] Estimated as explained in section "Recharge volumes in the main channels of the major streams"
[9] Based on estimation of main channel recharge

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