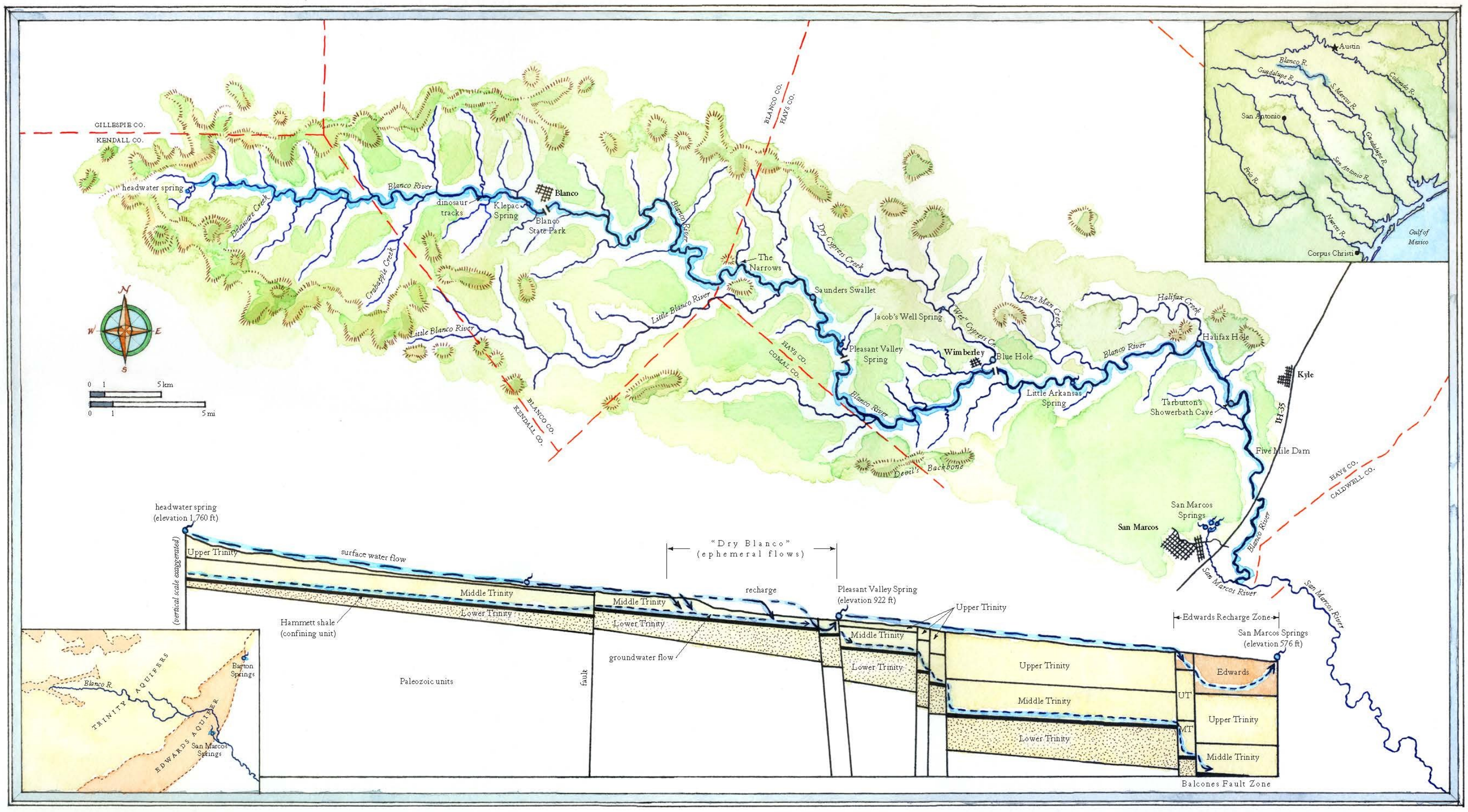
Bulletin of the

South Texas Geological Society

Volume LVII

5 Issue Number Five January 2017



INSIDE THIS ISSUE

Surface-water and Groundwater Interactions in the Blanco River and Onion Creek Watersheds: Implications for the Trinity and Edwards Aquifers of Central Texas

Brian B. Hunt, et al.

Technical Article

Surface-water and Groundwater Interactions in the Blanco River and Onion Creek Watersheds: Implications for the Trinity and Edwards Aquifers of Central Texas

Brian B. Hunt[1], Brian A. Smith[1], Marcus O. Gary[2], Alex S. Broun[3], Douglas A. Wierman[4], Jeff Watson[3], and David Johns[5]

(1) Barton Springs/Edwards Aquifer Conservation District, 1124 Regal Row, Austin, TX 78748,
(2) Edwards Aquifer Authority, 900 E. Quincy, San Antonio, TX 78215,
(3) Hays-Trinity Groundwater Conservation District, PO Box 1648, Dripping Springs, TX 78620,
(4) Meadows Center for Water and the Environment, Texas State University, 601 University Drive, San Marcos, TX 78666
(5) City of Austin Watershed Protection Department, 505 Barton Springs Rd, Austin, TX 78704

Abstract

Recent groundwater studies reveal complex surface and groundwater interactions within the streams that link the Trinity and Edwards Aquifers of the Hill Country and Balcones Fault Zone. Current numerical models do not adequately account for these interactions. The purpose of this paper is to summarize recent studies within the Blanco River and Onion Creek watersheds. These studies provide enhanced context by integrating detailed geologic, stratigraphic, and structural data with new hydrogeologic data including: gain-loss flow studies, potentiometric and head data, and geochemistry. Rainwater falling on the Trinity outcrops in the Hill Country may take a number of different pathways to arrive at Barton or San Marcos Springs, which emanate from the Edwards Aquifer. Some of the water may enter and discharge from the aquifers multiple times, while some water runs off to directly recharge the downstream Edwards Aquifers. Aquifer recharge in both Onion Creek and the Blanco River occurs through discrete karst features and losing stream reaches, in addition to diffuse recharge through permeable rock outcrops. Lastly, some of the water that enters the aquifers may flow deep into the subsurface with unknown discharge points. Geologic structure and stratigraphy influence recharge, discharge, and groundwater flow. In the Middle Trinity Aquifer, structures (faults) can be barriers to groundwater flow in some locations, while in other locations relay ramp structures allow for flow downdip into the Balcones Fault Zone. A refined conceptual model consistent with the results of past and current studies is described in this paper and should be considered water-resource policies and in future numerical modeling of the Trinity and Edwards Aquifers.

Introduction

The Edwards and Trinity Aquifers provide critical water resources to central Texas. Streams that create the Texas Hill Country landscape are hydrologically linked to the aquifer (groundwater) systems. Aquifers provide springflows that sustain the streams, and the streams, in turn, recharge the downstream aquifers.

Many studies, going back decades, document the surface and groundwater interactions in the Edwards Aquifer. However, despite the growing demand for water and increasing threats to surface water resources from both ecological and human health perspectives, few studies have been conducted to understand those stream interactions in the Hill Country Trinity Aquifers of central Texas. The purpose of this paper is to summarize hydrogeologic information from recent studies within the Blanco River and Onion Creek watersheds. These studies provide a greater understanding of the water resources in the area and have helped refine our conceptual model of the aquifer systems. This increased understanding can help guide policies for groundwater and surface-water management, future numerical modeling efforts, and scientific studies.

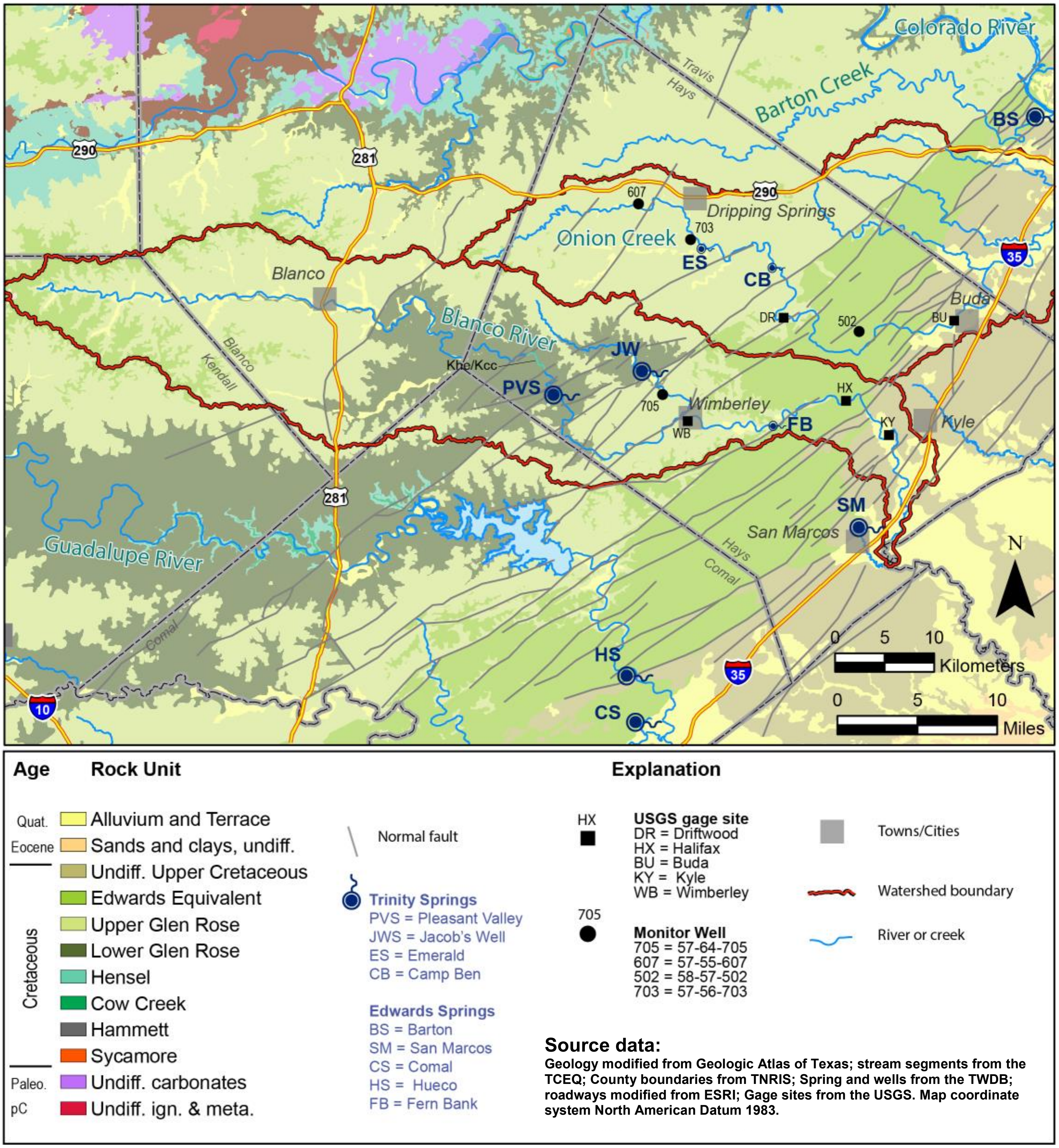


Figure 1. *Simplified geologic map of the study area showing the watersheds of Onion Creek and the Blanco River.*

Setting

The study area is comprised of the Onion Creek and Blanco River watersheds. Onion Creek is a tributary to the Colorado River, while the Blanco River is a tributary to the Guadalupe River system. Both watersheds traverse two major physiographic provinces in central Texas: the eastern edge of the Edwards Plateau (also known as the Hill Country) and the western edge of the Gulf Coastal Plain (also known as the Blackland Prairies) defined by the prominent Balcones Escarpment. These provinces are underlain by Cretaceous strata of the region and various geologic structures (Hill and Vaughn, 1898). This paper summarizes recent work focused on the upper reaches of both watersheds that are coincident with the Hill Country Trinity Aquifer system and the Edwards Aquifer recharge zone along the Balcones Escarpment (**Figure 1**).

Surface Water Hydrology

Stream beds and adjacent exposures within Onion Creek and the Blanco River have been the focus of many of these recent studies. The Blanco River watershed has more than twice the catchment area of Onion Creek, its length is nearly twice as long, and it has incised to a lower elevation. This, in part, explains some of the hydrogeologic differences between the two watersheds that will be discussed below. **Table 1** summarizes some hydrologic aspects of both streams in the study area.

Climate in the study area is very dynamic as seen in the orders of magnitude of fluctuations in stream-gage hydrographs from dry periods to floods (**Figure 2; Table 1**). Since 1925, the Blanco River at Wimberley has not ceased flowing, even during the 1950s drought, thus it is generally characterized as a perennial stream. Daily low flows at Wimberley reached 0.7 cfs in July 1956. In contrast, flows at the Onion Creek USGS station in Driftwood frequently cease flowing, amounting to about 10% of the time since 1979. Thus, Onion Creek is characterized as an intermittent stream.

Table 1. *Summary of Study Area Hydrology (USGS, 2016).*

	Study Stream Reach (mi)	Elevation Headwater (ft-msl)	Elev. Eastern Edw. Recharge Zone (ft-msl)	Drainage area (sq mi)	Average Daily Flow (cfs)	Peak Flow (cfs)	Low Flow (cfs)
Onion	48	1600	660[1]	166[1]	52[4]	16,600[4] (10/30/15)	0 (10% of time)[4]
Blanco	75	1960	620[2]	412[2]	143[3]	175,000[3] (5/24/15)	0.7 (July 1956)[3]

1-USGS 08158800 Onion Ck at Buda, TX
2-USGS 08171300 Blanco Rv near Kyle, TXUSGS
3-USGS 08171000 Blanco Rv at Wimberley, TX
4-USGS 08158700 Onion Ck near Driftwood, TX

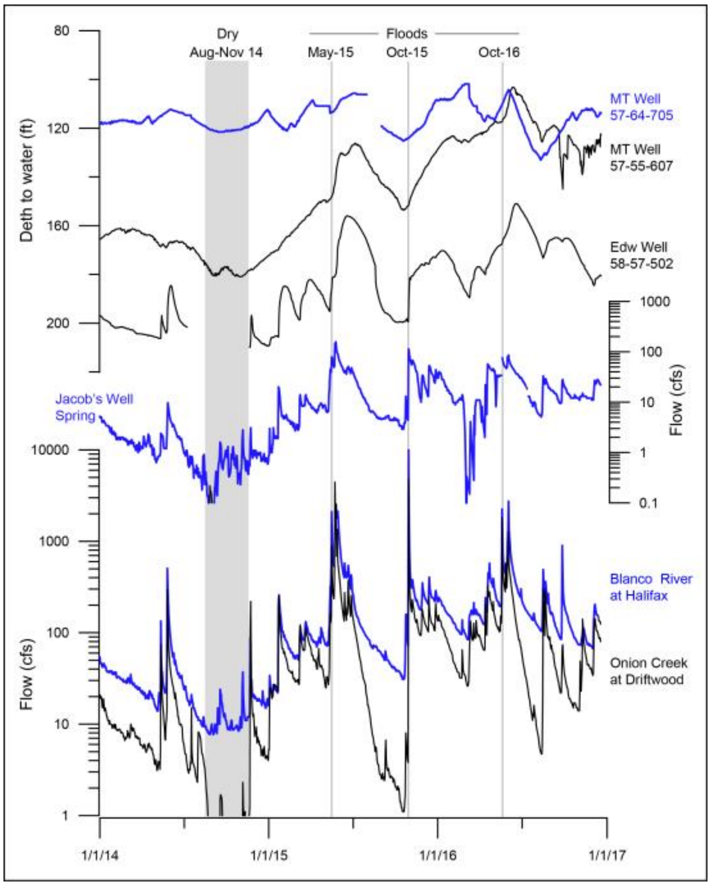


Figure 2. *Hydrograph showing surface-water and groundwater data from the Blanco River and Onion Creek. The hydrograph illustrates the hydrologic connection from surface water to groundwater in both the Middle Trinity and the Edwards Aquifers in both watersheds. Locations indicated on Figure 1. Blue color indicates locations within the Blanco River watershed, while black lines indicate locations within Onion Creek watershed. MT = Middle Trinity Aquifer; EDw =Edwards Aquifer well. Data sources: USGS (2016) and TWDB (2016a).*

Geology

Understanding the geology of the Trinity and Edwards Aquifers is critical to providing the context for any hydrogeologic data. An early synthesis of these geologic data and comprehensive references can be found in Wierman et al. (2010) and an accompanying geologic guidebook (Hunt et al., 2011). Since that publication, the authors have measured numerous sections and have conducted numerous geologic mapping, and field reconnaissance visits that have focused on the Blanco River and Onion Creek watersheds. Published geologic maps published by the University of Texas Bureau of Economic Geology (Collins, 2002a-e) provided the geologic base data and were modified with new information. Subsurface data include a database (n= >300) of geophysical logs, outcrops, cuttings, and driller's logs defining the tops of geologic formations. The information summarized below is derived from these previous publications and ongoing field work by the authors and others.

The Blanco River and Onion Creek watersheds are underlain by Lower Cretaceous strata (**Figure 1**). Sediments were deposited in an overall transgressive carbonate platform setting that greatly influenced the lithology, textures, and structures of the rocks. These shallow marine units form a heterogeneous package of stacked carbonate sequences reflecting shallow shelf to supratidal and restricted environments on the flat Comanche Shelf (**Figure 3;** Stricklin et al., 1971; Rose 1972; Wierman et al., 2010; Rose, 2016a).

In both the Onion Creek and Blanco River watersheds the western portions are underlain by the Trinity Group, while the eastern portions are underlain by the Edwards (Fredericksburg) Group as a result of juxtaposition along the Balcones Fault Zone (BFZ) (**Figure 1**). Limestone and dolomites dominate the exposed rocks in both watersheds; however, the lower-most Trinity Group rocks in the subsurface are clastic-carbonate couplets (Stricklin et al., 1971). Of particular interest to the hydrogeology is the Hensel formation that transitions from a siliciclastic-dominated unit west of the watersheds into a silty, shaley dolomite in the study area (**Figures 3 and 4**). The subsurface facies transition is thought to occur near the Ouachita front (Wierman et al., 2010).

Figure 4 presents geologic cross sections along key portions of Onion Creek and the Blanco River. The cross sections were constructed using geophysical logs, published geologic maps (Collins, 2002a-e), and the authors' geologic field observations.

Onion Creek Watershed Geology

Hilltops in the Onion Creek watershed are locally capped by thin remnants of the Edwards Group units—vestiges of the Edwards Plateau. The Upper Glen Rose Member of the Trinity Group is exposed in outcrop over much of the Onion Creek watershed west of the BFZ. The Upper Glen Rose Member is 355 ft thick in the upper reaches of the Onion Creek watershed and thickens to about 450 ft in the eastern portion of the study area. In outcrop the Upper Glen Rose is subdivided into eight informal lithologic units, which correlate to the classic work of Stricklin et al. (1971). These units generally consist of stacked and alternating limestones, dolomites, mudstones, and marls.

Recent work has focused on mapping Upper Glen Rose "Unit 3" (Stricklin et al., 1971) within the Onion Creek watershed (**Figure 3**). Unit 3 is 50 ft thick and is identified in both surface outcrops and subsurface cuttings by the presence of abundant *Orbitolina texana* (foraminifera) fossils in a calcareous mudstone. Mollusk steinkerns and skeletal fragments are also common in argillaceous, nodular grainstone, packstone, and clay units. Muller (1990) recognized Upper Glen Rose Unit 3 as an aquitard within upper Onion Creek watershed. Similar units are also recognized in recent mapping by the USGS (Clark et al., 2016). The thinning or absence of the Unit 3 aquitard over portions of the of Onion Creek watershed, combined with fractures and karst features, provides the potential for recharge into underlying units of the Upper and Lower Glen Rose (**Figure 4**; Watson, et al., 2017).

The top of the Lower Glen Rose is not exposed in the Onion Creek watershed, but is clearly recognized within 40 ft of ground surface in borehole geophysical logs of the Dripping Springs Water Supply Corporation (DSWSC) wells adjacent to Onion Creek. Thus, in portions of the Onion Watershed, there is only a thin (often fractured) veneer of the Upper Glen Rose overlying the Middle Trinity Aquifer (**Figure 4**; Wierman et al 2010, Plate 8).

The eastern portion of the Onion Creek watershed falls within the Balcones Fault Zone and corresponds to the Edwards Recharge Zone of the Edwards Aquifer. The Edwards Aquifer is composed of the Edwards Group limestones and the Georgetown Formation. The Edwards Group limestones consist of light gray, dense, thick-bedded dolomitic limestones with chert and is a highly karstic limestone. The Georgetown Formation crops out on the eastern portion of the study area and includes Antioch Cave. The Georgetown is about 50 ft thick and consists of alternating beds of thin, fine-grained limestone and marly fossiliferous limestone. The Del Rio Clay overlies the Georgetown Formation and is the primary confining unit of the Edwards Aquifer. The confined zone of the Edwards Aquifer, and its geologic units, are east of the study area (**Figure 1**).

Blanco River Watershed Geology

Similar to the Onion Creek watershed, hilltops in the upper Blanco River watershed are also capped by thin remnants of the Edwards Group units, and the Upper Glen Rose member is exposed throughout much of the upper watershed. However, older Trinity Group units are exposed at the surface from incision of the Blanco River and tributaries such as Little Blanco River and Cypress Creek. Within the Blanco River watershed the Upper Glen Rose, Lower Glen Rose, Hensel, and Cow Creek are all exposed at the surface (**Figures 1 and 4**). The Lower Glen Rose, about 250 ft thick, is characterized by fossiliferous limestone units with well-developed rudistid reef mounds and biostromes often found near the top and base of the unit. The shaley dolomitic Hensel facies, about 35 ft thick, is also exposed in the incised river valley and locally provides semi-confining aquifer properties. The top of the Cow Creek, a cross-bedded grainstone unit about 75 ft thick, is exposed in the bed of the Blanco River (**Figures 1 and 4**).

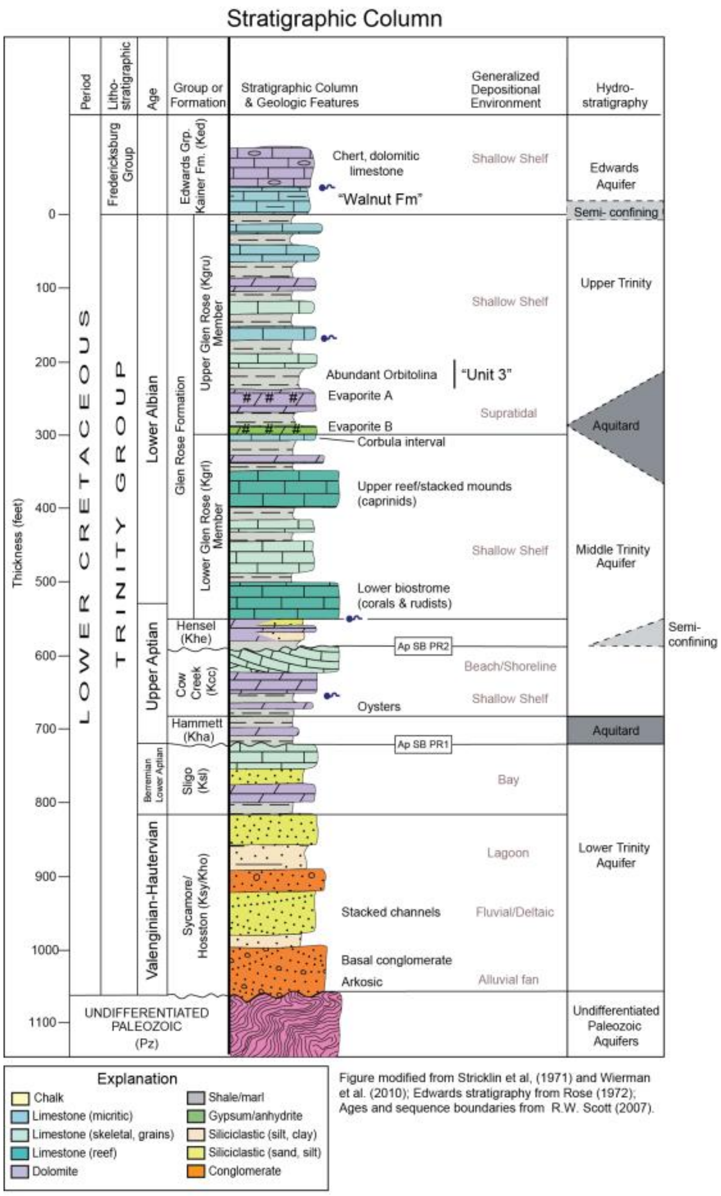


Figure 3. *Stratigraphy and hydrogeology of the study area. The focus of this work is on the Edwards Aquifer and the Upper and Middle Trinity Aquifers.*

Structure

Structure plays an important role in the development of the aquifers in central Texas, influencing flow of groundwater, and surface and groundwater interactions. The inset map in **Figure 5** illustrates the complex intersection of regional structures in the study area. The Llano Uplift is a structural dome in central Texas, which is related to the formation of the San Marcos Arch. These structures influenced Cretaceous deposition and subsequent structures, such as the Miocene Balcones Fault Zone (BFZ).

The BFZ produces the prominent physiographic feature known as the Balcones Escarpment in central Texas. The BFZ is a fault system consisting of numerous normal faults with hanging walls generally dropping down toward the Gulf of Mexico and with displacements ranging up to 800 feet. Faults are generally steeply dipping (45-85 degrees) to the southeast and strike to the northeast. The faults are described as "en echelon," which indicates that they are closely spaced, overlapping and subparallel. The BFZ is characterized by structures including horsts, grabens, anticlines, monoclines, and relay ramps (**Figures 1, 4 and 5**; Grimshaw and Woodruff 1986; Collins and Hovorka 1997; Collins, 2004).

Figure 5 is a structure contour of the top of the Cow Creek limestone. Contours were hand drawn using more than 300 control points (most of which are geophysical logs) and faults derived from the Geologic Atlas of Texas. The figure illustrates the strong structural style influence of the BFZ on the Cretaceous strata. Faults and fractures associated with the BFZ are found throughout both watersheds. However, it is within the BFZ that significant deformation occurs due to the transfer of displacement from the Mount Bonnell fault to the San Marcos fault to the southeast. The deformed geologic units form a large structural feature identified as a relay ramp, or transfer structure (**Figure 5**; Grimshaw and Woodruff, 1986).

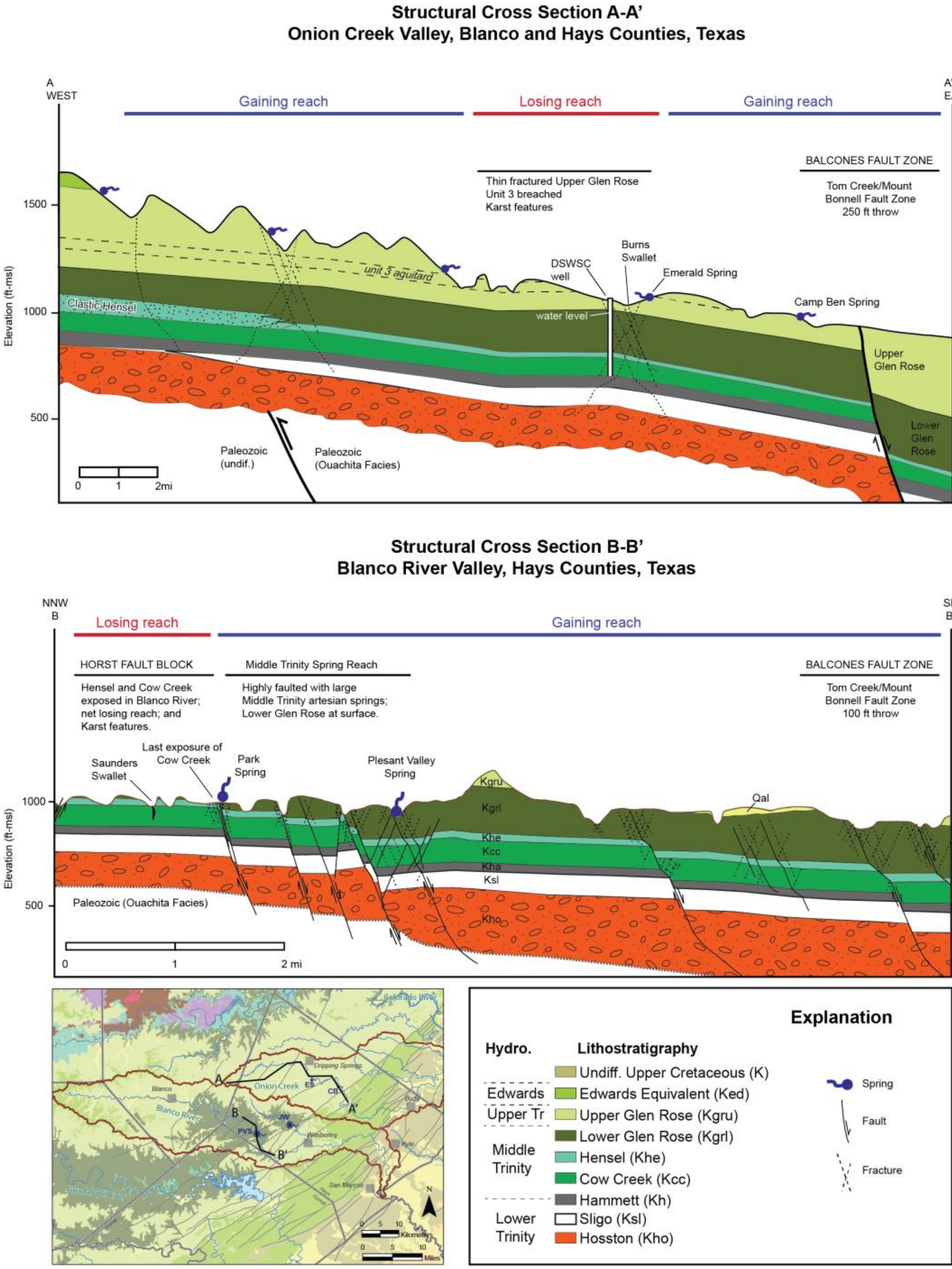


Figure 4. *Geologic cross sections along portions of Onion Creek (top) and the Blanco River (bottom).*

Onion Creek Structure

Despite the similarities in structural setting of the Onion Creek and Blanco River watersheds, rocks within the upper Onion Creek watershed are less deformed and influenced by the BFZ than rocks to the south in the Blanco River watershed. **Figure 5** indicates that structural dip of the Cow Creek is to the east within the Onion Creek watershed. The structure contours are relatively uniform as there are no significant faults from the headwaters to about mile 30 downstream in the study area, where the first mapped fault of the BFZ is encountered (**Figure 5**). Upper Glen Rose rocks west of the BFZ contain minor faults and numerous fractures. Thin-bedded limestones and dolomites of the Upper Glen Rose are commonly fractured and contain multiple-modal fracture sets. In the upper watershed major faults are either absent, present but masked by the Upper Glen Rose, or splay into numerous small faults due to the mechanical properties of the Upper Glen Rose units (Ferrill and Morris, 2008).

Blanco River Structure

Figure 5 illustrates the significant structural influence of the Balcones faulting in the Blanco River watershed. An east-trending plunging anticline along the northern margin of the Blanco River watershed demarks pervasive faulting and southeasterly dip of the Cow Creek structural contours. In addition, faulting is much more pervasive in the western portion of the Blanco River watershed than in the Onion Creek watershed. The anticline and pervasive faulting are likely an expression of the deformation associated with the relay-ramp structure. Another significant structure is a horst block, which has allowed for uplift and exposure of the Lower Glen Rose, Hensel and the Cow Creek limestone at the surface within the Blanco River bed (**Figure 4**).

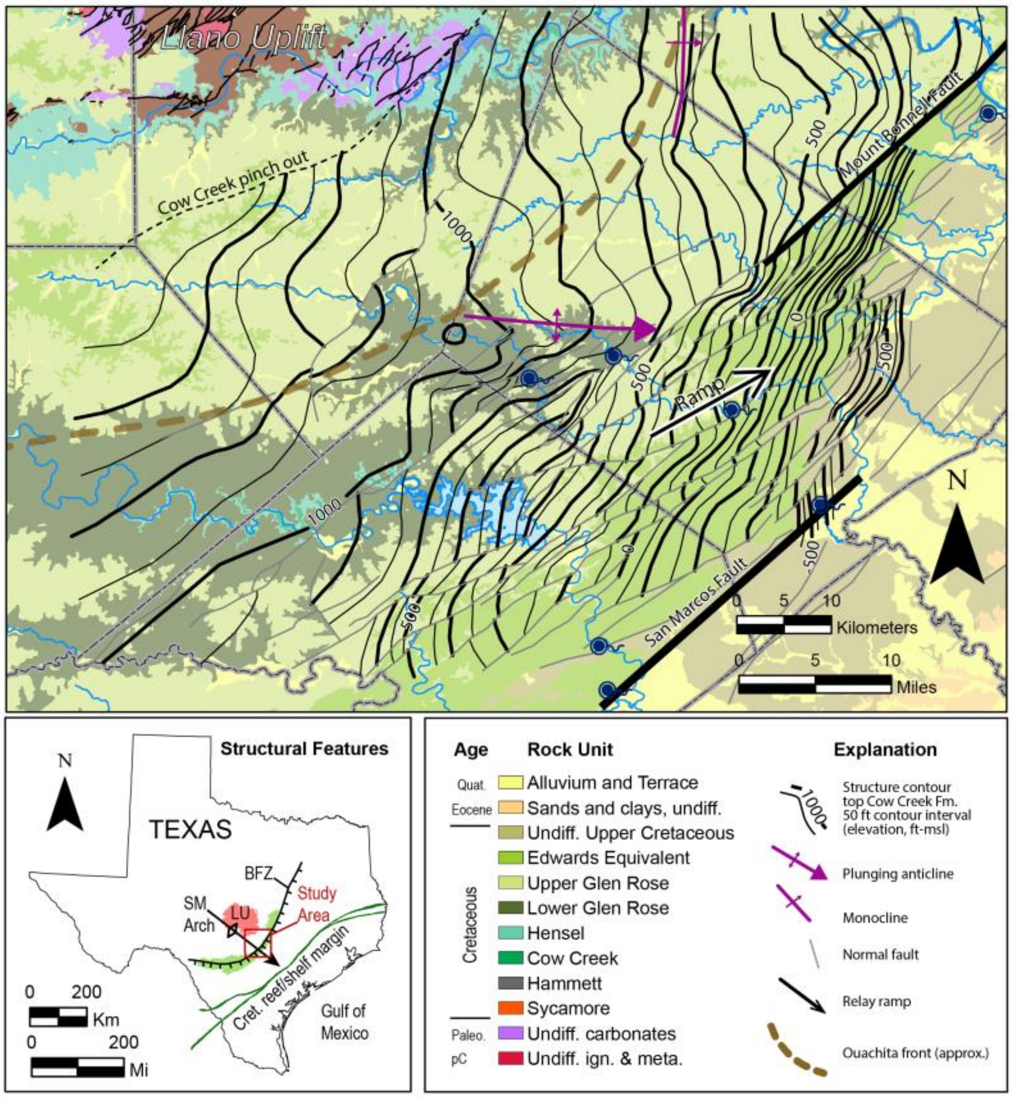


Figure 5. *Structure and geologic map of the study area. Structure contours on the top of the Cow Creek show dip to the ENE to the north of the anticline. South of the anticline the structural style consists of highly faulted blocks between the Mount Bonnell and San Marcos Faults forming a ramp structure. Ouachita front modified from Flawn et al., (1961). Inset map shows regional structures (after Ewing, 1991). SM Arch = San Marcos Arch, LU = Llano Uplift, BFZ = Balcones Fault Zone*

Hydrogeology

The Trinity Aquifers underlie the western portion of the study area while the Edwards Aquifer crops out over the eastern portion of the study area. The Trinity Group geological sections are organized into three regional hydrostratigraphic units: the Upper, Middle, and Lower Trinity (**Figure 3**). The Trinity Aquifers serve as sole-source water supplies for much of the central Texas Hill Country and the source of baseflows to the streams that cross the Hill Country. The Edwards Aquifer overlies the Trinity Aquifers in the BFZ, but faulting has juxtaposed the two aquifers in the western margins of the BFZ. The Edwards Aquifer is also a significant sole-source supply for hundreds of thousands of people in central Texas and its renowned springs such as Comal, San Marcos, and Barton Springs provide habitat for a variety of endangered species (Ashworth, 1983; Barker and Ardis, 1996; Barker et al., 1994; Mace et al., 2000).

The Upper Trinity Aquifer is composed of the Upper Glen Rose Member and consists of stacked and interbedded dolomites, limestones, marls, and mudstones that produce a series of thin local (perched) aquifers and aquitards (Muller, 1990). One of the important hydrologic functions of the Upper Trinity Aquifer is to provide baseflows to Hill Country streams. The Upper Trinity section in the study area is characterized by numerous small seeps and springs (**Figure 6**). Many of the springs are reported as perennial. The baseflows from this aquifer have long been recognized as an important source of water for ecological and recreational needs in the Hill Country, and as a source of recharge to the downstream Edwards Aquifer (Ashworth, 1983; Barker et al., 1994).

The Middle Trinity Aquifer consists of the Lower Glen Rose, Hensel, and Cow Creek formations. All units of the Middle Trinity are karstic carbonates. Underlying the Cow Creek is the Hammett Shale, a regional confining layer separating the Middle and Lower Trinity aquifers. The Cow Creek is the most prolific regional aquifer unit in the Middle Trinity. At the surface the Cow Creek is karstic and has developed recharge features, such as Saunders Swallet in the Blanco River (**Figure 4**). The Cow Creek also provides substantial Blanco River baseflows through Jacob's Well and Pleasant Valley Springs (both artesian springs). These baseflows ultimately recharge the Edwards Aquifer down gradient (Smith et al., 2014). The Middle Trinity has recently been described as having two interconnected aquifer zones related to its physiographic setting and depth of burial: 1) the shallow Hill Country Middle Trinity, and 2) deeply buried Balcones Fault Zone (BFZ) Middle Trinity (Hunt et al., 2017).

The Hensel is a water-bearing unit west of the study area, and is thought to be conducive to recharge directly from the surface or through overlying units. Eastward, the Hensel becomes a silty dolomite and behaves as a confining, or semi-confining unit on top of the Cow Creek, which is locally breached with fractures and solution features. The Lower Glen Rose is also an important aquifer unit within the Middle Trinity Aquifer with the best production occurring within the lower rudist reef facies, which has vertical and lateral heterogeneity. The Lower Glen Rose is also karstic with numerous mapped caves in the study area (**Figure 6**).

The BFZ was critical to the hydrogeologic evolution of the Edwards and Middle Trinity Aquifers. Faulting provided the hydrogeologic architecture (e.g. recharge areas vs. confined aquifers) and the initiation point for karst processes (DeCook, 1963; Slade et al., 1986; Sharp, 1990). The units were never buried deeply, thus preserving primary and secondary porosity and permeability. Later structural movement along the BFZ fractured the brittle limestones and dolomites in the study area. Uplift, erosion, and formation of the Hill Country has exposed these carbonate units to infiltration of meteoric water, and therefore karst processes (Barker et al., 1994; Barker and Ardis, 1996; Rose, 2016b). Structures such as joints and fractures influence the location and development of karst recharge features. These features often are located within stream channels and are capable of high rates of groundwater recharge of up to 100 cubic feet per second (cfs) (Smith and Hunt, 2013).

Aquifer Recharge

Most studies of the Trinity Aquifer describe recharge as broadly distributed and relatively low with about 4 % of total rainfall recharging the aquifers (Ashworth 1983). Although, recent modeling (Jones et al. 2011) of the Trinity has incorporated studies that document focused recharge along some streams outside of the study area (Ockerman, 2007), the Blanco River and Onion Creek are described and modeled as perennial gaining streams (Mace et al. 2000; Jones et al. 2011).

Conversely, the majority of water recharging the Edwards Aquifer in the study area comes from flow in the creeks and rivers (Slade et al., 1986). Slade (2014, 2015) estimates that 75% of the water entering the Edwards Aquifer in the area between Kyle and Barton Springs comes from infiltration of water in the stream beds, with the remaining 25% infiltrating in the uplands between the streams. Other studies indicate more recharge (up to 28%) occurs in the uplands (Hauwert and Sharp, 2014; Hauwert, 2015). All these cited studies indicate recharge along streams is an important component--with Onion Creek the largest contributor of the watersheds to Barton Springs. However, during extreme drought conditions the Blanco River is the only source of recharge to the Barton Springs segment of the Edwards Aquifer (Smith et al., 2012).

Hydrographs of surface flows, springs, and groundwater elevations in the Middle Trinity and Edwards Aquifers demonstrate rapid hydrologic communication in both the Onion Creek and Blanco River watersheds (**Figure 2**). Similarly Hunt et al. (2016) demonstrate that water levels in a Cow Creek well (DSWSC #2; 5756703) located adjacent to the losing reach showed a rapid rise that correlated with rapidly increasing creek flows. Potentiometric surfaces and Middle Trinity monitor wells along the creek support a downward flow potential for surface water to the Middle Trinity Aquifer (**Figure 2**). Mounding of potentiometric contours appears to occur around recharge areas in the Onion Creek and Blanco watersheds (**Figure 9**). Similar potentiometric mounding is also seen around Antioch Cave within Onion Creek in the Edwards Aquifer. Antioch Cave is a major karst feature that recharges the Edwards Aquifer (Smith et al., 2010). Gain-loss studies summarized below have identified losing stream reaches where recharge to the Middle Trinity Aquifer occurs in Onion Creek and the Blanco River.

An example of recharge in the Blanco River is Saunders Swallet, located in the bed of the Blanco River (**Figures 7 and 8**) where Cow Creek limestone is exposed at the surface. Some of the water entering the Cow Creek Limestone likely discharges into the Blanco River again at Pleasant Valley Spring where it migrates upward through solution-widened fractures. In this area, the Hensel consists mostly of silty dolomite with low permeability and acts as an aquitard. The Hammett Shale acts as an aquitard below the Cow Creek. Any water in the Cow Creek that does not exit the aquifer at this point probably follows a deep pathway to the east.

An example of recharge to the Middle Trinity along Onion Creek is the upper losing reach containing features like Burns Swallet (**Figures 7 and 8**). Surface waters recharge through the thin, fractured, and karstic Upper Glen Rose into the Lower Glen Rose and ultimately the Cow Creek. Unlike along the Blanco River, flow in the Middle Trinity may not subsequently discharge at Trinity springs. Instead, the water moves down structural dip, perhaps along a relay ramp to the east, or flows to the northeast toward the Colorado River.

Gain-Loss Flow Studies

Gain-loss measurements are needed to characterize recharge and discharge areas along streams. Previous studies or observations indicate that over the Edwards Aquifer Recharge Zone, Onion Creek can have a flow loss of about 200 cfs (Smith et al., 2011). However, the Blanco River generally has less recharge than Onion Creek with fewer known large recharge features and a shorter stretch over the recharge zone. The USGS has conducted some flow studies on the Blanco River and portions of Onion Creek (summarized in Slade et al., 2002). However, additional gain-loss data are needed to characterize the Trinity Aquifer system in the study area. Historical flow data were compiled (Wierman et al., 2010) and additional synoptic flow measurements were conducted. Those data are discussed in Smith et al. (2014) for the Blanco River and Hunt et al. (2016) for Onion Creek.

The gain-loss studies document complex surface and groundwater interactions with alternating gaining and losing reaches present during both high and low creek-flow conditions. Gaining reaches are due to the presence of springs and spring-fed tributaries that increase flows in the streams, while losing reaches result from recharge features, such as sinkholes, fractures, and caves, which drain water from the stream into the aquifer. The recent studies confirm the previous understanding about recharge to the Edwards Aquifer and recognize, for the first time, recharge to the Middle Trinity along Onion Creek and the Blanco River. Therefore, both diffuse and discrete recharge along streams are important processes for the Middle Trinity.

Figure 6 illustrates the generalized net losing and gaining reaches within the Onion Creek and Blanco River watersheds. **Figure 7** illustrates the distance-flow hydrograph from the Blanco River and Onion Creek watersheds for the various synoptic flow events. Results from these studies are summarized in **Table 2**.

Map Key	Reach Name	Creek	Length (mi)	Flow (cfs)	Geology	Comments
A	Upper Gaining	Onion	13	+30	Edwards Hilltops, Upper Glen Rose	Shallow Upper Trinity aquifer and gravity springs
		Blanco	32	+10	Edwards Hilltops, Upper Glen Rose	Shallow Upper Trinity aquifer and gravity springs
B	Trinity Recharge Zone	Onion	5	-3 net (up to -15)	Thin fractured Upper Glen Rose	Burns Swallet recharge feature
		Blanco	11	-10	Lower Glen Rose, Hensel, and Cow Creek	Saunders Swallet recharge feature in Cow Creek
C	Middle Gaining	Onion	17	+85	Upper Glen Rose	Shallow Upper Trinity aquifer and Emerald and Camp Ben Mc Colluch Springs
		Blanco	27	+75	Lower Glen Rose and Upper Glen Rose	Upper and Lower Glen Rose springs; Middle Trinity artesian springs: PVS and JWS
D	Edwards Aquifer Recharge Zone	Onion	9	-110	Edwards Group	Karst features: Crippled Crawfish and Antioch Caves
		Blanco	5	-20	Edwards Group	Karst features: Halifax Sink, Johnson Swallet
E	Lower Gaining	Onion	ND	ND	Upper Cretaceous and Quaternary	
		Blanco	ND	ND	Upper Cretaceous and Quaternary	

Table 2. *Summary of Onion and Blanco River gain-loss reach characteristics based on Smith et al., 2014 and Hunt et al., 2016. Reach indicated on **Figures 6 and** 7.*

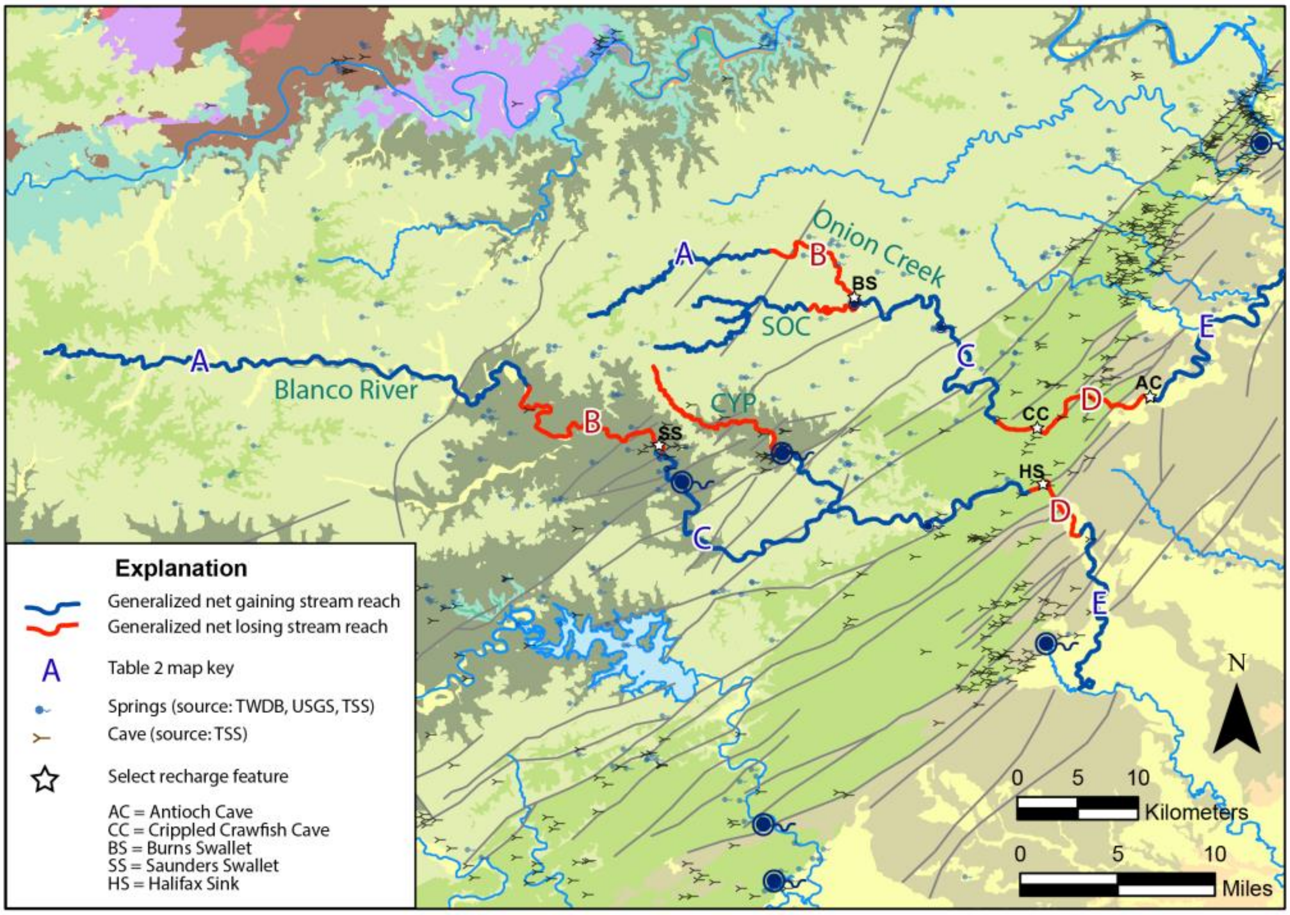
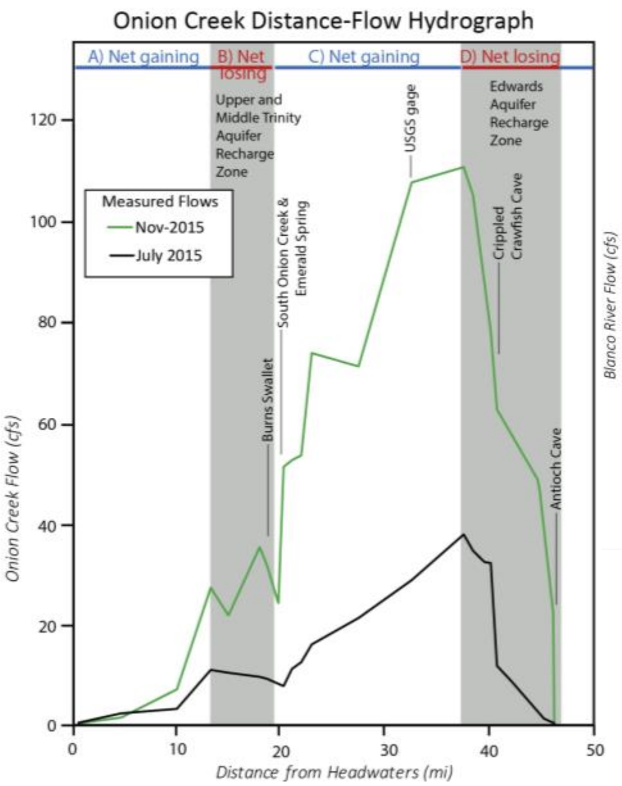


Figure 6. *Summary of flow gain-loss map of Blanco River and Onion Creek watersheds. Table 2 provides description of reach. SOC= South Onion Creek; CYP= Cypress Creek. Data summarized from (Smith et al., 2014 and Hunt et al., 2016).*



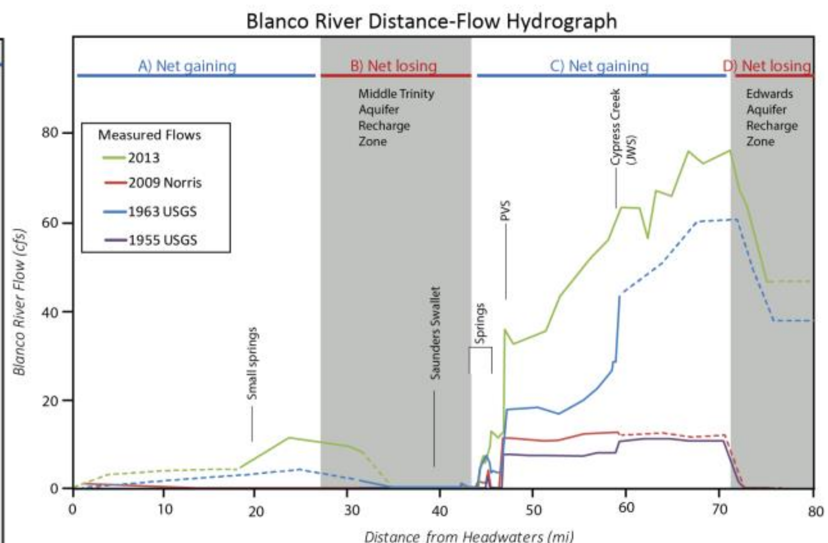


Figure 7. *Blanco River and Onion Creek distance-flow hydrograph. The Onion Creek distance-flow hydrograph is modified from Hunt et al. (2016). The Blanco River distance-flow hydrograph is modified from Smith et al. (2014).*

Figure 8. *Karst recharge features. Left: Saunders Swallet developed in the Cow Creek Limestone and located within the Blanco River; Right: Burns Swallet developed in the Upper Glen Rose and located within Onion Creek.*

Groundwater Flow

Groundwater levels and potentiometric surface maps provide critical information about the hydrologic relationships of recharge, discharge, and storage within an aquifer, and the direction of groundwater flow. **Figure 9** is a potentiometric map of the Middle Trinity Aquifer generated with more than 150 control points in Hays, Travis, Comal, and Blanco Counties (Hunt et al., 2010). Regional groundwater flow directions in the Middle Trinity generally follow the dip of the strata (Mace et al., 2000; Wierman et al., 2010). Detailed potentiometric maps of the Middle Trinity demonstrate the anisotropic nature of karst flow in some areas of the Blanco watershed (Watson et al., 2014).

Fault displacement has been shown to have varying effects on groundwater flow, with major faults acting as barriers to flow in some locations and having little effect in others (Ferrill et al. 2008). The potentiometric map of **Figure 9** shows groundwater flow eastward into the BFZ "across" faults. Indeed head data suggest that faults with significant displacements are barriers to flow as shown by the NE-trending flow along the Mount Bonnell Fault (**Figure 9**). Where displacements are minimal or where permeable units are juxtaposed against each other, flow can occur across the faults. Relay ramps **(Figure 5**) may provide a mechanism or pathway for groundwater to flow around faults, where displacements are significant, as suggested by the head and geochemical data (**Figures 9 and 10**; Hunt et al., 2015).

As groundwater flows down-dip within the Trinity units it encounters rocks with increasingly abundant evaporite minerals (gypsum/anhydrite) in the Upper and Lower Glen Rose formations. Evaporite minerals can occlude the porosity so that rocks have low permeability and poor water quality. Evaporite minerals were initially present in the same rocks to the west, where they are near surface, but they have largely been removed by infiltration of meteoric water. The Cow Creek does not appear to have abundant evaporite minerals, thus it can have high-yielding, fresh water, which is why it is a target for water supply throughout the Hill Country and BFZ. A multiport monitor well was installed near Onion Creek (near Buda; **Figure 1**) that penetrated the Cow Creek Limestone at a depth of 1,300 ft. Water samples collected from the Cow Creek are of moderately low total dissolved solids (TDS) values (about 900 mg/L) (Wong et al. 2014). Considering the structure (**Figure 5**), potentiometric maps (**Figure 9**), and TDS contours (**Figure 10)**, it is likely that the source of the water encountered in the deeply confined Cow Creek originated in the Onion Creek or Blanco River watersheds. However, it is unknown where this deep water is naturally discharging.

Water in the Blanco River or Onion Creek that reaches the recharge zone of the Edwards Aquifer will either enter karst features along that stretch to recharge the Edwards, or will flow downstream to join the San Marcos River or Colorado Rivers (Smith et al. 2014). After recharging the Edwards Aquifer the groundwater can either flow south to discharge at San Marcos Springs, or it may flow north to discharge at Barton Springs, or it may flow in both directions depending on hydrologic conditions (Smith et al., 2012).

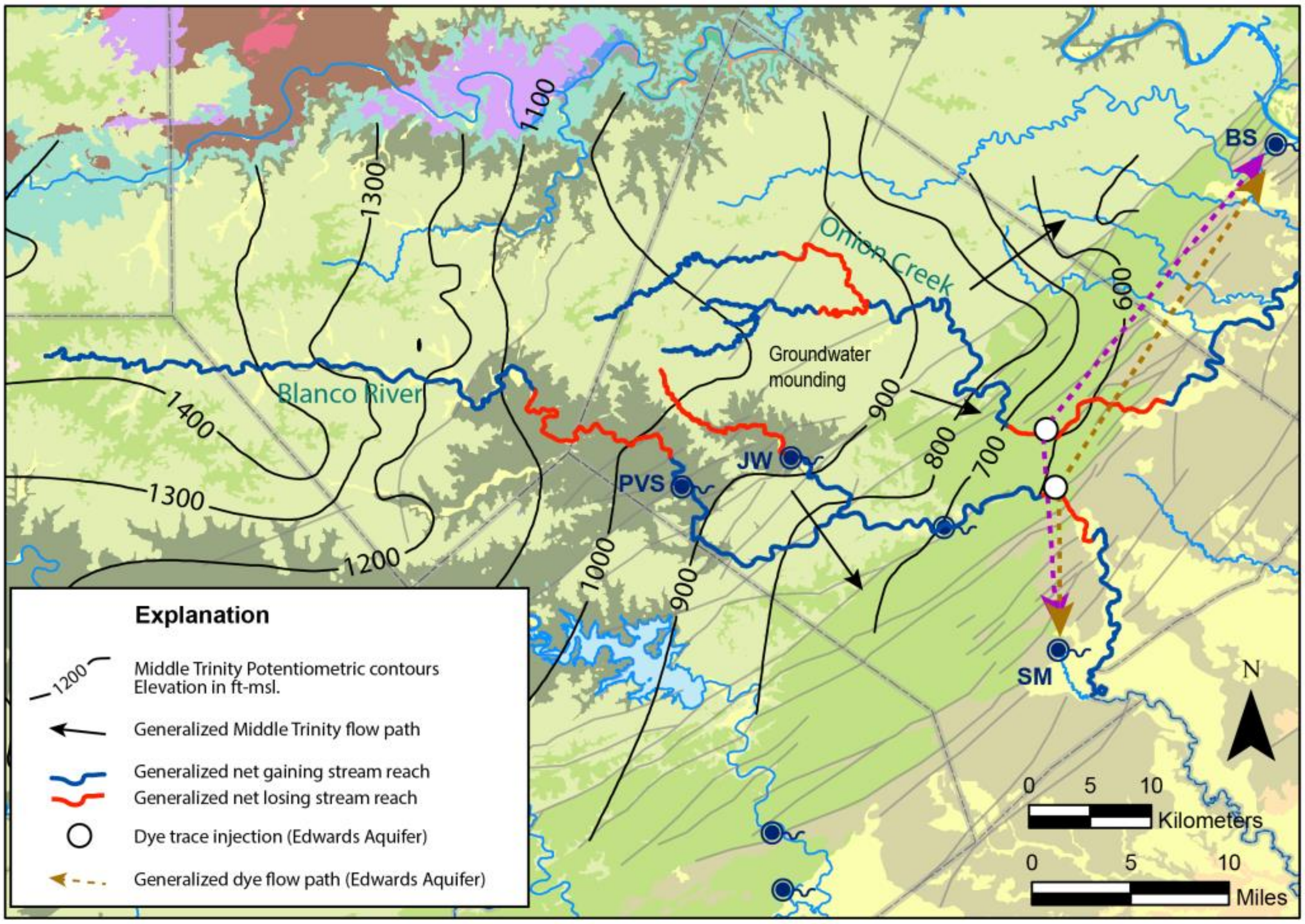


Figure 9. *Generalized potentiometric map of the Middle Trinity Aquifer and flow paths (dashed lines) within the Edwards Aquifer. Potentiometric contours show flow from west to east in the study area and a general mounding effect over upper portions of the Blanco River and Onion Creek net losing sections. Potentiometric contours from Hunt et al. (2010) and dye trace results summarized from Smith et al. (2012).*

Geochemistry

Major ion and isotope chemistry can provide additional information about the source, recharge, and flow paths of groundwater. The Texas Water Development Board (TWDB) funds the analyses of ion and isotope chemistry for surface and groundwater throughout Texas (TWDB, 2016b), including numerous samples from central Texas. A database with more than 500 samples was queried and evaluated as part of recent studies.

Figure 10 is a contour map of the total dissolved solids (TDS, mg/L) within the Middle Trinity Aquifer. The 500 mg/L contour, indicative of fresh water, helps to define where recharge is likely occurring. In general, the contours encircle the losing reach of both Onion Creek and the Blanco River and it's losing tributaries, supporting the evidence for recharge in those areas. While direct observation of Middle Trinity recharge (**Figure 8**) conclusively demonstrates a hydrologic connection, geochemistry can be utilized to make the same conclusion about the losing portion of the section of Onion Creek underlain by the Upper Glen Rose. Chemical analysis of groundwater samples from Middle Trinity Dripping Springs Water Supply Corporation (DSWSC) wells #2 (5756703) and #3 (5756704), indicate ion chemistry similar to surface water (**Figure 11**). The variation from magnesium/ sulfate-type waters to calcium/bicarbonate-type waters in samples over time indicates local dynamic recharge from Onion Creek with relatively rapid transmission along karst features.

Isotopes of modern carbon (PMC; 102% and 73%) and relatively high levels of tritium (H^{3+}; 1.8 TU) suggest very young water (TWDB, 2016b; Hunt et al., 2016; Bruce Darling, personal communication, December 20, 2016). **Figure 10** shows that samples with greater than 0.5 TUs in groundwater samples generally occur within the areas containing less than 500 mg/L TDS. The presence of tritium of greater than 0.5 TUs can indicate that a portion of the water is young (less than 50 years). **Figure 10**, combined with samples in **Figure 11**, further indicate recharge is occurring along the upper losing reaches in each watershed.

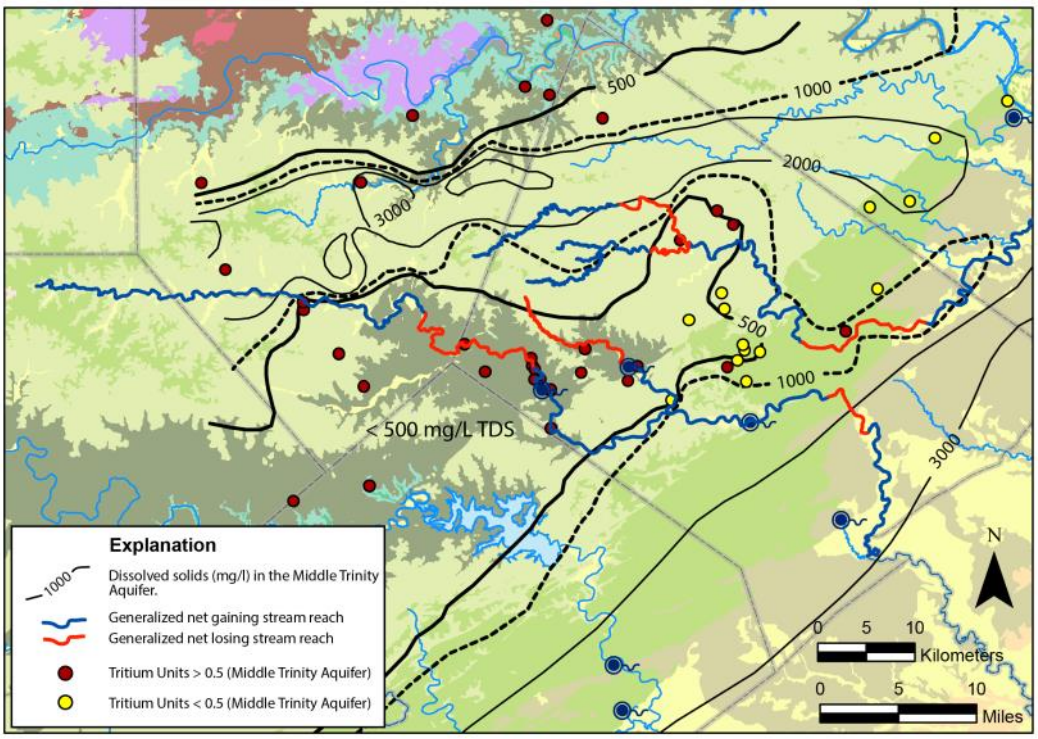


Figure 10. *Total dissolved solids and tritium map of the Middle Trinity Aquifer. Contours show fresh water (less than 500 mg/l) over the net losing portions of the Blanco River and Onion Creek. Samples that have greater than 0.5 TU indicate some portion of modern or recent water and generally occur within the 500 mg/L contour.*

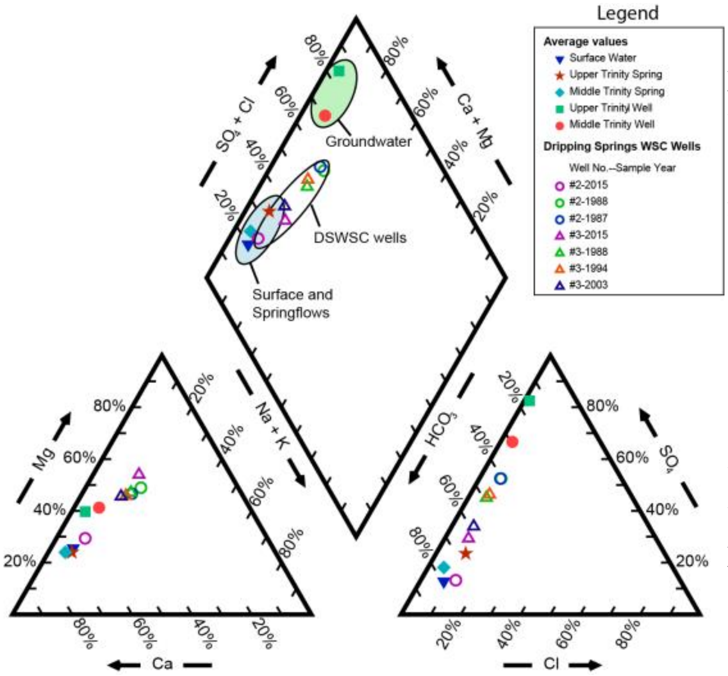


Figure 11. *Piper diagrams. Groundwater samples from DSWSC wells #2 and #3 (Middle Trinity well completions) indicated an ion chemistry similar to surface water. These wells are located adjacent to the upper losing reach within Onion Creek (**Figures 1 and 4**).*

Summary and Conclusion

A multiple disciplinary approach was used to gather, evaluate and interpret hydrogeologic data within the Blanco River and Onion Creek watersheds of Central Texas. **Figure 12** presents conceptual models of surface and groundwater interactions in the Blanco River and Onion Creek. The model is consistent with the observed hydrology, geology, and hydrogeology of past and current studies. The hydrogeology of both watersheds is generally similar and thus they have compatible conceptual models.

Based on this model, we now recognize that rainwater falling in the Hill Country in both watersheds may take a number of different pathways to arrive at Barton or San Marcos Springs. Some of the water may enter and discharge from the aquifers multiple times, while some water runs off to directly recharge the downstream Edwards Aquifers. Aquifer recharge in both Onion Creek and the Blanco River occurs through discrete karst features and losing streams, in addition to diffuse recharge through permeable rock outcrops. Lastly, some of the water that enters the aquifers may flow deep into the subsurface with unknown discharge points. Relay ramps provide a mechanism for lateral flow of the Middle Trinity Aquifer into the subsurface of the BFZ.

These conceptual models can be used as the basis for future numerical modeling efforts of the Hill Country Trinity Aquifers and its interactions with the Edwards Aquifer across the BFZ. Future numerical or aquifer management models, and policies, should incorporate this information.

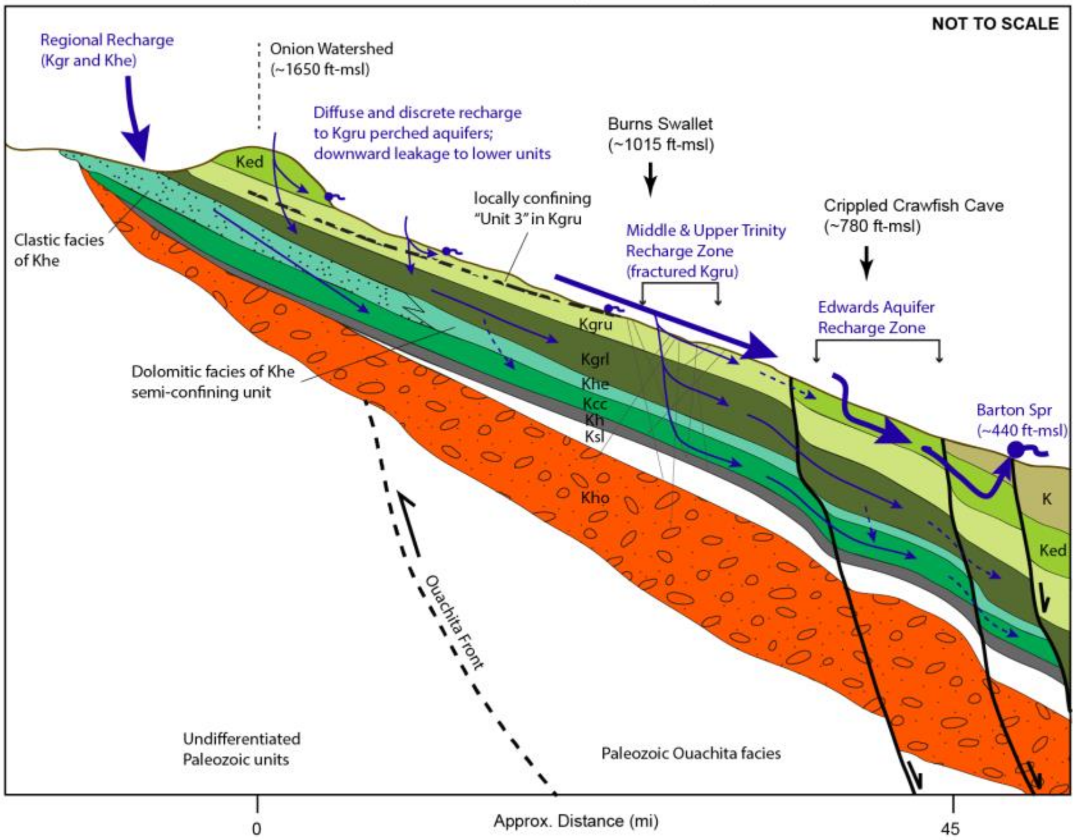
Future Studies

Future studies should collect data under a variety of hydrologic conditions to quantify the components of the water budget (ET, runoff, and recharge) to the Middle Trinity Aquifer. Multiport monitor wells adjacent to the losing reaches should also help characterize vertical inter-aquifer and intra-aquifer recharge and flow within the Upper, Middle, and Lower Trinity Aquifers. Dye tracing could help establish groundwater basins, such as around Jacob's Well, and delineate limits of surface and groundwater interactions.

Acknowledgements

We extend our thanks to the cooperation and support of landowners within each watershed that made these studies possible. We would also like to thank the Texas Water Development Board (Janie Hopkins and Chris Muller) who funded and supported geochemical sampling and maintain continuous water level monitoring and other online resources.

Onion Creek Conceptual Diagram



Blanco River Conceptual Diagram

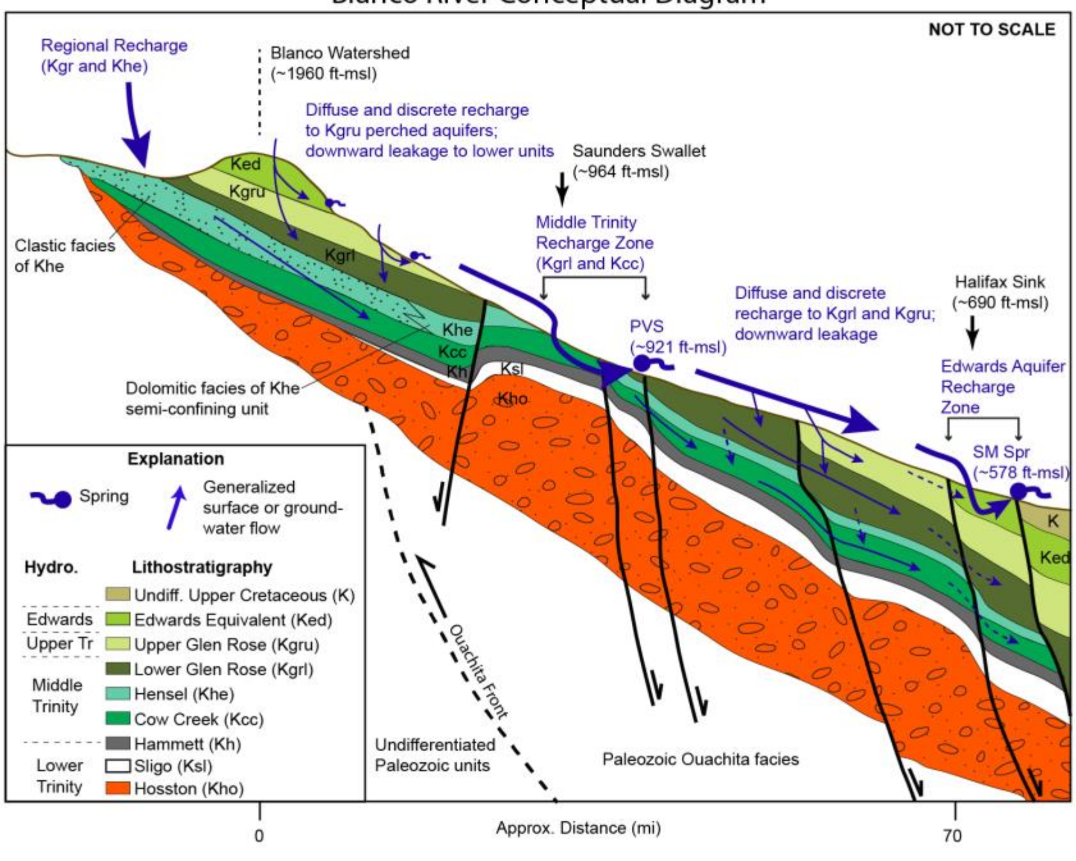


Figure 12. *Conceptual model of surface and groundwater interactions and groundwater flow in the Blanco River and Onion Creek. Dashed arrows indicate flow may be localized.*

References

Ashworth, J.B., 1983, Ground-water availability of the Lower Cretaceous formations in the Hill Country of south-central Texas. Texas Department of Water Resources Report 273, p 173

Barker, R., P. Bush, and E. Baker, 1994, Geologic History and Hydrogeologic Setting of the Edwards-Trinity Aquifer System, West-Central Texas: U.S. Geological Survey, Water-Resources Investigations Report 94-4039, 49 p.

Barker, R.A., and A.F. Ardis, 1996. Hydrogeologic Framework of the Edwards-Trinity Aquifer System, West- Central Texas, US Geological Survey Professional Paper 1421-B. Available from: http://pubs.er.usgs.gov/publication/pp1421B

Clark, A.K., J.A. Golab, and R.R. Morris, 2016, Geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Texas: U.S. Geological Survey Scientific Investigations Map 3366, 1 sheet, scale 1:24,000, pamphlet, https://doi.org/10.3133/sim3366.

Collins, E.W., 1995, Structural Framework of the Edwards Aquifer, Balcones Fault Zone, Central Texas. Gulf Coast Association of Geological Societies Transactions 45: 35-142.

Collins, E.W., and S.D. Hovorka, 1997, Structure map of the San Antonio segment of the Edwards Aquifer and Balcones Fault Zone, south-central Texas: structural framework of a major limestone aquifer: Kinney, Uvalde, Medina, Bexar, Comal and Hays Counties. The University of Texas at Austin, Bureau of Economic Geology, Miscellaneous Map No. 38, scale 1:250,000, text, p 14

Collins, E.W., 2002a, Geologic map of the Rough Hollow quadrangle, Texas: University of Texas at Austin, Bureau of Economic Geology, Open-File Map STATEMAP Study Area 9, scale 1:24,000. https://repositories.lib.utexas.edu/handle/2152/31882

Collins, E.W., 2002b, Geologic map of the Driftwood quadrangle, Texas: University of Texas at Austin, Bureau of Economic Geology, Open-File Map STATEMAP Study Area 9, scale 1:24,000. < https://repositories.lib.utexas.edu/handle/2152/30310>

Collins, E.W., 2002c, Geologic map of the Payton quadrangle, Texas: University of Texas at Austin, Bureau of Economic Geology, Open-File Map STATEMAP Study Area 9, scale 1:24,000. < https://repositories.lib.utexas.edu/handle/2152/31877>

Collins, E.W., 2002d, Geologic map of the Dripping Springs quadrangle, Texas: University of Texas at Austin, Bureau of Economic Geology, Open-File Map STATEMAP Study Area 9, scale 1:24,000. < https://repositories.lib.utexas.edu/handle/2152/31729>

E.W., 2002e, Geologic map of the Henly quadrangle, Texas: University of Texas at Austin, Bureau of Economic Geology, Open-File Map STATEMAP Study Area 9, scale 1:24,000 <https://repositories.lib.utexas.edu/handle/2152/31835>

DeCook, K.J., 1963, Geology and ground-water resources of Hays County, Texas: U.S. Geological Survey Water-Supply Paper 1612, 72 p.

Ewing, T.E., 1991, Structural framework. In: Salvador A. (ed) The Gulf of Mexico basin. Geological Society of America, The Geology of North America, vol J, pp 31–52

Ferrill, D.A. and A.P. Morris, 2008, Fault zone deformation controlled by carbonate mechanical stratigraphy, Balcones fault system, Texas: AAPG Bulletin, vol. 92, no. 3, p. 359-380

Ferrill D.A., A.P. Morris, D.W. Sims, R. Green, N. Franklin, D.J. Waiting, 2008, Geologic Controls on Interaction Between the Edwards and Trinity Aquifers, Balcones Fault System, Texas, South Texas Geological Society Bulletin. p. 21-45.

Flawn, P.T., A. Goldstein, Jr., P. B. King and C. E. Weaver, 1961, The Ouachita System: University of Texas, Austin, Bureau of Economic Geology Publication 6120, 401 p.

Grimshaw, T.W. and C.M. Woodruff, 1986, Structural style in an en echelon fault system, Balcones Fault Zone, Central Texas. Geomorphologic and Hydrologic Implications. In: Abbott PL, Woodruff CM (eds) The Balcones escarpment. Geological Society of America, Central Texas, pp 71–76

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

Hauwert, N.M., 2015, New Recharge Studies for Central Texas. In Austin Geological Society Guidebook No. 35. pgs 65-74.

Hill, R.T., and T.W. Vaughan, 1898, Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Texas, with reference to the occurrence of underground waters: USGS 18th Annual Report, Part 2, p. 193-321.

Hunt, B.B., B.A. Smith, J. Beery, N.M. Hauwert, and D. Johns, 2005, Structural Influence on Groundwater Flow as Evidenced by Groundwater Dye Tracing in the Barton Springs Segment of the Edwards Aquifer, Central Texas: Implications for Modeling Conduits: Geological Society of America: South-Central Meeting, Abstracts with Programs Vol. 37, No. 3, San Antonio, Texas, April 1, 2005.

Hunt, B.B., and B.A. Smith, 2010, Spring 2009 Potentiometric Map of the Middle trinity Aquifer in Groundwater Management Area 9, Central Texas: Barton Springs Edwards Aquifer Conservation District Report of Investigations 2010-0501, 26 p.

Hunt, B.B., D.A. Wierman, A.S. Broun, C.M. Woodruff, and R.G. Fieseler, 2011, Surface to Subsurface Trinity Lithostratigraphy: Implications for Groundwater Availability in the Hill Country, Easter Blanco and Northern Hays Counties, Texas: Austin Geological Society Guidebook 33, 24 p. + Appendices, November 2011.

Hunt, B.B., B.A. Smith, A. Andrews, D.A. Wierman, A.S. Broun, and M.O. Gary, 2015, Relay ramp structures and their influence on groundwater flow in the Edwards and Trinity Aquifers, Hays and Travis Counties, Central Texas, Sinkhole Conference, October 5-10, 2015, Rochester, Minnesota

Hunt, B. B., A.S. Broun, D.A. Wierman, D.A. Johns, and B.A. Smith, 2016, Surface-water and groundwater interactions along Onion Creek, Central Texas: Gulf Coast Association of Geological Societies Transactions, v. 66, p. 261–282.

Hunt, B.B., B.A. Smith, M.O. Gary, A.S Broun, and D.A. Wierman, 2017, An Evolving Conceptual Model of the Middle Trinity Aquifer, Hays County, Central Texas. Geological Society of America Abstracts with Programs, San Antonio, Texas, March 13, 2017.

Johnson, S., G. Schindel, , G. Veni, N. Hauwert, B. Hunt, B. Smith, and M. Gary, 2012, Tracing Groundwater Flowpaths in the Vicinity of San Marcos Springs, Texas: Edwards Aquifer Authority, San Antonio, Texas, August 2012, 139 p.

Jones, I. C., R. Anaya, and S. C. Wade, 2011, Groundwater availability model: Hill Country portion of the Trinity Aquifer of Texas: Texas Water Development Board Report 377, Austin, 165 p.

Mace, R.E., A.H. Chowdhury, R. Anaya, and S.C. Way, 2000, Groundwater availability of the Trinity Aquifer, Hill Country Area, Texas—Numerical simulations through 2050. Texas Water Development Board Report 353, p 119

Muller, D.A., 1990, Ground-water evaluation in and adjacent to Dripping Springs, TX: Texas Water Development Board Publication 322, Austin, 61 p.

Ockerman, D.J., 2007, Simulation of streamflow and estimation of ground-water recharge in the upper Cibolo Creek watershed, south-central Texas, 1992–2004: US Geological Survey Scientific Investigations Report 2007–5202, p 34.

Rose, P.R., 1972, Edwards Group, surface and subsurface, Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations no. 74, 198 p.

Rose, P.R., 2016a, Stratigraphy of Fredericksburg-Washita Division (Albian), Comanche-Cretaceous, Texas, Emphasizing Person and Georgetown Formations. *Lowery et al (eds) in* Proceedings: Mesozoic of the Gulf Rim and Beyond: New Progress in Science and Exploration of the Gulf of Mexico Basin, 35th Annual GCSSEPM Foundation Perkins---Rosen Research Conference, December 8-9, Houston, Texas. p. 490-534

Rose, P.R., 2016b, Late Cretaceous and Tertiary Burial History, Central Texas. GCAGS Journal, v. 5 (2016), p. 141-179.

Sharp, J.M., 1990, Stratigraphic, geomorphic and structural controls of the Edwards Aquifer, Texas, USA. In: Simpson ES, Sharp JM Jr (eds) Selected Papers on Hydrogeology: Heise, Hannover, Germany, International Association of Hydrogeologists, vol 1, pp 67–82

Slade, R.M. Jr., M.E. Dorsey, and S.L. Stewart, 1986, Hydrology and water quality of Barton Springs and associated Edwards aquifer in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 86-4036, ll7 p. http://pubs.er.usgs.gov/pubs/wri/wri864036

Slade, R.M., Jr., J.T. Bentley, and D. Michaud, 2002, Results of Streamflow Gain-Loss Studies in Texas, With Emphasis on Gains from and Losses to Major and Minor Aquifers, U.S. Geological Survey Open-File Report 02-068, 131 p. + 2 over-size sheets.

Slade, R.M., Jr., 2014, Documentation of a recharge-discharge water budget and main-streambed recharge volumes, and fundamental evaluation of groundwater tracer studies for the Barton Springs segment of the Edwards Aquifer: Texas Water Journal, Vol 5 No. 1. https://journals.tdl.org/twj/index.php/twj/article/view/6988

Slade, R.M., Jr., 2015, Recharge-discharge water budget based recharge rates for the Barton Springs segment of the Edwards aquifer, Austin Geological Society Guidebook No. 35, pg 87-93.

Smith, B.A. and B.B. Hunt, and J. Beery, 2010, Recharge Enhancement and Protection of a Karst Aquifer in Central Texas: in Advances in Research in Karst Media, eds. B. Andreo, F. Carrasco, J. J. Duran, and J. W. LaMoreaux, 4th International Symposium on Karst, April 26-30, 2010 Malaga, Spain, Springer, pp. 37-42.

Smith, B.A., B.B. Hunt, and S.B. Johnson, 2012, Revisiting the Hydrologic Divide Between the San Antonio and Barton Springs Segments of the Edwards Aquifer: Insights from Recent Studies: Gulf Coast Association of Geological Societies Journal Vol. 1, 62nd Annual Convention, October 21 -24, 2012, Austin, TX.

Smith, B.A., and B.B. Hunt, 2013, Enhanced recharge to the Barton Springs segment of the Edwards Aquifer, Central Texas, Carbonates and Evaporites, May 2013, Volume 28, Issue 1-2, pp 67-73.

Smith, B.A., B.B. Hunt, A.G. Andrews, J.A. Watson, M.O. Gary, D.A. Wierman, and A.S. Broun, 2014, Hydrologic Influences of the Blanco River on the Trinity and Edwards Aquifers, Central Texas, USA, in Hydrogeological and Environmental Investigations in Karst Systems, (Eds) B. Andreo, F. Carrasco, J. Duran, P. Jimenez, and J. LaMoreaux, Environmental Earth Sciences, Springer Berlin Heidelberg, Volume 1, pp 153-161.

Stricklin, F. L., Jr., C.I. Smith, and F.E. Lozo, 1971, Stratigraphy of Lower Cretaceous Trinity deposits of Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 71, 63 p.

TWDB (Texas Water Development Board), 2016a, Automated Groundwater Levels <https://waterdatafortexas.org/groundwater> Accessed December 2016.

TWDB (Texas Water Development Board), 2016b, Groundwater Database (GWDB) Reports <https://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp> Accessed December 2016

USGS (U.S. Geological Survey), 2016, National Water Information System: Mapper < https://maps.waterdata.usgs.gov/mapper/index.html > Accessed December 2016

Watson, J.A., A.S Broun, B.B. Hunt, D.A. Wierman, and B.A. Smith, 2017, Mapping the Upper Glen Rose Unit 3 Aquitard: Implications for Recharge to the Middle Trinity Aquifer, Hays County, Texas. Geological Society of America Abstracts with Programs, San Antonio, Texas, March 13, 2017.

Watson, J.A., B.B. Hunt, M.O. Gary, D.A. Wierman, B.A. Smith, 2014, Potentiometric Surface Investigation of the Middle Trinity Aquifer in Western Hays County, Texas: BSEACD Report of Investigations 2014-1002, October 2014, 21 p.

Wierman, D.A., A.S. Broun, and B.B. Hunt (Eds), 2010, Hydrogeologic Atlas of the Hill Country Trinity Aquifer, Blanco, Hays, and Travis Counties, Central Texas: Preparted by the Hays-Trinity , Barton/Springs Edwards Aquifer, and Blanco Pedernales Groundwater Conservation Districts, July 2010, 17 plates+DVD.

Wong, C.I., J.S. Kromann, B.B. Hunt, B.A. Smith and J.L. Banner, 2014, Investigation of Flow Between Trinity and Edwards Aquifers (Central Texas) Using Physical and Geochemical Monitoring in Multiport Wells. Vol. 52, No. 4–Groundwater–July-August 2014 (pages 624–639).