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# Surface-Water and Groundwater Interactions Along Onion Creek, Central Texas

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## ABSTRACT

Onion Creek is an important hydrologic link between two major aquifers in Central Texas. Multiple small springs discharging from the Trinity Aquifers sustain base flow in Onion Creek, which in turn recharges the Edwards Aquifer, ultimately discharging at Barton and San Marcos Springs. The creek generally contains clear, low nutrient water with high ecological and recreational value. This watershed is rapidly being developed and is experiencing significant population growth and land use changes, thus increasing demand for water supplies and potentially affecting regional hydrology. Several wastewater treatment plants are operating in the watershed with additional treatment plants being planned. Despite the critical importance of Onion Creek to the community, no comprehensive gain-loss studies have been conducted that characterize the surface and groundwater interactions across the Trinity (Upper Glen Rose) and Edwards Aquifers. This paper presents the results of a flow study in Onion Creek and its tributaries extending 46 miles from the headwaters in Blanco County to downstream of the Edwards Aquifer recharge zone in Hays County. A total of 69 flow sites were established and acoustic Doppler velocimeters (ADV) were used to make 139 wading flow measurements from January through December 2015. Detailed geologic, hydrogeologic, and geochemical data were incorporated into the evaluation to understand the hydrogeologic significance of the data. Two synoptic flow-measurement events were done during low and high flow conditions in July and November 2015, respectively. This study reveals complex surface and groundwater interactions in the Onion Creek watershed. Flow losses are documented to occur along a creek reach underlain by the Upper Glen Rose. These losses combined with other hydrogeologic and geochemical data suggest Onion Creek provides some recharge to the Middle Trinity Aquifer in those reaches. A better understanding of the surface water and groundwater interactions along the creek is important for groundwater and surface-water management in an area undergoing significant population growth.

## INTRODUCTION

Onion Creek is an important hydrologic link between two major aquifers in Central Texas. Multiple small springs, discharging from the Upper Trinity Aquifer (Upper Glen Rose Member), sustain base flow in Onion Creek that in turn recharges the Edwards Aquifer. Ultimately, this water discharges at Barton and San Marcos Springs. Previous studies have characterized the stream losses along the Blanco River over the Edwards Aquifer Recharge Zone (Slade et al., 1986; Smith et al., 2001) and more recently portions of the Middle Trinity Aquifer (Smith et al., 2014). Muller (1990) conducted a study of groundwater in the Dripping Springs area and indicated Onion Creek could be a source of recharge to the Dripping Springs Water Supply System wells completed in the Middle Trinity Aquifer. However, no comprehensive gain-loss studies have been conducted that characterize the surface and groundwater interactions in the upper Onion Creek watershed. Such information is critical to the conceptual model of the aquifer and future numerical models.

The purpose of this study is to characterize the groundwater and surface-water interactions in the upper Onion Creek watershed primarily underlain by the Upper Glen Rose Member. The study integrates flow measurements taken during two synoptic events with hydrogeologic and geochemical data.

## STUDY AREA

The area under study is the upper watershed of Onion Creek underlain by Lower Cretaceous strata. Data were collected on the main Onion Creek channel and many of its tributaries extending about 46 miles from the headwaters in eastern Blanco County to downstream of the Edwards Aquifer Recharge Zone in Hays County (Fig. 1). Within the upper watershed, baseflows are fed by multiple fresh-water springs along its path that issue from Lower Cretaceous, Trinity Group strata. (Upper Glen Rose Member). This portion of the creek is described as an overall gaining stream and is mapped as the "Contributing Zone" to the Edwards Aquifer Recharge Zone for regulations guiding construction (TCEQ, 2008). Onion Creek is recognized as a losing stream as it crosses the Balcones Fault Zone (BFZ) and the outcrop of the Edwards Group units, providing about a third of the recharge to the Barton Springs segment of the Edwards Aquifer (Slade et al., 1986). East of Buda and downstream of the study area, Onion Creek flows another 27 miles over Upper Cretaceous and Quaternary units before its confluence with the Colorado River near Austin, Texas.

The hydrology of Onion Creek is dynamic and subject to both severe drought and flash floods. Multiple factors contribute to these severe events, but the Hill Country terrain and the Balcones Escarpment are significant geographic features (Slade and Patton, 2002). Drought significantly affected the study area in 2009 and 2011 when portions of the creek, which normally contain perennial flow, ceased flowing. Flood waters frequently over flow creek banks and inundate homes and roads. An evaluation of hydrologic data in Central Texas demonstrated increasing variability and decreasing baseflows over time (Hunt et al., 2012).

## GEOLOGIC SETTING

Onion Creek traverses 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 Plains (also known as the Blackland Prairies) defined by the prominent Balcones Escarpment. These provinces are underpinned by the Cretaceous geology of the region and its geologic structures (Figs. 1 and 2; Hill and Vaughn, 1898).

During the early Cretaceous period, sediments were deposited in an overall transgressive carbonate platform setting that greatly influenced the lithology, textures, and structures in the rocks. These shallow marine units form a heterogeneous package of stacked carbonate sequences reflecting shallow shelf to supratidal and restricted environments. 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; Hunt et al., 2011). Regional stratigraphy is presented in Figure 2.

### Lithostratigraphy of the Upper Onion Creek Watershed

The Upper Glen Rose Member of the Trinity Group crops out over much of the western reaches of Onion Creek. Although previous authors had mapped the Upper Glen Rose (Barnes, 1974; DeCook, 1963; Grimshaw, 1970; Collins, 2002a-c), the important zonation of the strata into recognizable, correlative units was defined by Stricklin et al. (1971). Subsequent detailed investigations by Muller (1990), Ward and Ward (2007), and Clark and Morris (2015) has further refined the lithostratigraphy (Fig. 3). Measured surface sections and published analyses were tied to the subsurface units through correlation with a series of geophysical logs and samples of drill cuttings from area water wells in this study (Figs. 1-3). Much of the Upper Glen Rose area in western Hays County is covered or intrastratal karst (Klimchouk and Ford, 2000). Surface karst features, including caves, sinkholes, and subsurface karstic porosity in water-well boreholes are common (personal communication, Alex S. Broun).

The Oswald well anchors the structural cross section (A-A’) in the west, proximal to the headwaters of Onion Creek (Figs. 1 and 3). The Upper Glen Rose Member is 355 ft thick at Oswald and is subdivided into eight informal lithologic units, which correlate to the classic work of Stricklin et al. (1971). At the base of the section is the Lower Glen Rose Member with the regionally recognized “Corbula Bed” (Stricklin et al., 1971; Scott et al., 2007). At the top of the interval the distinctive Walnut Clay formation, with its characteristic Ceratostreon texanum oyster, was correlated to the Divide Pass measured surface section (Fig. 3). The hydrostratigraphy of the Upper Glen Rose, as defined by Muller (1990), is correlated to the Stricklin et al. (1971) interpreted unit subdivision and the measured section of this study (Fig. 3).

Upper Glen Rose Unit 1 is 20 ft thick in the Oswald borehole and consists of dolomite, dolomitic mudstone and siltstone. This interval is identified as Unit 1 “Solution Zone” in Stricklin et al. (1971) and is correlated to the “Lower Evaporite” of Clark and Morris (2015). It is a prominent marker unit and can be identified in both surface and subsurface locations. Gypsum beds are present in the subsurface as evidenced by cuttings samples and low gamma ray geophysical signature. In outcrop, the evaporite is altered leaving characteristic “boxwork” textures, usually dolomite in composition. Unit 1 is commonly associated with seeps and springs although, as Mueller (1990) points out, “all units in the Dripping Springs Valley can yield small quantities of fresh water”.

Unit 2 at the Oswald well is 50 ft thick and contains grainstone to wackestone, micritic-skeletal-coated grains and calcareous mudstone. Unit 3, which is 50 ft thick, can be identified in both the surface and subsurface cuttings characterized by the presence of abundant Orbitolina texana (foraminifera) fossils in a calcareous mudstone. Mollusk steinkerns and skeletal fragments are also common in argillaceous grainstone, packstone, and clay units.

Unit 3 was identified by Muller (1990) as the basal “aquitard” for the “shallow aquifer” contained in the overlying Units 4 and 5. This clay-prone unit outcrops in the vicinity of Dripping Springs (Fig. 3). It is located in the Onion Creek tributary bed of Blue Creek and others. It underlies units 4 and 5 in the city where shallow perched water is found at depths of 18 to 20 ft in construction boreholes.

Units 4 and 5 are a combined 55 ft thick in the Oswald well. They consist of interbedded dolomitic packstone, calcarenite, and mudstone. These two units form what Muller (1990) describes as the “shallow aquifer” in the Dripping Springs area. Several seeps and springs are associated with these units including the primary springs in town (Dripping Springs and Walnut Springs).

Unit 6 is 80 ft thick at the Oswald location where it consists of grainstone-packstone, skeletal-peloid-micritic limestone with miliolids, monoplurid rudists, and mudstone. It outcrops at the Dreyer borehole location and contains the Loriolia rosana maker bed (Figs. 1 and 3).

Units 7 and 8 (undifferentiated at the Oswald well) are about 100 ft thick and composed of alternating dolomites and dolomitic marls. Although poorly fossiliferous in the subsurface, beds with oysters and casts (steinkerns) of bivalves and gastropods are found in outcrop north of Dripping Springs.

Upper Glen Rose strata can be correlated from the Blanco County outcrop eastward along the Onion Creek watershed through the use of geophysical logs, cuttings samples, and outcropping beds. Cross section A-A’ (Figs. 1 and 2) connects a series of water-well boreholes with good geophysical log correlation from Oswald in the west, to the Maddux well in the east. Critical to the results of this study is the erosional thinning of the Upper Glen Rose section from 355 ft thick at the Oswald well to 40 ft thick at the Dripping Springs Public Water Supply Well No.1 (DSWSC #1; Fig. 2). Erosional thinning removed Unit 3 from portions of Onion Creek (Fig. 2) and in the bed of Onion Creek near DSWSC #1, the Upper Glen Rose Unit 1 is interpreted to be less than 20 ft thick. No Lower Glen Rose outcrop with the “Corbula Bed” was identified in the creek (Fig. 2), but the shallow contact is clearly recognized in nearby borehole geophysical logs of the DSWSC wells.

### Structure

Trinity Group strata dip eastward at 1 to 2 degrees from the outcrop of Paleozoic rocks of the Llano Uplift to the BFZ due to structural (depositional) dip. In the BFZ dips increase to the east due to structural (faulting) influences. Surface erosion from the Onion Creek headwaters downstream has a steeper gradient than the depositional dip, therefore older strata are exposed the farther east one moves from the headwaters until reaching the BFZ (Fig. 2).

Structures are known to influence groundwater flow in the Trinity Aquifer in the region (Hunt et al., 2015); however, there are no significant faults from the headwaters to about mile 29 downstream in the study area where the first mapped fault of the BFZ is encountered (Figs. 1 and 3). Minor faults and fractures are present above mile 29 (Fig. 1). Below about mile 29, northeast-southwest trending normal faults of the BFZ have been mapped cutting across Onion Creek and appear to influence the course of the creek. Monoclinal-folding, trending northeast-southwest, associated with suspected fracture zones has been interpreted from structural mapping of the Cow Creek formation, but these features were not observed at the surface (Wierman et al., 2010). The Upper Glen Rose west of the BFZ and may mask fault trends in the study area. For example, northwest-trending faults in the Lower Glen Rose exposed along the Blanco River are along strike with fractures and minor faults and lineament trends mapped in the Onion Creek watershed (Fig. 1).

Fracturing plays an important role in the hydrogeology of the creek and solution-enlarged fractures are commonly observed. Thin-bedded limestones and dolomites of the Upper Glen Rose are commonly fractured and contain multiple-modal fracture sets. Vertical fractures exposed in outcrop cut through the more competent carbonate beds, but show no obvious indications of slippage.

## HYDROGEOLOGY

The Edwards and Trinity Aquifers are the two major aquifer systems in the study area. The Trinity Aquifers are composed of diverse Trinity Group units, which are organized into three regional hydrostratigraphic units: the Upper, Middle, and Lower Trinity. The Edwards Aquifer overlies the Trinity Aquifers, but faulting has juxtaposed the two aquifers in the BFZ (Ashworth, 1983; Barker and Ardis, 1996; Barker et al., 1994; Mace et al., 2000). The Trinity Aquifers underlie the western portion of the study area while the Edwards Aquifer underlies the eastern portion of the study area.

The Upper Trinity Aquifer is composed of the Upper Glen Rose Member and is discussed in the next section. The Middle Trinity Aquifer consists of the Lower Glen Rose, Hensel, and Cow Creek Formations. All units of the Middle Trinity are carbonates and karstic. 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 (Fig. 2). The Hensel is a water-bearing unit west of the study area and eastward becomes a confining, or semi-confining unit, 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 rudist reef facies which has vertical and lateral heterogeneity. Regional groundwater flow directions in the Middle Trinity generally follow the regional dip of the strata which is to the southeast (Mace et al., 2000; Hunt, et al., 2009; Wierman et al., 2010). The Hammett Shale, an important regional confining unit, separates the Middle and Lower Trinity Aquifers (Fig. 2). The Lower Trinity Aquifer is composed of the Sligo and Hosston Formations and is increasingly becoming targeted for groundwater production in the Hill Country due to limits on the overlying aquifers. The Lower Trinity is beyond the scope of this paper and the reader is referred to Wierman et al., (2010) for more information.

Current numerical groundwater flow models of the Trinity Aquifer reflect a conceptual model of water-bearing units functioning as a leaky aquifer system (Muller, 1990; Jones et al., 2011). For this study area, recharge in the numerical model (Jones et al., 2011) was distributed over the surface as 4% of annual precipitation. Recharge to the Middle Trinity is modeled to occur as direct recharge where exposed, or percolation through the Upper Glen Rose. In this study area, the model considers streams and rivers (such as Onion Creek and the Blanco River) as drains from the aquifer rather than sources of recharge to the aquifer (Jones et al., 2011).

Little work has been done on the surface-water and groundwater interactions (recharge) along Onion Creek over the Trinity Aquifers that could inform the conceptual and numerical models. This was true for the Blanco River until the recent study of Smith et al. (2014) that demonstrated the Blanco River has complex surface-water and groundwater interactions with alternating gaining and losing reaches present during both high- and low-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, in part, from discrete recharge features (karst features) that drain water from the river into the aquifer. Some of that water comes back out as springflow, but some remains in the Middle Trinity.

Onion Creek may be hydrogeologically similar to the Blanco River providing recharge to the Middle Trinity Aquifer. Statements by Muller (1990) about the Dripping Springs Water Supply Corporation well field adjacent to Onion Creek support that hypothesis:

> “Onion Creek may serve as a source of recharge for the system at the WSC well field. Consequently, any pollution to Onion Creek could result in contamination to the Lower Glen Rose (Deep) aquifer which is hydrologically connected to the underlying water-bearing units of the Trinity Group aquifer currently providing ground water to the WSC well.”

## Upper Trinity Aquifer and Associated Springs

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 aquifers and aquitards (Muller, 1990). The Upper Trinity Aquifer is a complex and heterogeneous stacked and perched aquifer system with local to regional flow systems.

One of the important hydrologic functions of the Upper Trinity Aquifer is to provide baseflows to the streams of the Hill Country, such as Onion Creek. The Upper Trinity section in the study area is characterized by numerous small seeps and springs. Many of the springs are reported as perennial (Ashworth, 1983). 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 (Barker et al., 1994). Indeed, the area of outcropping Upper Trinity units in the study area is concurrent with what the TCEQ designates as the "Contributing Zone of the Edwards Aquifer" (TCEQ, 2008).

The Upper Trinity Aquifer is not considered a significant regional aquifer in the Hill Country, or the Onion Creek watershed. The Upper Trinity typically has low yield and generally poor water quality (Ashworth, 1983). Wells are typically completed today in the Middle Trinity Aquifer and to a lesser extent, the Lower Trinity Aquifer. Historically the Upper Trinity was an important aquifer and water supply for the ranching communities throughout the Hill Country. Private homes and ranches line the wooded banks of Onion Creek, and the city of Dripping Springs derives its name from springs emanating from an Upper Glen Rose outcrop. The shallow depth to groundwater allowed for the early development of the City of Dripping Springs. However, in the past 10 years, or more, there have been hundreds of wells drilled in northern Hays County with few, if any, wells completed solely within the Upper Glen Rose (personal communication, Alex Broun).

Historically there have been several localized areas of low-volume residential groundwater production from the Upper Trinity, such as the area around Dripping Springs. Depth to water in the Dripping Springs area can range from less than one foot to 60 ft. The shallow water producing zones of the Upper Glen Rose are Units 4 and 5, with these zones being perched on top of Unit 3 (Muller, 1990). Springs have been observed to originate at the interface of Zones 3 and 4, such as the Dripping Springs and Blue Creek Spring.

Due to lack of a sufficient number of wells with consistent well completions in the Upper Glen Rose, which has localized areas of perched groundwater, it is difficult to determine groundwater flow directions on a regional basis. Shallow groundwater flow and subsequent discharge occurs in seeps in topographic lows and in streams and their tributaries. Muller (1990) indicated groundwater flow in the upper, shallow units to be generally southwesterly towards Onion Creek within the City of Dripping Springs, although there is a northerly component of flow north of Highway 290.

### Geochemistry

Water geochemistry was reviewed in order to help characterize surface-groundwater interactions. Surface-water chemistry of Onion Creek shows low concentrations of nutrients typical of Hill Country creeks (Mabe, 2007). Nitrate-nitrogen concentrations measured downstream of RR12 in 2014 to 2015 averaged 0.087 mg/L (detection limit of 0.008 mg/L). However, gradual increases in nutrient concentrations are evident and likely due to population growth. Mahler et al. (2011) report concentrations of nitrate that have increased six to ten times from 1990 to 2008 compared to the 2008 to 2010 time period in a study that included two sites on Onion Creek. They attribute the change to an increase in the number of septic tanks and land application of treated wastewater based on isotopic compositions. Gilroy and Richter (2011) show statistically significant spatial increases in nitrate and sulfate from upstream creek reaches to the USGS gauge at Farm to Market 150 (FM 150) and a significant temporal increase in chloride at the FM 150 gauge. The Texas Commission on Environmental Quality (TCEQ, 2014) has added Onion Creek to its 303(d) list as impaired for sulfate.

## METHODS AND DATA SOURCES

Flow monitoring sites were selected based on stream channel conditions and accessibility. Sites were identified according to characteristics described in Turnipseed and Sauer (2010). Ideal characteristics include sites with relatively straight channels with uniform flow free of obstructions creating eddies, slack water, and turbulence. Deep-water sites with low velocities were also avoided.

A total of 69 sites in the study area were directly measured or qualitatively described during the study period January through December 2015. Field work and flow measurements began January 2015 as part of the reconnaissance and selection of sites prior to the July synoptic event. Most sites were measured multiple times prior to the July and November synoptic events. Thirty-five of the sites were located directly on the main Onion Creek channel with the remainder situated along tributaries. Two springs in smaller tributaries were also measured directly. Qualitative observations of flow were limited to the very low flows primarily in tributaries or where no flow existed in the main channel of Onion Creek (Table 1). All the measured and qualitative flow data and metadata were compiled into a geodatabase. Original FlowTracker files are archived at the Barton Springs/Edwards Aquifer Conservation District (BSEACD). Queries of the database were used to create maps (ArcMap™) and hydrographs (Goldenware Grapher™) used in this report.

A total of a 196 quantitative and qualitative measurements were made during the study period. Of these, 139 measurements were made using the flow measurement techniques described herein. The quantitative wading measurements of streamflow were made using acoustic Doppler velocimeters (ADV) (Fig. 4). The Hays Trinity Groundwater Conservation District (HTGCD), BSEACD, and the City of Austin (CoA) used a hand-held FlowTracker ADV manufactured by SonTek/YSI. The FlowTracker ADV is mounted on a standard wading rod and measures currents in 2D and provides discrete data on depth and velocity. Techniques and standards for making discharge measurements at streamflow gaging stations are described in Turnipseed and Sauer (2010) and Nolan et al. (2007). Data collected for this project generally followed the standards and protocols cited above. For example, the FlowTracker was used to collect data at each station using the “0.6 method” for water less than 1.5 ft deep, or the “0.2/0.8 method” for 1.5 ft and deeper water. Both FlowTracker units used in this study were calibrated by the U.S. Geological Survey (USGS) Hydrologic Instrumentation Facility within 6 months of field use.

Uncertainty estimates of each discharge measurement are calculated by FlowTracker and are stored in each electronic file and are reported in Table 1. The two methods for calculating uncertainty in the FlowTracker are the International Organization for Standardization (ISO, 2003) and the Statistical (also called “Stats”; Sauer and Meyer, 1992) methods. The ISO is a published international method and is widely used to estimate an average uncertainty. Using the ISO method for data from the main channel of Onion Creek (n=45) the average uncertainty is about 3.7% (range 2.1-8.3%). The Statistical Method was developed by the U.S. Geological

Survey and is the preferred method to estimate uncertainty according to the manufacturer of the FlowTracker (Huhta and Sloat, 2007). The Stats method estimated an average uncertainty for the main channel of Onion Creek (n=45) of about 7.3% (range 1.7-30.4%). The high 30.4 value was over the Edwards Recharge zone and could be omitted as an outlier and thus error is reduced to an average of 6.7%. Many agencies rate data as "good" if the uncertainty is within 5% and "fair" if the uncertainty is within 8% (Huhta and Sloat, 2007). Levels of uncertainty are higher for data from smaller tributary channels and also for low-flow conditions, when compared to uncertainty within larger channels and higher flow conditions.

Continuous stream flow values were obtained from the USGS site at the Driftwood station (site 08158700; USGS, 2016). For this study, a new gaging site was established below the Ranch Road 12 Bridge at Onion Creek. An absolute pressure transducer (In-Situ Rugged Troll 100) was attached to the bridge pier in the stream during the period of study. The probe is rated for 15 psi and recorded gage height every 10 minutes. A rating curve for flow was not developed for this site.

Continuous water-level data were obtained online from the Texas Water Development Board's automated water-level database (TWDB, 2016a) for the Hanks well (State well number 5755607). Data for the DSWSC#2 (5756703) were obtained from the Hays Trinity Groundwater Conservation District (unpub. data). Both wells are completed in the Middle Trinity and are very close (<300 ft) to Onion Creek. All four of the DSWSC wells (Nos. 1-4) are in relative close proximity and completed in the Middle Trinity Aquifer. Geophysical log information for the cross section was obtained from DSWSC #1 (5756702). DSWSC #1 was originally completed in the Lower Trinity, but was recompleted in 2014 as a Middle Trinity well. The DSWSC #1 well has a continuous water-level recorder maintained by the TWDB.

Well completion information from DSWSC and the TWDB was reviewed for DSWSC wells 1-4. Wells 1, 3 and 4 appear to be cased and grouted with cement from the ground surface down to the Cow Creek. Information available for the completion of DSWSC #2 is inconsistent. Further investigation is needed to confirm the completion for DSWSC #2. A fifth well is located near well DSWSC #3. The well is capped and may be a previous test well. To date, no construction information on this well has been found.

Water-chemistry data in the Onion Creek watershed are available from TWDB for wells and springs (TWDB, 2016b), the U.S. Geological Survey (USGS, 2016) for surface water from a gauge at FM 150, and the City of Austin for surface water (CoA, unpub. data). Geochemical data were obtained from DSWSC #2 (5756703) and #3 (5756704) (TWDB, 2016b).

Detailed geologic and hydrogeologic data were incorporated into the evaluation to understand the hydrogeologic significance of the data (HTGCD and BSEACD, unpub. data). Geologic data include measured sections (Fig. 1) and outcrop descriptions combined with published literature (Fig. 3).

## RESULTS

Flow measurements and site information from the main channel of Onion Creek from the two synoptic events in July and November 2015 are presented in Table 1. Additional measurements were taken in the tributaries and main channel during these two synoptic events (Figs. 5 and 6). Results show a complex interaction of surface and groundwater with losing and gaining reaches of creeks and tributaries to Onion Creek. Generalized reaches of Onion Creek and South Onion Creek, that show net losses in flow for both synoptic events, are indicated in map view on Figures 5 and 6. Additional confirmation measurements along the losing stretch were made in December 2015 (Table 1; Fig. 7). Figure 7 shows flow in the main channel versus distance from the headwaters of Onion Creek and illustrates the gains and losses of the main channel, with net losing reaches indicated. Results, summarized in Figure 8, indicate four distinct hydrogeologic reaches during both low- and high-flow conditions in the main channel of Onion Creek. Those reaches are described here as:

A. Upper Glen Rose net gaining reach #1: gains of 11 and 27 cfs from mile 0 (headwaters) to mile 13.
B. Upper Glen Rose net losing reach: net losses of 3 cfs with up to 17 cfs locally from mile 13 to mile 20. Figure 9 is a photograph of a karst feature within this reach. A flow of 0 cfs was recorded between synoptic events (September 2015), while reaches above and below had flow. Aerial photographs (Google Earth® dates 4/29/2006, 10/30/2008, and 3/23/2013) confirmed this as a dry (losing) reach of Onion Creek. Similarly, South Onion Creek from its confluence with Onion Creek, to about 3 miles upstream, is a losing reach with a loss of about 3 cfs.
C. Upper Glen Rose net gaining reach #2: gains of 21 and 84 cfs from mile 20 to mile 37.
D. Edwards Group net losing reach: losses of 29 and 108 cfs from mile 37 to mile 46 where water recharges through numerous karst features. This reach corresponds to the Edwards Aquifer Recharge Zone.

## DISCUSSION

### Surface-Water and Groundwater Exchange

It is well known that Upper Trinity seeps and springs provide baseflows and account for the gaining reaches to Onion Creek and its tributaries. It has been long established that the streams provide recharge to the Edwards Aquifer (Hill and Vaughn, 1898; Slade et al., 1986). However, this study, for the first time, documents reaches of Onion and South Onion Creeks that lose flow (Figs. 5-9) to the Upper and Middle Trinity Aquifers. The following lines of evidence suggest that the losing reaches of Onion and South Onion Creeks are one source of recharge to the Middle Trinity Aquifer.

First, under relatively high- and low-flow conditions the creek consistently loses flow in the same areas. The occurrence of karst features in these reaches supports that this is a losing creek (Fig. 9).

Second, potentiometric surfaces (Hunt et al., 2009) and Middle Trinity monitor wells along the creek support a downward flow potential under wet and dry hydrologic conditions from Onion Creek to the Middle Trinity Aquifer. Depth to water in the Middle Trinity Aquifer from the ground surface can range from 100 to 200 ft at the Hanks well and 25 to 150 ft at DSWSC #2 (Figs. 10 and 11).

Third, recharge in the losing reaches elevates groundwater levels. The hydrograph for DSWSC #2 (5756703), which is primarily Cow Creek production (Middle Trinity), shows a rapid response to high creek flows during heavy rainfall that may be from recharge of the surrounding surface runoff (Fig. 10). Additionally, high flow in the creek appears to result in increased recharge, and higher heads in the vicinity of the losing reaches of both Onion and South Onion Creeks. Figures 10 and 11 illustrate that higher elevations in water levels can occur in DSWSC#2 than the upgradient Hanks well (3.8 miles northwest) during periods of high creek flow.

Fourth, a relatively thin and fractured Upper Glen Rose may enhance recharge to the Middle Trinity Aquifer in this area. Based on the structural cross section in Figure 3 and other publications (Muller, 1990; Wierman, et al. 2010), there is only a very thin remnant of the Upper Glen Rose section in this area of about 20 ft.

Finally, isotope and ion geochemistry suggest recharge is occurring. Chemical analysis of groundwater samples from DSWSC wells #2 and #3 indicated an ion chemistry similar to surface water (Table 2; Figure 12). Isotopes of modern carbon resulted in 102% and 73% (TWDB, 2016b), respectively, indicating some portion of modern recharge from surface water. Relatively high levels of tritium (1.8 TU) in DSWSC#3 also suggest recent water (Table 2). Geochemistry and isotope samples were taken during the study period of June and July 2015.

While the evidence above indicates surface water recharging the Middle Trinity, and supported in part by data from the DSWSC wells, the magnitude of the surface recharge to the Middle Trinity Aquifer is unknown. For example, a logical conclusion from the data is that water produced from the Middle Trinity DSWSC wells is a mixture of both groundwater moving downgradient from the west and more localized recharge that varies in quantity as hydrologic conditions change.

Some of the recharging surface water along Onion Creek may resurface at springs downgradient of the losing creek reaches, while some of the water may also remain within the Upper Trinity and move down-gradient in the aquifer. In addition, geological surface mapping (Collins, 2002b) and field identification shows remnant outcrop of Quaternary terrace deposits (gravels) all along Onion Creek and its tributaries. Surface-water loss to these porous rocks may account for minor amounts of the measured flow loss along the reaches and subsequent gain as the creek cuts into these shallow deposits. However, this would not account for the additional evidence outlined above, indicating recharge to the Middle Trinity Aquifer from Onion Creek.

## Geochemistry

Analytical results for ion chemistry were separated on the basis of Upper and Middle Trinity Aquifers and surface water. Ion chemistry shows that springs discharging from the Upper and

Middle Trinity Aquifers are similar to surface water compositions and classified as calcium/bicarbonate-type waters (Fig. 12). This supports the conceptual model that springflows provide stream baseflows. However, groundwater from Upper and Middle Trinity wells have average concentrations that are magnesium/sulfate-type waters. Individually, wells from both the Upper and Middle Trinity Aquifers tend to be predominantly calcium rich with some enrichment in magnesium, but have a wide range in variation between bicarbonate and sulfate enrichment. The differences in individual wells are likely related to the variable depths and geologic units in which the wells are completed and the amount of gypsum in the formation. Specifically the geochemistry from the DSWSC #2 and #3 (Table 2; Figure 12) plots as calcium/bicarbonate water for some samples, similar to springs and surface water, suggesting a fresh-water signature. The variation from magnesium/sulfate-type waters to calcium/bicarbonate-type waters in each of these wells over time likely reflects local dynamic recharge from Onion Creek with relatively rapid transmission along karst features.

### Future Studies

These studies provide strong evidence that water flowing in Onion creek is recharging the Upper and Middle Trinity Aquifers along certain reaches of the streams. The greatest uncertainty of these studies is how much, how quickly, and under what conditions does recharge occur. In addition, other reaches of the creek that have a net gain in flow (reaches A and C) may still recharge the Upper and Middle Trinity Aquifers. However, more data would be needed to address that question.

To address these uncertainties the authors and various agencies and individuals are continuing to collect hydrogeologic data and plan additional studies. Future efforts or studies could involve: injecting dye into karst features (or losing creek reaches) and monitoring wells and downstream springs to establish the fate of creek-flow losses; more detailed synoptic flow studies and the establishment of additional stream gages with continuous recorders; additional surface and groundwater samples for chemical analysis, and dedicated monitor wells with discrete sampling zones.

## CONCLUSIONS

Results of this study indicate complex surface and groundwater interactions in the Onion Creek watershed. For the first time, flow losses are documented to occur along a creek reach underlain by the Upper Glen Rose that has implications for recharge to the Middle Trinity Aquifer. Flow losses combined with other hydrogeologic and geochemical data suggest Onion Creek provides recharge to the Upper and Middle Trinity Aquifer in those reaches. A better understanding of the surface water and groundwater interactions along the creek is important for groundwater and surface water management in an area undergoing significant population growth. These results will also guide future studies and influence changes to the conceptual model of the Trinity Aquifers.

## ACKNOWLEDGMENTS

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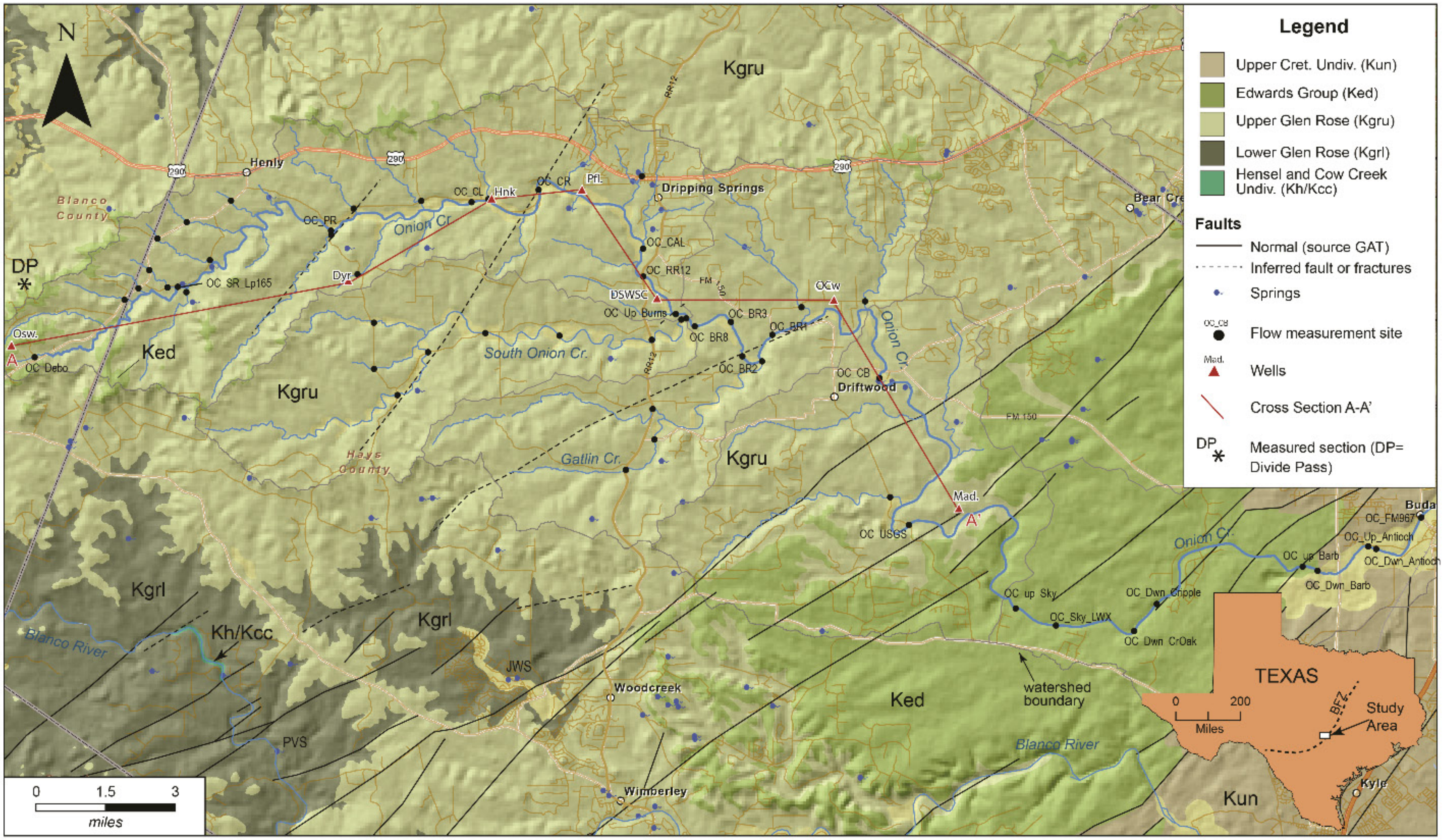

Figure 1. Location map of study area. Geologic base map from the Geologic Atlas of Texas (GAT). All sites are indicated (n=69), but only the main channel of Onion Creek results (n=22) are labeled and in Table 1.

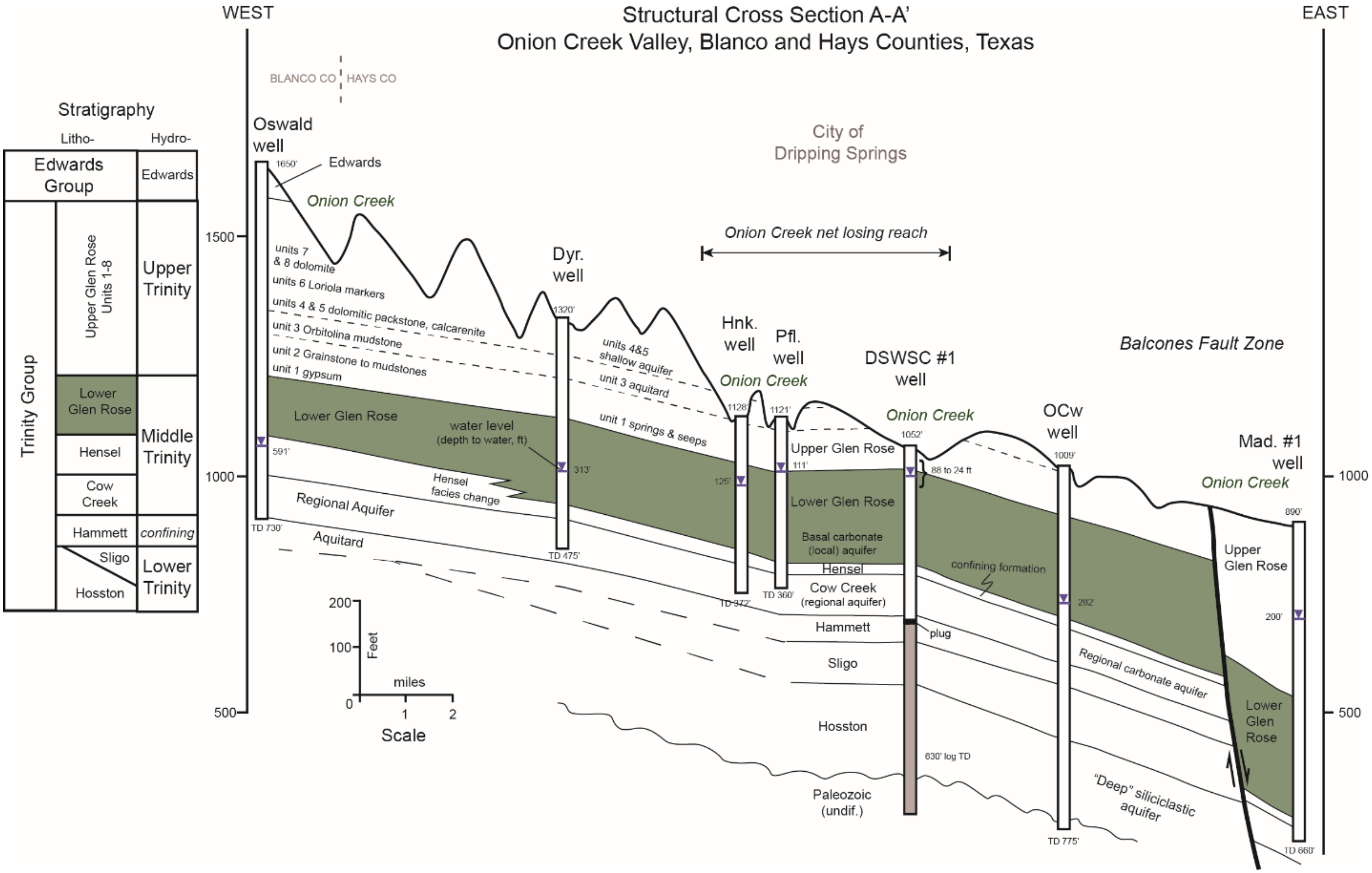

Figure 2. Structural cross section of study area and regional litho- and hydrostratigraphy. Line of section indicated on Figure 1. Note the thin Upper Glen Rose coinciding with the losing reach of Onion Creek in the area of the DSWSC well.

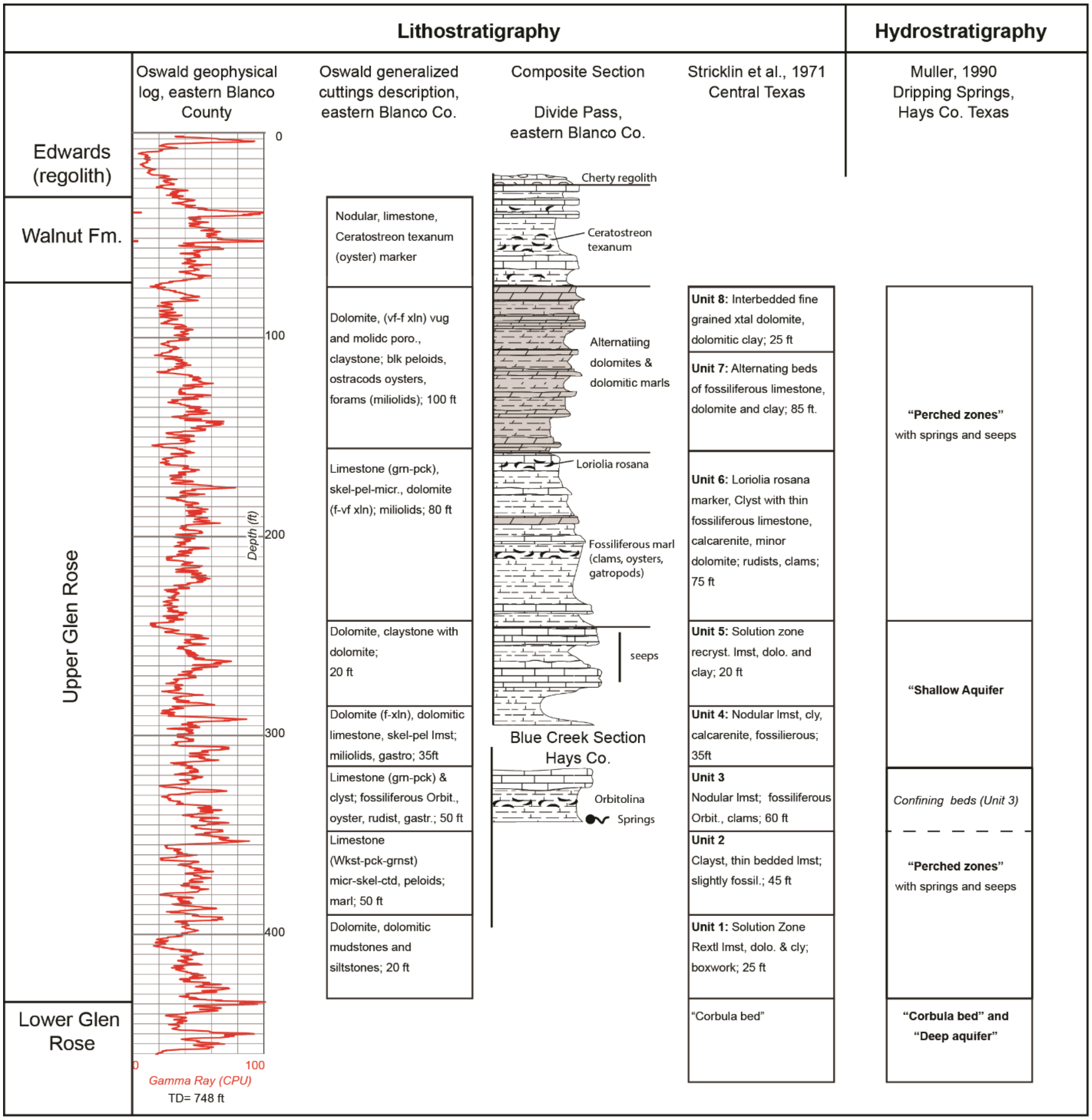

Figure 3. Study area lithostratigraphy and hydrostratigraphy focusing on the Upper Glen Rose member. Regional stratigraphy shown in Figure 2.

Figure 4. Photo of wading flow measurement using the FlowTracker instrument at the Onion Creek at FM 150 (USGS site). Photo taken 1/6/15.

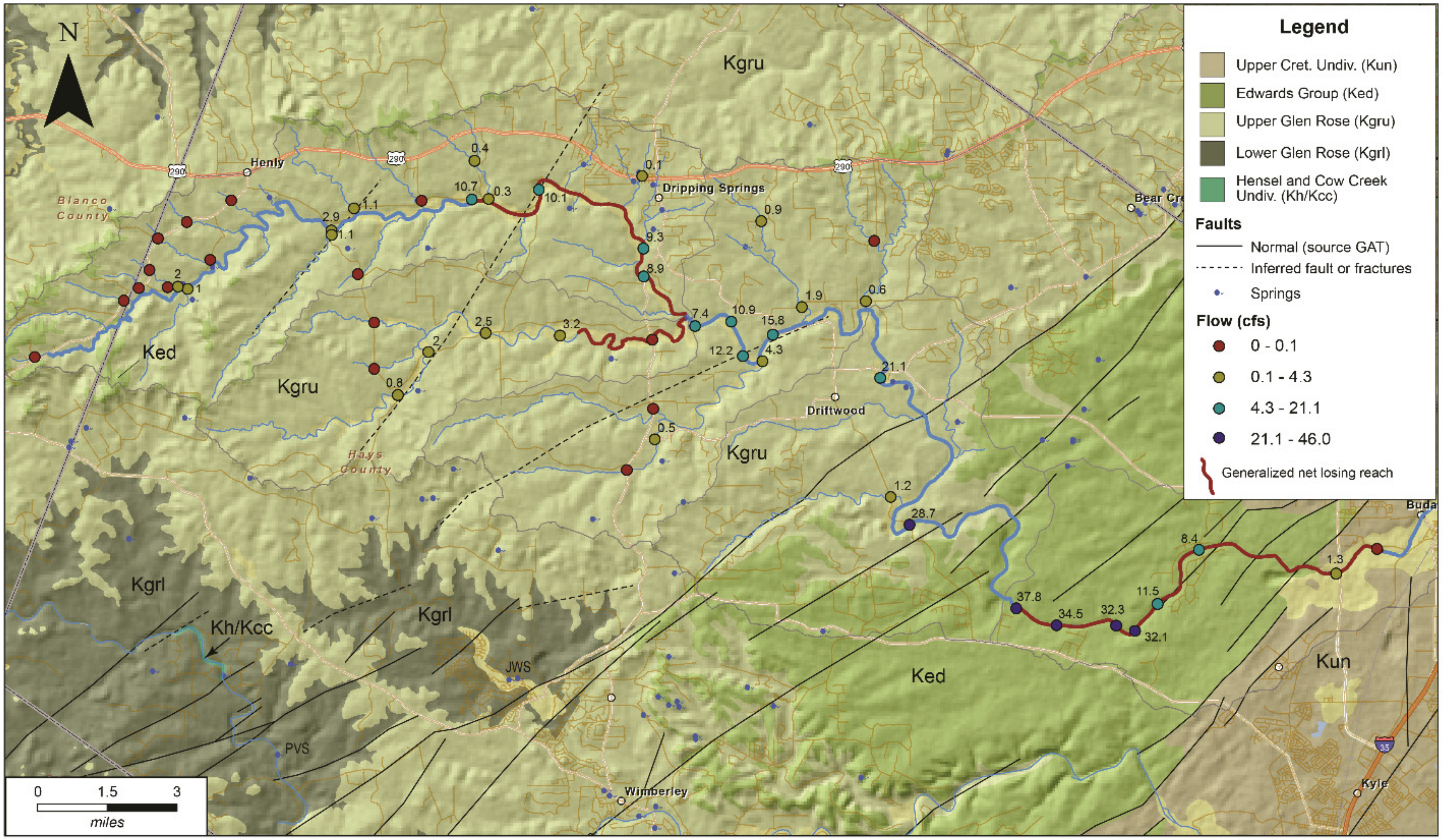

Figure 5. All flow results from the July 2015 synoptic event. The synoptic event included 21 sites in the main channel of Onion Creek and 20 sites in tributaries.

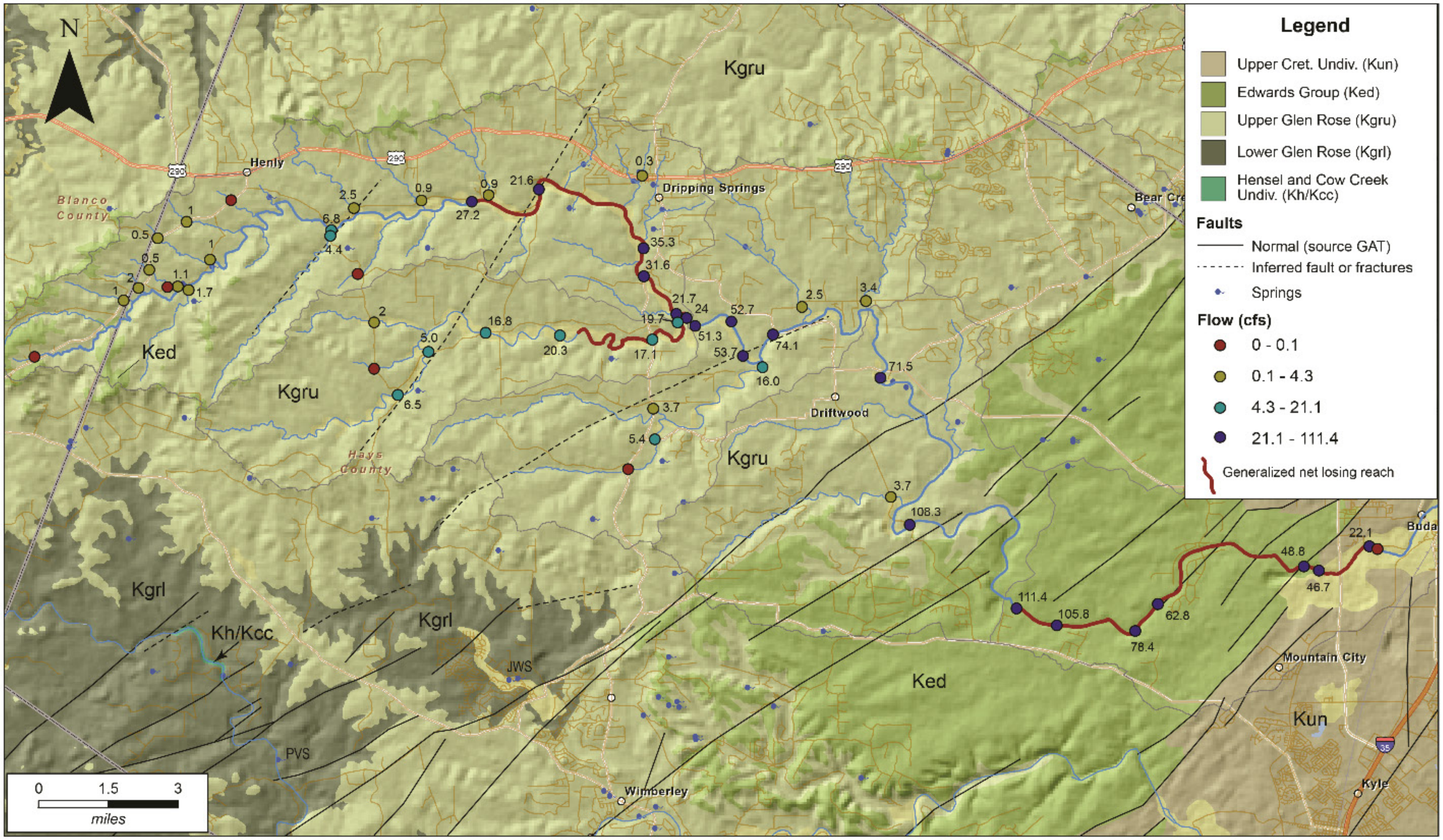

Figure 6. All flow results from the November 2015 synoptic event. The synoptic event included 22 sites in the main channel of Onion Creek and 20 sites in tributaries.

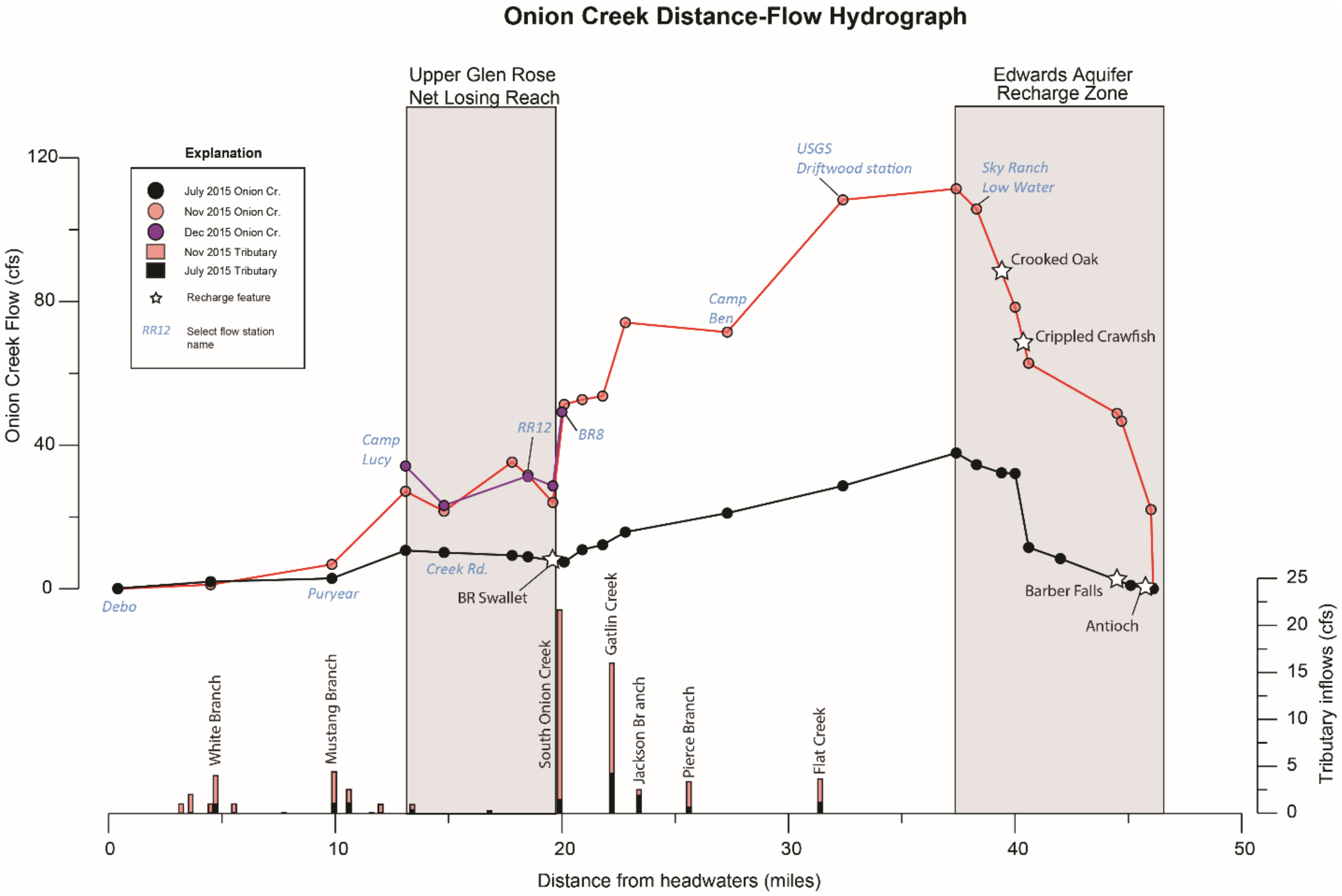
Onion Creek Distance-Flow Hydrograph

Figure 7. Flow in the main channel of Onion Creek plotted versus distance.

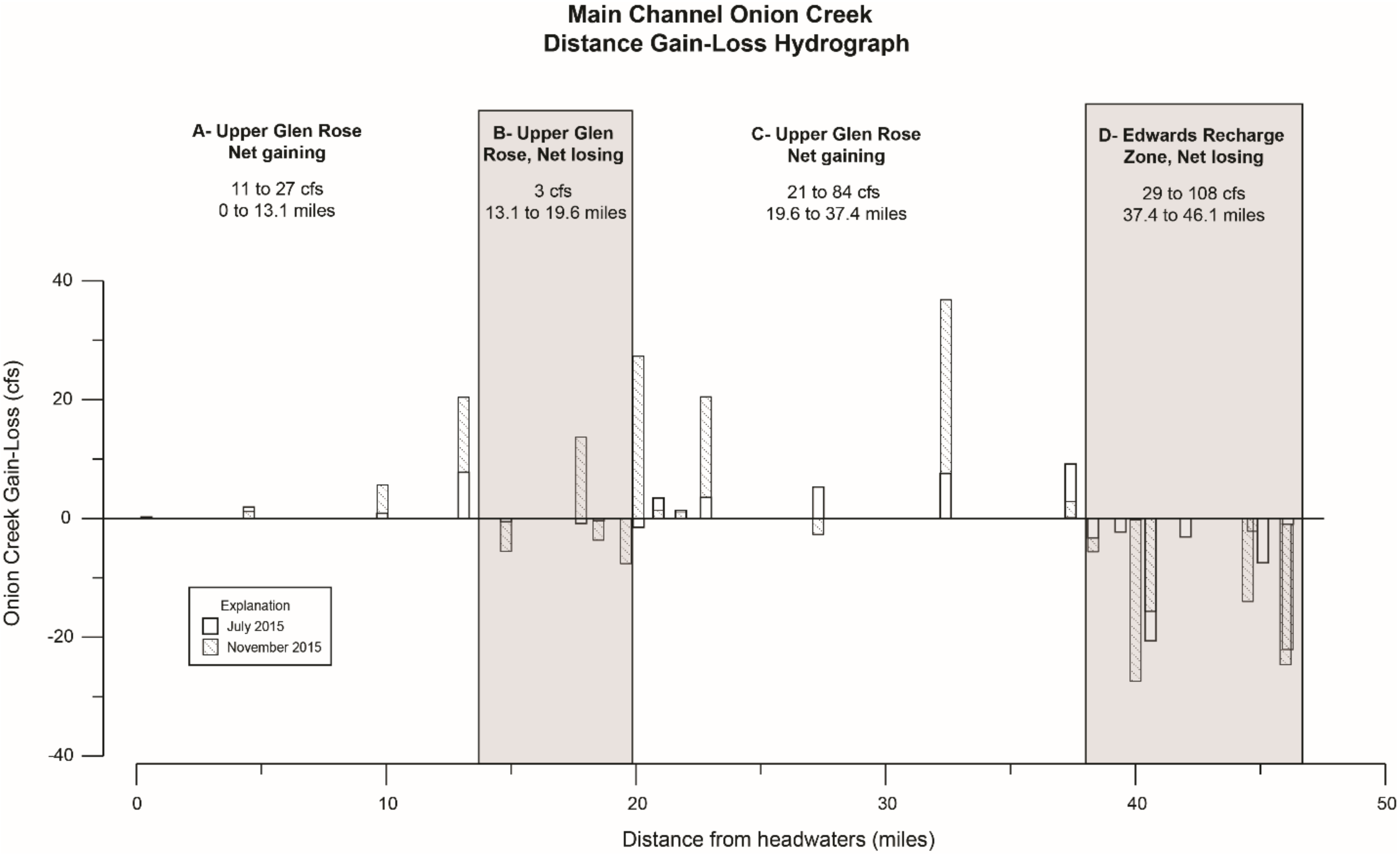

Figure 8. Flow gains and losses plotted versus distance. Data at each site represents the gain or loss from the preceding site immediately upstream in the main channel of Onion Creek.

Figure 9. Photograph of swallet (karstic sinking stream feature) within Onion Creek. The swallet is developed along fracture and water is whirlpooling into the rock at the tip of the hammer. Feature is within the identified losing reach of Onion Creek about 19.7 miles downstream from the headwaters. Photo taken 8/6/15.

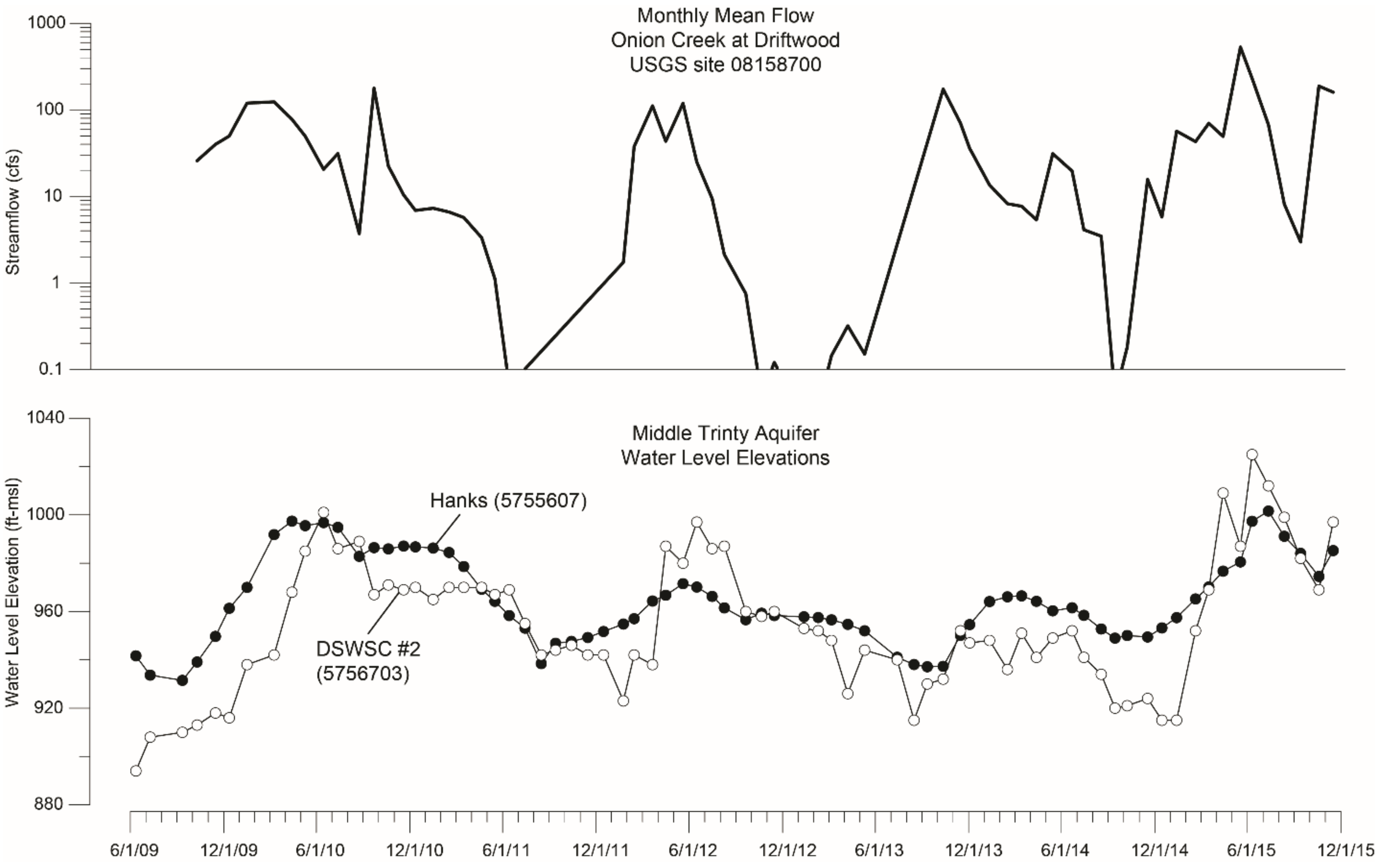

Figure 10. Hydrograph showing Onion Creek flows versus the Hanks well (5755607; TWDB, 2016a) and DSWSC #2 (5756703; HTGCD unpub. data), which are Middle Trinity Aquifer wells adjacent to Onion Creek. Note during wet periods, the DSWSC #2 well has a higher elevation than the upgradient Hanks well, which is located 3.8 miles to the northwest.

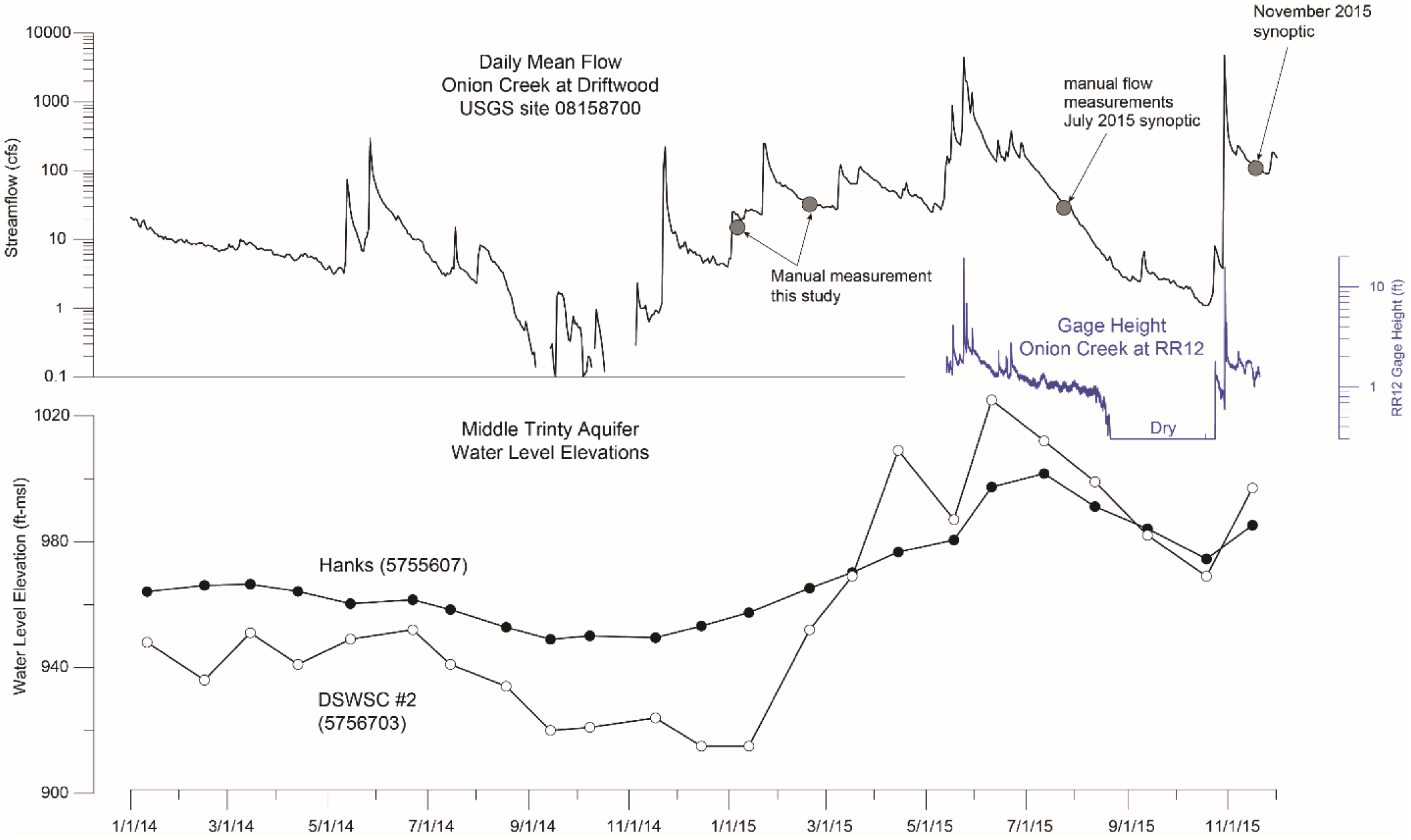

Figure 11. Hydrograph of Onion Creek flow (USGS, 2016) and Onion Creek at Ranch Road 12 gage height data with the Hanks well (5755607; TWDB, 2016a) and DSWSC #2 (5756703 HTGCD unpub. data), which are Middle Trinity Aquifer wells. Note that during each of the synoptic events, which occurred during a relatively wet year, the heads in the DSWSC#2 were higher than the upgradient Hanks well. Also note the general agreement of manual measurements taken during this study compared to the USGS Gaging station.

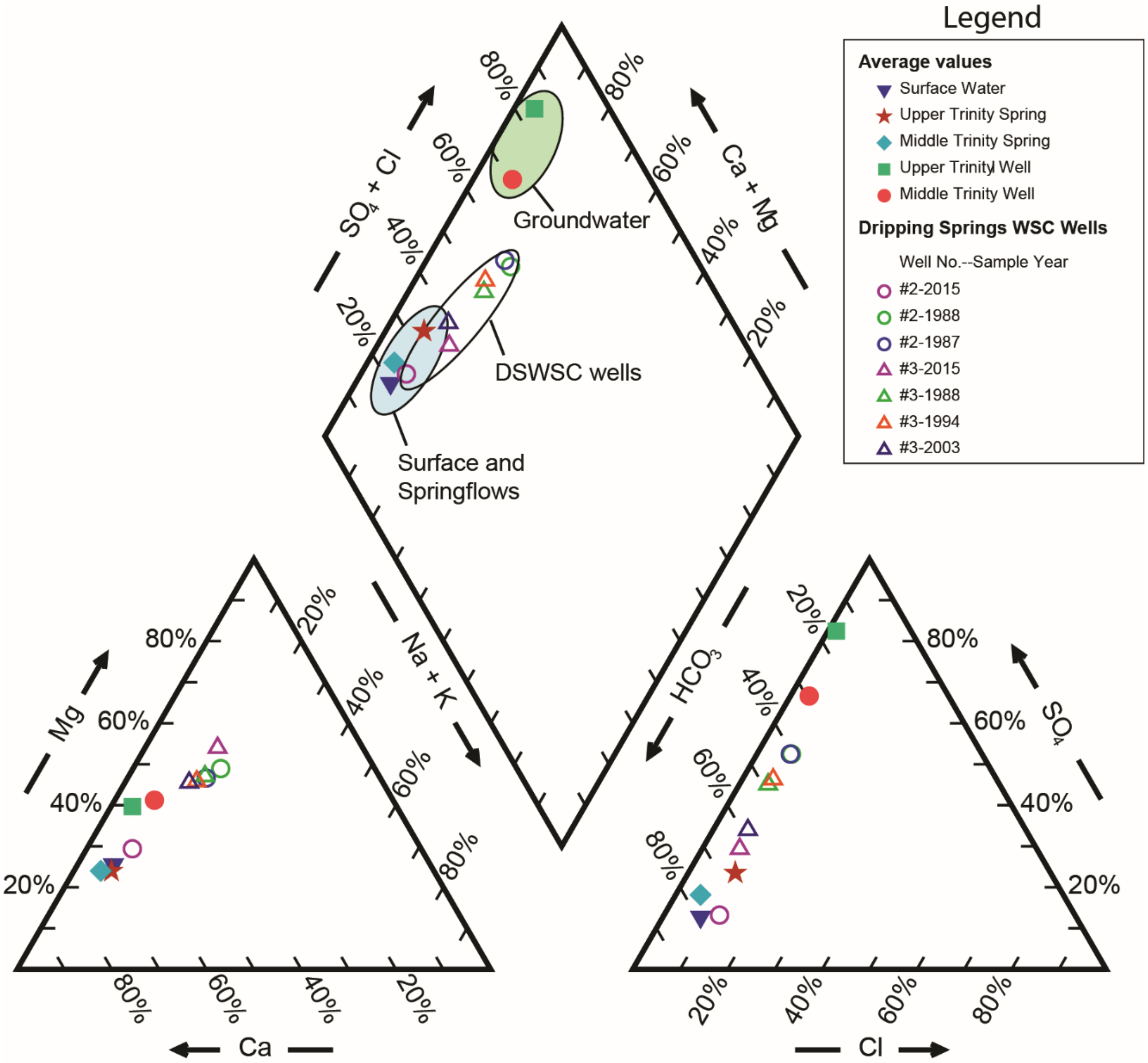

Figure 12. Piper diagram showing groundwater and surface-water geochemistry. All values are average except for the indicated DSWSC #2 and #3 wells, which represent single sampling events (Table 2). Note the variability of chemistry from the DSWSC wells with some samples overlapping surface-water chemistry. Samples taken in 2015 had similar chemistry as surface water in Onion Creek, and they contained high percent modern carbon and tritium, indicating a very young age of the water.

Table 1. Summary of flow results from main channel of Onion Creek for July and November 2015 synoptic events. Flag: o= qualitative flow observation; and m=quantitative flow measurement.

| Synoptic | Date | Site ID | Distance (miles) | Total Discharge (cfs) | Gain/loss (cfs)* | Site Name | Ddlat | Ddlong | flag | ISO % | Stats % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jul-15 | 7/23/2015 | OC_Debo | 0.4 | 0.1 |  | Onion Creek at Debo rd | 30.135695 | -98.281188 | o |  |  |
|  | 7/23/2015 | OC_SR_Lp165 | 4.5 | 2.0 | 1.9 | SR Loop 165 | 30.157570 | -98.236524 | o |  |  |
|  | 7/23/2015 | OC_PR | 9.9 | 2.9 | 0.9 | Onion Creek at Pursley Road | 30.175170 | -98.188690 | m | 4.5 | 2.2 |
|  | 7/23/2015 | OC_CL | 13.1 | 10.7 | 7.8 | Onion Creek at Camp Lucy | 30.184740 | -98.144780 | m | 4.7 | 17.9 |
|  | 7/23/2015 | OC_CR | 14.8 | 10.1 | -0.6 | Onion Creek at Creek Road | 30.187910 | -98.123860 | m | 5.7 | 18.2 |
|  | 7/23/2015 | OC_CAL | 17.8 | 9.3 | -0.8 | Caliterra | 30.169530 | -98.091338 | m | 6.2 | 5.1 |
|  | 7/23/2015 | OC_RR12 | 18.5 | 8.9 | -0.4 | Onion Creek at RR12 | 30.160780 | -98.091240 | m | 3.2 | 4.3 |
|  | 7/23/2015 | OC_BR8 | 20.1 | 7.4 | -1.5 | BR Ranch 8 | 30.145278 | -98.075195 | m | 3.7 | 14.0 |
|  | 7/23/2015 | OC_BR3 | 20.9 | 10.9 | 3.4 | BR Ranch 3 | 30.146664 | -98.063825 | m | 4.3 | 6.5 |
|  | 7/23/2015 | OC_BR2 | 21.8 | 12.2 | 1.4 | BR Ranch 2 | 30.135936 | -98.060247 | m | 3.5 | 6.4 |
|  | 7/23/2015 | OC_BR1 | 22.8 | 15.8 | 3.5 | BR Ranch 1 | 30.142650 | -98.050939 | m | 3.0 | 4.2 |
|  | 7/23/2015 | OC_CB | 27.3 | 21.1 | 5.3 | Onion Creek at Camp Ben | 30.129160 | -98.017420 | m | 3.8 | 3.6 |
|  | 7/24/2015 | OC_USGS | 32.4 | 28.7 | 7.6 | Onion Creek downstream USGS gauge | 30.083336 | -98.008231 | m | 4.1 | 4.8 |
|  | 7/17/2015 | OC_up_Sky | 37.4 | 37.8 | 9.2 | Upstream WQPL | 30.057325 | -97.974918 | m | 3.3 | 7.6 |
|  | 7/17/2015 | OC_Sky_LWX | 38.3 | 34.6 | -3.3 | Low-water Crossing | 30.051976 | -97.962332 | m | 5.6 | 22.6 |
|  | 7/17/2015 | OC_Up_CrOak | 39.4 | 32.3 | -2.3 | upstream of crooked oak | 30.051906 | -97.943807 | m | 2.8 | 6.5 |
|  | 7/17/2015 | OC_Dwn_CrOak | 40.0 | 32.1 | -0.2 | Upstream Crippled Crawfish | 30.050201 | -97.937917 | m | 3.7 | 5.7 |
|  | 7/17/2015 | OC_Dwn_Cripple | 40.6 | 11.5 | -20.6 | Downstream Crippled Crawfish | 30.058688 | -97.930834 | m | 3.2 | 14.2 |
|  | 7/16/2015 | OC_Ruby | 42.0 | 8.4 | -3.1 | Ruby Ranch | 30.075524 | -97.917959 | m | 2.8 | 11.8 |
|  | 7/16/2015 | OC_FM1626 | 45.1 | 1.0 | -7.4 | FM 1626 and Downstream Barber | 30.068084 | -97.875153 | m | 8.3 | 30.4 |
|  | 7/16/2015 | OC_Dwn_Antioch | 46.1 | 0.0 | -1.0 | Downstream Antioch | 30.075834 | -97.862412 | o |  |  |
| Nov-15 | 11/18/2015 | OC_Debo | 0.4 | 0.0 | 0.0 | Onion Creek at Debo rd | 30.135695 | -98.281188 | o |  |  |
|  | 11/20/2015 | OC_SR_Lp165 | 4.5 | 1.1 | 1.1 | SR Loop 165 | 30.157570 | -98.236524 | m | 5.0 | 11.9 |
|  | 11/19/2015 | OC_PR | 9.9 | 6.8 | 5.6 | Onion Creek at Pursley Road | 30.175170 | -98.188690 | m | 4.0 | 3.7 |
|  | 11/19/2015 | OC_CL | 13.1 | 27.2 | 20.4 | Onion Creek at Camp Lucy | 30.184740 | -98.144780 | m | 3.7 | 6.3 |
|  | 11/19/2015 | OC_CR | 14.8 | 21.6 | -5.6 | Onion Creek at Creek Road | 30.187910 | -98.123860 | m | 3.9 | 3.7 |
|  | 11/19/2015 | OC_CAL | 17.8 | 35.3 | 13.7 | Caliterra | 30.169530 | -98.091338 | m | 5.7 | 10.1 |
|  | 11/19/2015 | OC_RR12 | 18.5 | 31.6 | -3.6 | Onion Creek at RR12 | 30.160780 | -98.091240 | m | 3.2 | 12.7 |
|  | 11/19/2015 | OC_Up_BR | 19.6 | 24.0 | -7.6 | Upstream BR | 30.149065 | -98.081042 | m | 4.0 | 6.5 |
|  | 11/19/2015 | OC_BR8 | 20.1 | 51.3 | 27.3 | BR Ranch 8 | 30.145278 | -98.075195 | m | 4.0 | 5.8 |
|  | 11/19/2015 | OC_BR3 | 20.9 | 52.7 | 1.3 | BR Ranch 3 | 30.146664 | -98.063825 | m | 2.4 | 2.4 |
|  | 11/19/2015 | OC_BR2 | 21.8 | 53.7 | 1.0 | BR Ranch 2 | 30.135936 | -98.060247 | m | 2.9 | 1.7 |
|  | 11/19/2015 | OC_BR1 | 22.8 | 74.1 | 20.5 | BR Ranch 1 | 30.142650 | -98.050939 | m | 3.7 | 3.2 |
|  | 11/19/2015 | OC_CB | 27.3 | 71.5 | -2.7 | Onion Creek at Camp Ben | 30.129160 | -98.017420 | m | 3.1 | 2.6 |
|  | 11/18/2015 | OC_USGS | 32.4 | 108.3 | 36.8 | Onion Creek downstream USGS gauge | 30.083336 | -98.008231 | m | 2.6 | 2.3 |
|  | 11/18/2015 | OC_up_Sky | 37.4 | 111.4 | 3.1 | Upstream WQPL | 30.057325 | -97.974918 | m | 2.3 | 3.5 |
|  | 11/18/2015 | OC_Sky_LWX | 38.3 | 105.8 | -5.6 | Low-water Crossing | 30.051976 | -97.962332 | m | 2.4 | 3.8 |

|  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 11/18/2015 | OC_Dwn_CrOak | 40.0 | 78.4 | -27.4 | Upstream Crippled Crawfish | 30.050201 | -97.937917 | m | 2.1 | 3.0 |
|  | 11/18/2015 | OC_Dwn_Cripple | 40.6 | 62.8 | -15.6 | Downstream Crippled Crawfish | 30.058688 | -97.930834 | m | 2.7 | 5.7 |
|  | 11/18/2015 | OC_up_Barb | 44.5 | 48.8 | -14.0 | Upstream Barber Falls | 30.070363 | -97.885332 | m | 2.8 | 2.8 |
|  | 11/18/2015 | OC_Dwn_Barb | 44.7 | 46.7 | -2.2 | Downstream Barber Falls | 30.069022 | -97.880701 | m | 3.5 | 3.4 |
|  | 11/20/2015 | OC_Up_Antioch | 46.0 | 22.1 | -24.6 | Upstream Antioch | 30.076632 | -97.864871 | m | 4.8 | 5.7 |
|  | 11/20/2015 | OC_Dwn_Antioch | 46.1 | 0.0 | -22.1 | Downstream Antioch | 30.075834 | -97.862412 | o |  |  |
| **Dec-15** | 12/7/2015 | OC_CL | 13.1 | 34.2 |  | Onion Creek at Camp Lucy | 30.184740 | -98.144780 | m | 3.3 | 5.5 |
|  | 12/7/2015 | OC_CR | 14.8 | 23.2 | -11.0 | Onion Creek at Creek Road | 30.187910 | -98.123860 | m | 2.7 | 5.3 |
|  | 12/8/2015 | OC_CAL | 17.8 | 34 | 10.8 | Caliterra | 30.169530 | -98.091338 | m | 3.3 | 5.5 |
|  | 12/8/2015 | OC_RR12 | 18.5 | 31.4 | -2.6 | Onion Creek at Creek Road | 30.187910 | -98.123860 | m | 2.7 | 3.6 |
|  | 12/9/2015 | OC_Up_BR | 19.6 | 28.7 | -2.7 | Upstream BR | 30.149065 | -98.081042 | m | 3.1 | 7.0 |
|  | 12/9/2015 | OC_BR8 | 20.1 | 49.2 | 20.5 | BR Ranch 8 | 30.145278 | -98.075195 | m | 2.7 | 2.4 |
|  | 12/9/2015 | OC_USGS | 32.4 | 85.9 | 36.7 | Onion Creek downstream USGS gauge | 30.083336 | -98.008231 | m | 2.3 | 3.2 |
| ***from preceeding station** |  |  |  |  |  |  |  |  | Max | 8.3 | 30.4 |
|  |  |  |  |  |  |  |  |  | Min | 2.1 | 1.7 |
|  |  |  |  |  |  |  |  |  | avg | 3.7 | 7.3 |
|  |  |  |  |  |  |  |  |  | n | 45 | 45 |

Table 2. Summary of geochemical data used in Figure 12. Source of data includes USGS (2016), TWDB (2016b), and CoA (unpub. data).

| **Parameter** | **Units** | **Avg. Surface Water RR12** | **Avg. Surface Water USGS FM 150** | **Avg. Upper Trinity Spring** | **Avg. Middle Trinity Springs** | **Avg. Upper Trinity Wells** | **Avg. Middle Trinity Wells** | **DSWSC #2 (5756703)** | **DSWSC #2 (5756703)** | **DSWSC #2 (5756703)** | **DSWSC #2 (5756703)** | **DSWSC #3 (5756704)** | **DSWSC #3 (5756704)** | **DSWSC #3 (5756704)** | **DSWSC #3 (5756704)** | **DSWSC #3 (5756704)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | | | | | | | | 6/21/2016 | 7/20/2015 | 6/27/1988 | 7/28/1987 | 6/21/2016 | 6/1/2015 | 8/6/2003 | 6/28/1994 | 6/27/1988 |
| **Calcium** | mg/L | 76.8 | 71.0 | 118.9 | 93.8 | 342.3 | 182.4 | | 71.0 | 106.0 | 114.0 | | 60.4 | 76.6 | 97.0 | 95.0 |
| **Magnesium** | mg/L | 18.4 | 16.5 | 25.8 | 19.8 | 149.6 | 90.9 | | 20.9 | 98 | 88 | | 64.8 | 52.3 | 70 | 74 |
| **Sodium** | mg/L | 12.0 | 8.3 | 14.9 | 7.6 | 22.0 | 28.6 | | 11.7 | 61.0 | 52.0 | | 28.4 | 24.7 | 37.0 | 41.0 |
| **Potassium** | mg/L | 1.4 | 1.3 | 2.0 | 1.7 | 12.8 | 9.2 | | 1.8 | 15.0 | 11.0 | | 9.6 | 6.6 | 9.8 | 11.0 |
| **Bicarbonate** | mg/L | NT | 254.20 | 353.80 | 308.80 | 301.60 | 328.20 | | 265 | 395 | 388 | | 297 | 337 | 369 | 398 |
| **Sulfate** | mg/L | 40 | 33 | 101 | 59 | 1255 | 596 | | 37.7 | 411 | 397 | | 111 | 156 | 288 | 292 |
| **Chloride** | mg/L | 24.9 | 14.4 | 30.2 | 12.2 | 16.4 | 25.7 | | 23.6 | 42.0 | 39.0 | | 21.1 | 23.4 | 30.0 | 29.0 |
| **TDS** | mg/L | NT | 271.5 | 485.5 | 350.5 | 1970.5 | 1217.2 | | 308 | 943 | 930 | | 474 | 530 | 742 | 751 |
| **Alkalinity** | mg/L | 206 | 207 | 290 | 255 | 247 | 270 | | 217 | 324 | 318 | | 243 | 276 | 302 | 326 |
| **Fluoride** | mg/L | 0.2 | 0.2 | 0.3 | 0.2 | 1.9 | 1.6 | | 0.25 | 2.7 | 2.6 | | 1.2 | 1.79 | 2.14 | 2.3 |
| **NO2+NO3-N** | mg/L | 0.087 | 0.263** | 7.15 | 6.1 | 1.1 | 1.4 | | 0.04 | | | | 0.02* | 0.02* | 0.04 | 0.04* |
| **Spec Cond** | uS/cm | 521 | 488 | 692 | 562 | 2064 | 1451 | 489 | 557 | 1760 | 1705 | 686 | 692 | 874 | | 1377 |
| **pMC** | % | na | na | na | na | na | na | | 102 | na | na | | 73 | na | na | na |
| **Tritium** | TU | na | na | na | na | na | na | | na | na | na | | 1.8 | na | na | na |
| **COUNT** | | 13 | 103/161*** | 7 | 30 | 22 | 131 | | | | | | | | | |

***detection limit**

****Combined filtered and unfiltered samples**

***** 103 samples for ions and 161 for nitrate**

**na= not applicable**