Hydrogeology of the Saline Edwards Zone, Southeast Travis County, Central Texas

BSEACD Report of Investigations 2017-1015
October 2017

Barton Springs/Edwards Aquifer Conservation District
1124 Regal Row
Austin, Texas

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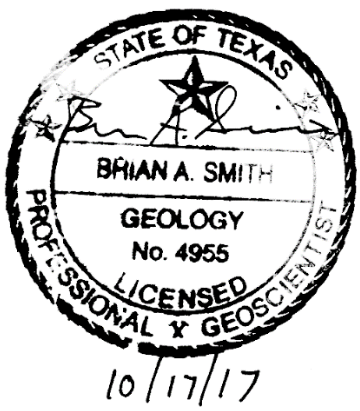
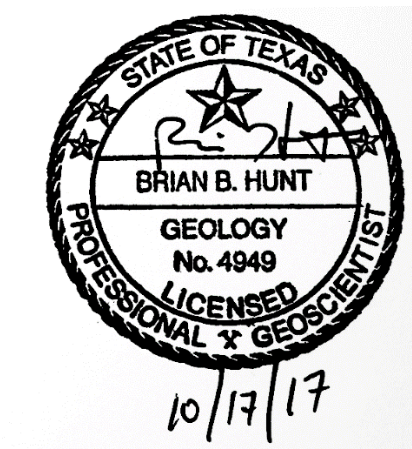
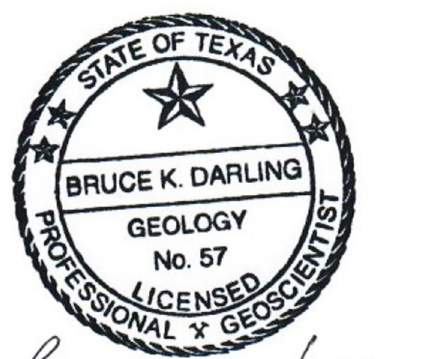




Geochemical evaluations and interpretation were performed by a licensed geoscientist of the Texas Board of Professional Geoscientists (TBPG).



Cover Page: Drilling of saline Edwards multiport well and pond with produced waters. Photograph taken August 2016.

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Aerial photograph of the multiport well (right side) and the water-holding tanks containing all produced water. Photo taken 11/2/2016.

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Summary

Increased demand for water in central Texas is causing water users and providers to look for additional sources of water. The saline portion of the Edwards Aquifer (saline Edwards Aquifer) has often been mentioned as a source of water for desalination or aquifer storage and recovery (ASR). The resource has not previously been considered by large water suppliers because of limitations of data, regulatory framework, and fear of saline encroachment into the freshwater Edwards. Recent legislative efforts combined with hydrogeologic and engineering studies have renewed interest in the saline Edwards Aquifer.

This report documents a hydrogeologic study conducted by the Barton Springs/Edwards Aquifer Conservation District (District) of the saline Edwards Aquifer in southeastern Travis County providing baseline information for an engineering study of desalinization and ASR. This hydrogeologic study is part of an engineering study is conducted by Carollo Engineers, Inc. and is partially funded by a Texas Water Development Board (TWDB) regional facility planning grant and the District.

In August 2016, a multiport monitor well was installed to a depth of 1,100 ft through the entire saline Edwards Aquifer with 18 permanently isolated zones from which head, water chemistry, and permeability data can be collected. Four zones were completed in the units overlying the Edwards Group and 14 zones were completed within the Edwards and associated units. Data collected in the multiport well allow for the detailed hydrogeologic characterization of the various units.

Hydrostratigraphy

Drilling properties, cuttings, geophysical logs, and multiport well data help to describe the hydrostratigraphy of the saline Edwards Aquifer. Data indicate confining units above the saline Edwards Aquifer include the overlying Taylor Clay, Austin Chalk, Eagle Ford (Zone 18), Buda (Zone 17), Del Rio Clay (Zone 16), and the Georgetown Formation (Zone 15). The top of the Edwards Group is at a depth of 564 ft from the surface. The saline Edwards Aquifer is defined in this study to include the Person Formation (Zones 12-14, 111 ft thick), Kainer Formation (Zones 3-11, 340 ft thick), and the top of the Upper Glen Rose (Zones 1 and 2; 75 ft thick). Zone 12 at the base of the Person Formation is the regional dense member (RDM, 22 ft thick) and appears to be an aquitard separating the Person and Kainer Formations. The Walnut Formation (Zone 3, 42 ft thick; aka Basal Nodular Member) has relatively low permeabililty and may also be an aquitard between the Edwards Group and the top of the Upper Glen Rose units.

Head values

Depth to water from land surface in the Edwards zones varied from 36 to 38 ft after conversion to freshwater equivalents. The highest heads within the Edwards are within the Kainer Formation (Zones 4-11) which are about 2 ft higher than the overlying Person Formation (Zones 12-14). This vertical distribution of heads appears to be similar to the data presented in the Kyle transect wells to the south (Thomas et al., 2010). Lateral gradients indicate that heads in the saline zone are generally higher than in the freshwater Edwards, especially during drought conditions. This suggest that the flow potential is from the saline zone in the east to the freshwater zone in the west. During wet periods there is potential for the gradient to reverse. However, there is a time lag in head changes between the saline and freshwater Edwards.

Permeability

Slug testing data indicate transmissivity values range over orders of magnitude between 0.02 and 15,000 ft^2/day in the saline Edwards units. Cuttings and thin sections indicate the majority of the Edwards Group from the borehole to be dolomite or dolomitic in composition and contain a high degree of intercrystalline and moldic porosity. Estimates of well yield in this study indicate the Person Formation (Zones 14 and 13; 79 ft thick; 2,470 ft^2/d) and Kainer Formation (Zones 4-11; 271 ft thick, 7,140 ft^2/d) could have well yields greater than 1,300 gallons per minute (gpm) and 4,300 gpm, respectively.

Geochemistry

Geochemical data compiled for this investigation illustrate that the composition of groundwater from hydrostratigraphic zones 1 to 11, 13 and 14 is a sodium-chloride type water, with variable concentrations of total dissolved solids. TDS increases from 13,000 mg/L in the Upper Glen Rose (Zone 2, -1,025 ft) to 18,500 mg/L in the Kainer formation (Zone 6, -855 ft) and decreases to 13,500 mg/L at the top of the Kainer (Zone 11, -685 ft). Above the Regional Dense Member aquitard (Zone 12), TDS is less than 9,400 mg/L in the Person formation (Zones 13 and 14, -615 ft and -575 ft, respectively). Although the origin of salinity remains unknown, the geochemical data appear to allow for the elimination of at least two potential sources of salinity: seawater (or residual seawater) and halite dissolution.

Results from this hydrogeologic study indicate that the saline Edwards Aquifer can serve as a source of water for a desalination facility and as a reservoir for ASR.

Introduction

The saline portion of the Edwards Aquifer (saline Edwards Aquifer) has often been mentioned as a source of water for desalination or aquifer storage and recovery (ASR). However, because of limitations of data, the regulatory framework, and potential costs, the resource has not been considered by water suppliers. The Barton Spring/Edwards Aquifer Conservation District (District) has developed rules to encourage desalinization and ASR projects within the saline Edwards. Furthermore, Senate Bill 1532, passed in2013, allowed specific pilot testing for the feasibility of these projects.

In 2015, the District was awarded a regional facility planning grant (TWDB Grant No. 1548321870) to study the feasibility of ASR and desalinization for the saline Edwards Aquifer. A kickoff meeting with stakeholders was held on February 25, 2016. Participants in the study include Texas Disposal Systems, Texas State University, Creedmoor-Maha Water Corporation, cities of Kyle, Buda, and San Marcos, and Hays and Travis Counties. The main subcontractor for the project is Carollo Engineers, Inc., with subcontractors ASR Systems LLC and NewGen LLC.

The District's role was to help provide hydrogeologic characterization for the study. This report documents the installation of a multiport well and hydrogeologic data collected from the well.

Study Area

The study area is within southern Travis County about 1.5 miles east of the freshwater Edwards Aquifer in the Balcones Fault Zone (BFZ). The freshwater aquifer segment is known as the Barton Springs segment of the Edwards Aquifer (**Figure 1**). The location of the multiport well is on the property of Texas Disposal Systems, Inc.

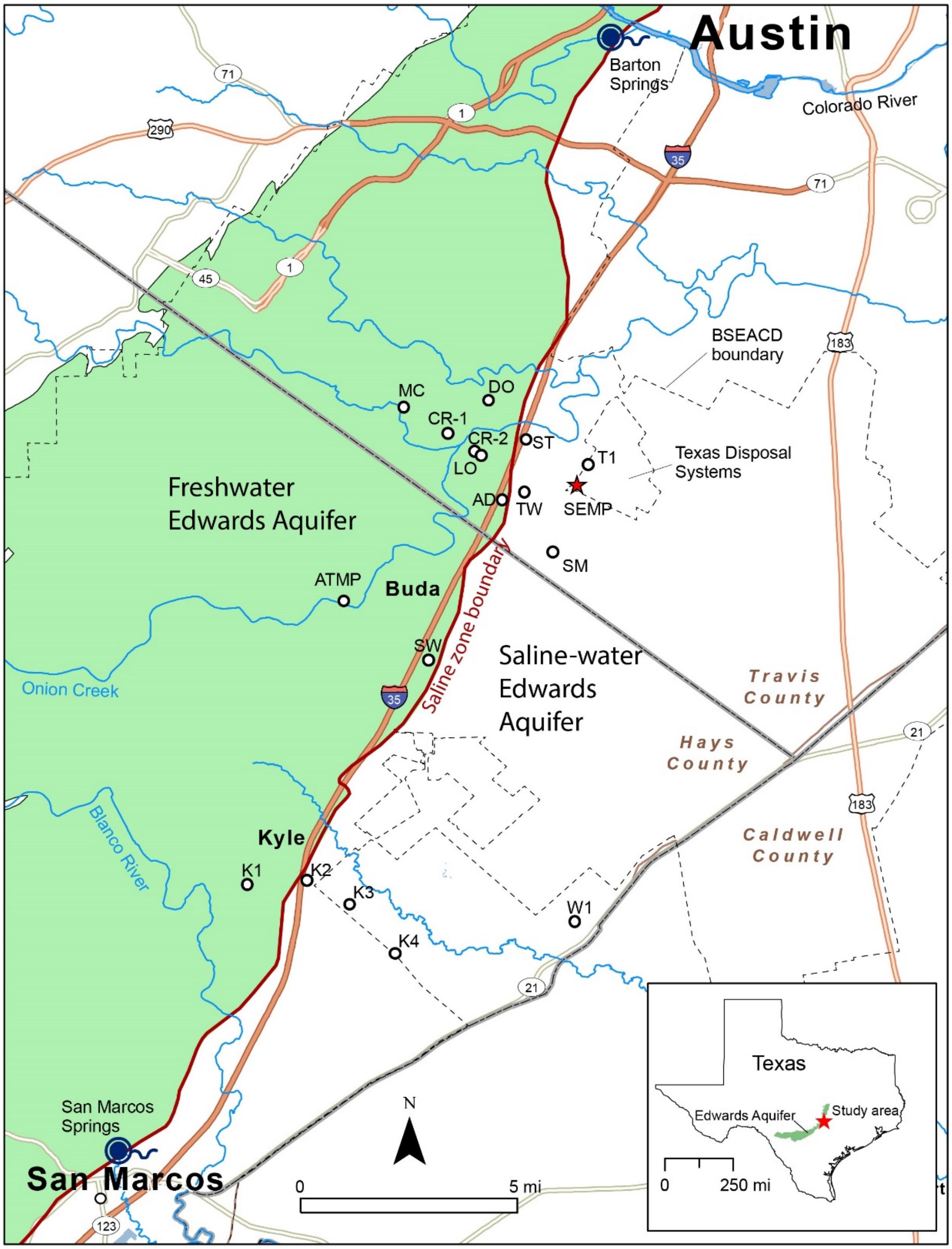


Figure 1. *Location map of the Barton Springs segment of the Edwards Aquifer. The focus of this study is east of the freshwater Edwards Aquifer in Hays and Travis Counties. Saline boundary from Hunt et al., 2014. Wells of interest noted in this study include (from south to north): K1-K4, Kyle transect; W1, Walton test well; SW, Sweeney monitor well; ATMP, Antioch multiport well; SM, Sunfield monitor well; AD, Adkins well; TW, TWDB test well; SEMP, multiport well; T1, TDS test well; ST, St. Albans well; CR, Creedmoor-Maha; MC, McCoys monitor well; and DO, Dowell monitor well.*

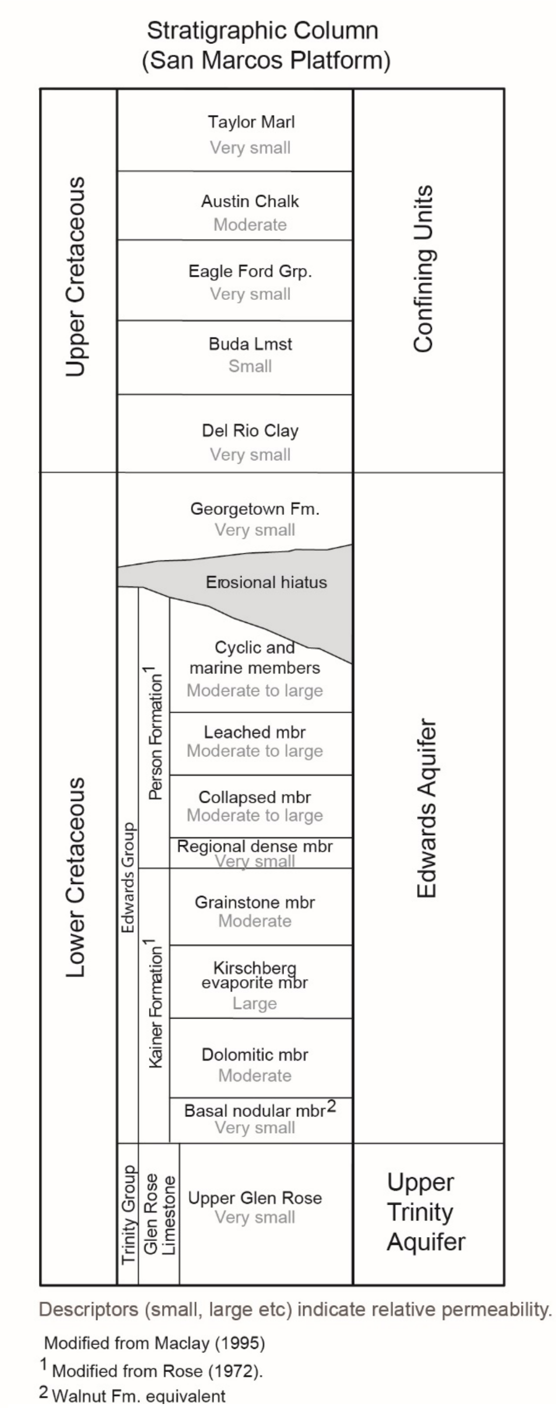


***Figure 2.** Regional stratigraphic column and hydrostratigraphy in the study area.*

Geology

The Edwards Aquifer is composed of about 450 feet of limestone and dolomite of the Cretaceous Edwards Group and Georgetown Formation (**Figures 2 and 3**). The carbonate sediments that make up the Edwards Group accumulated on the Comanche Shelf as shallow marine, intertidal, and supratidal deposits. The Georgetown Formation, disconformably overlying the Edwards Group, was deposited in a more openly circulated, shallow-marine environment (Rose, 1972).

Structure

The Balcones Fault Zone (BFZ) produces the prominent physiographic feature known as the Balcones Escarpment in central Texas. The BFZ is a dominant structural feature extending in an arcuate pattern from Del Rio along the border with Mexico, toward Dallas in north Texas. The BFZ trends from west to east near San Antonio then changes to a northeast trend near Austin. The BFZ is a fault system consisting of numerous normal faults with hanging walls generally dropping down toward the Gulf of Mexico with displacements ranging from 100 to 800 ft. There are up to 1,200 ft of total displacement across the BFZ. Faults are generally steeply dipping (45-85 degrees) with stratigraphy a fundamental control on the geometries and dips (Ferrill and Morris, 2007). The faults are described as "*en echelon*," which indicates closely-spaced, overlapping and subparallel. Depending on location, the faults can occur at oblique angles to the overall regional structural trend. The faults extend down into the Ouachita rocks (Paleozoic) and may also pass into extensionally reactivated Ouachita faults (Ewing, 1991); but they may also have listric geometries that terminate or sole out into shales at depth (Collins and Hovorka, 1997).

In the study area, faults generally trend to the NE (Figure 3) with steep dips to the southeast (**Figure 4**) (Brune and Duffin, 1983; Collins and Hovorka, 1997). Mapped faults in the study area and proximal to the well include a NE-trending normal fault with about 100 ft of throw down to the southeast (**Figure 3**).

Structure contours of the bottom of the Edwards Aquifer are shown on **Figure 3**. Steep gradients occur within the BFZ and locally where significant faulting has offset the units. In the study area, from the freshwater boundary to about 600 ft east of the multiport well, the contours indicate a structural dip of the Edwards of about 240 ft per mile.

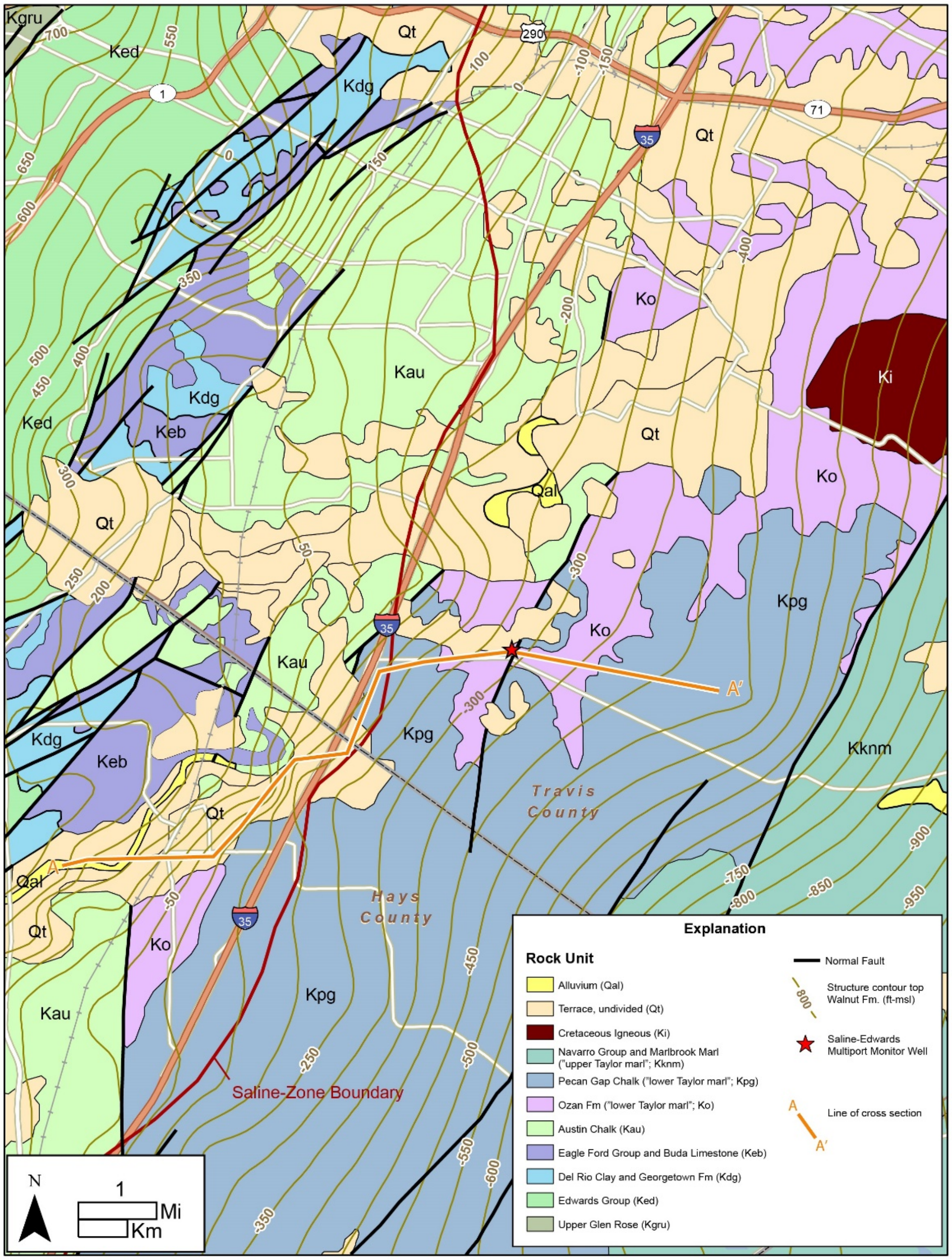
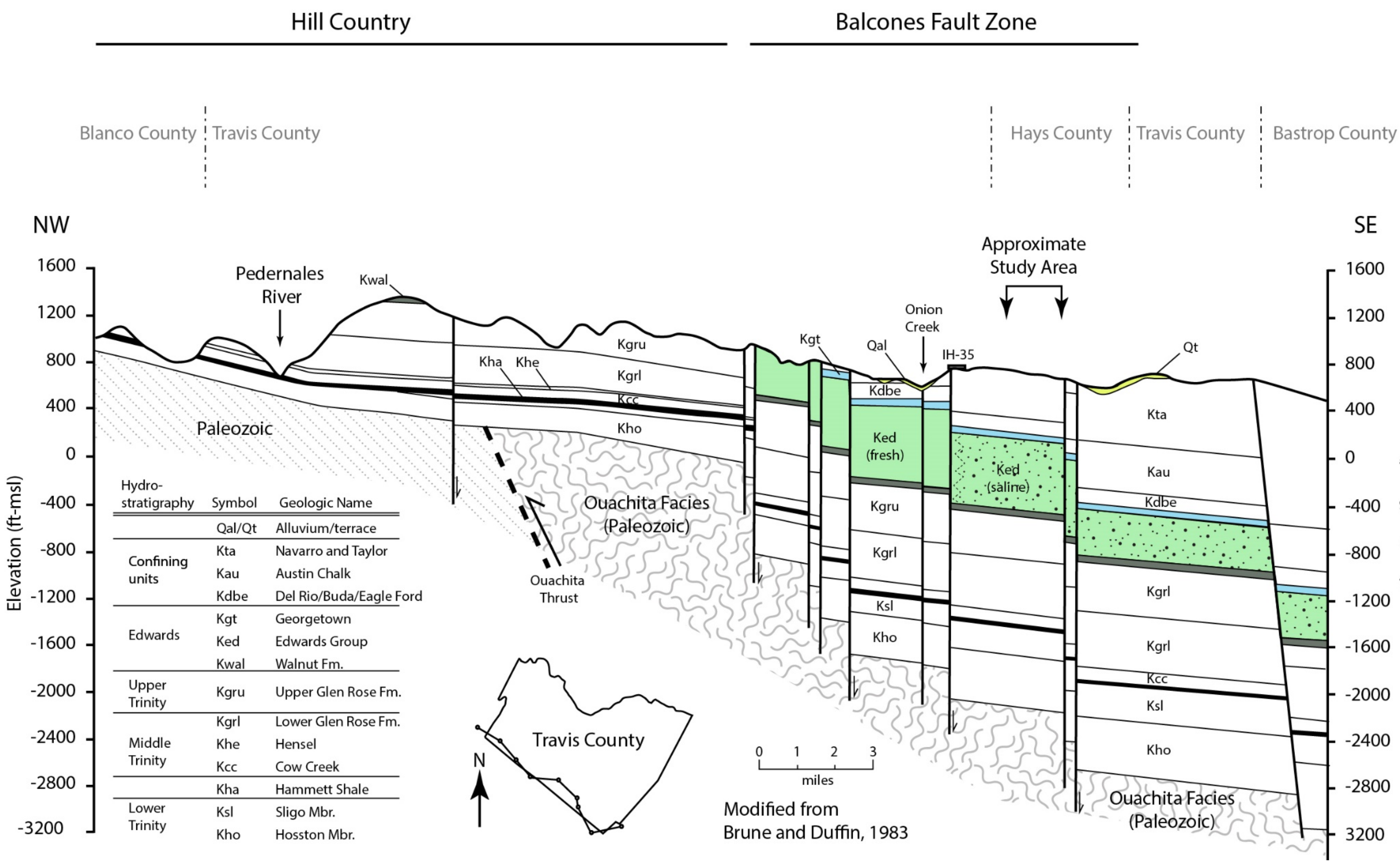


Figure 3. *Geologic map and structure contour of the Walnut (base of the Edwards). Geologic map from the Geologic Atlas of Texas (GAT). Structure contour units in feet above mean sea level (source: BSEACD unpublished data). Cross section A-A' shown in Figure 14.*



Hydro-stratigraphy	Symbol	Geologic Name
	Qal/Qt	Alluvium/terrace
Confining units	Kta	Navarro and Taylor
	Kau	Austin Chalk
	Kdbe	Del Rio/Buda/Eagle Ford
Edwards	Kgt	Georgetown
	Ked	Edwards Group
	Kwal	Walnut Fm.
Upper Trinity	Kgru	Upper Glen Rose Fm.
Middle Trinity	Kgrl	Lower Glen Rose Fm.
	Khe	Hensel
	Kcc	Cow Creek
	Kha	Hammett Shale
Lower Trinity	Ksl	Sligo Mbr.
	Kho	Hosston Mbr.

Figure 4. *Regional cross section modified after Brune and Duffin, 1983.*

Hydrogeology

The Edwards Aquifer (**Figures 1 and 2**) is a significant water supply for 2 million overall people in central Texas, and its renowned springs, such as Comal, San Marcos, and Barton Springs, provide habitat for a variety of endangered species and recreational opportunities for residents and visitors.

The Edwards and Trinity Aquifers of central Texas are stratigraphically stacked and structurally juxtaposed in the BFZ. Studies have long recognized the importance of faulting for the development of the Edwards Aquifer (Hill and Vaughan, 1898; DeCook, 1963; Abbott, 1975; Sharp, 1990). The freshwater Edwards Aquifer is a karst aquifer developed in faulted and fractured limestones and dolomites (**Figures 3 and 4**). 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; Ferrill et al., 2004). Development of the freshwater Edwards Aquifer was influenced significantly by fracturing and faulting and subsequent dissolution of limestone and dolomite units by infiltrating meteoric water (Abbott, 1975; Sharp, 1990; Hovorka et al., 1996; Hovorka et al., 1998; Barker and Ardis, 1996; Small et al., 1996). In addition, development of the aquifer is also thought to have been influenced by deep dissolution processes along the freshwater/saline-water interface, what is known as hypogene speleogenesis (Klimchouk, 2007; Schindel et al., 2008). Permeability is generally enhanced parallel to faults and fractures and decreases perpendicular to faults and fractures in the Edwards Aquifer (Maclay and Small, 1986; Hovorka et al., 1996; Ferrill et al., 2004; Ferrill et al., 2008).

Saline Edwards Aquifer

The saline Edwards Aquifer is defined as the Edwards Group rock units that contain water with greater than 1,000 mg/L total dissolved solids (**Figures 1 and 4**). The saline Edwards Aquifer occurs east (in the Austin area) and south (in the San Antonio area) of the freshwater Edwards Aquifer. Fluids in the Edwards Group rocks are described as Na-Ca-Cl brines that have increasing salinities (up to 290,000 mg/L) down-dip to the eastern extent of the subsurface Edwards Group equivalent rocks known as the Stuart City Reef (Land and Prezbindownski, 1981). Because of limitations placed on pumping the freshwater Edwards Aquifer, the saline Edwards Aquifer has been viewed as a potential alternative source of water for desalinization or as a reservoir for aquifer storage and recovery (ASR).

Total dissolved solids (TDS) is a measure of water salinity and reflects the amount of dissolved minerals in units of milligrams per liter (mg/L), or parts per million (ppm). Terms used to describe the salinity of water are not consistent. **Table 1** provides a summary of definitions and terms for the area of interest. In this report the term “saline” is used synonymously with the term “brackish”. The term “saline zone” is used to describe the area east of the freshwater zone where groundwater can be produced that contains greater than 1,000 mg/L TDS. Water with less than 1,000 mg/L is considered fresh, generally does not need treatment, and is suitable for most uses. Brackish groundwater generally describes water with 1,000 to 10,000 mg/L TDS (George et al., 2011; NGWA, 2010). Water with greater than 1,500 mg/L TDS may be used for irrigation, depending on the concentrations of certain ions (chloride, sodium etc.). Water with up to 3,000 mg/L TDS can be suitable for livestock (George et al., 2011).

Table 1. *Summary of definitions and terms*

Term	TDS (mg/L)	Source	Comment
Freshwater	< 1,000	George et al., 2011	This is also the threshold for secondary drinking water standards set by the TCEQ*.
Brackish water	1,000 to 10,000	NGWA, 2010	
Slightly saline	1,000 to 3,000	NGWA, 2010	
Moderately saline	3,000 to 10,000	NGWA, 2010	
Highly saline	10,000 to 35,000	NGWA, 2010	
Brine	>35,000		Salinity of seawater is about 35,000 mg/L

*EPA and the WHO have a secondary standard of 500 mg/L

Freshwater/saline-water Interface

The freshwater/saline-water interface represents a transition from the rapid-flowing freshwater system to the slow-moving saline fluids down dip of the freshwater Edwards Aquifer. Hydrogeologic characteristics of the freshwater/saline-water interface of the Edwards Aquifer have been studied for some time. In the study area the interface (boundary) between the freshwater and saline-water zones of the Edwards Aquifer were first mapped by Petitt and George (1956). As new data and studies of the boundary have become available, it has been periodically refined (Flores, 1990; Schultz, 1993; Hunt et al., 2014). Maps and cross sections have been generated that indicate the salinity of Edwards groundwater east and west of the freshwater/saline-water interface (**Figures 1 and 4**; Hunt et al., 2014; SWRI, 2003; Flores 1990; LBG-Guyton, 2003; Brune and Duffin, 1983; Baker, et al., 1986).

The freshwater/saline-water interface is often depicted as a two-dimensional (X-Y) boundary. In fact it is a very complex boundary that has three (Z) and four (time) dimensional variability not represented by a simple map boundary (**Figures 1 and 4**). The boundary is likely not vertical because of the heterogeneity of the lithologic units in the Edwards overprinted by diagenesis, structure, and the variable densities of the water.

While faulting has long been known to influence the formation and processes within the freshwater Edwards Aquifer, less is known about the role of structure in the formation or hydrologic functioning of the saline Edwards Aquifer. Petitt and George (1956) first note that faults appear to influence the freshwater/saline-water interface in some locations, but not in others. In Hays and Travis Counties, Baker et al., 1986 reported that faulting appears to have a strong influence on the interface, which parallels mapped faults. However, inspection of **Figure 3** illustrates that this may not be a consistent effect as the interface is mapped northward toward the Colorado River at high angles to mapped faults. Lambert et al. (2010) discuss a well drilled on the freshwater/saline-water interface (**Figure 1; Supplement 1**). The data and conceptualized diagram for this well clearly indicate a wedge of saline water below the freshwater-bearing intervals extending about 1 mile southeast to northwest between two faults.

Studies have established a somewhat muted hydrologic connection between the freshwater and saline zones (Senger and Kreitler, 1984; Slade et al., 1986; Mahler, 2008; Lambert et al., 2010). Increases in salinity at Barton Springs and some wells during drought conditions, when hydraulic gradients from the saline zone are toward the freshwater zone, support that hypothesis (Slade et al., 1986; Garner and Mahler, 2007). However, substantial increases in salinity have not occurred to date despite severe droughts and heavy pumping. This lack of increased salinity supports the ideas of Groschen and Buszka (1997) that substantial flows of saline water into the freshwater zone are unlikely due the compartmentalization (both vertical and horizontal isolation) of the Edwards saline zone.

Hunt et al. (2014) show TDS values in certain wells along the interface vary over time and could be interpreted as indicating saline-water encroachment. However, most of these wells are open well bores that are likely drilled across a complex, non-vertical freshwater/saline-water interface. Accordingly, the boreholes themselves may be pathways for an apparent "encroachment" of salinity as hydrologic conditions vary. This is supported by Lambert et al. (2010) who document intra-aquifer flow within the borehole and flow reversals with changing hydrologic conditions. Competing heads within a borehole drilled across different hydrogeologic units is a likely explanation for the sudden conductivity changes within a monitor well near Barton Springs (Hunt et al., 2014; 58-50-216).

San Antonio Water System (SAWS), in partnership with the U.S. Geological Survey (USGS), has installed about 20 monitor wells in 6 transects across the freshwater/saline-water interface to provide data about possible movement of the interface. The four wells installed along the Kyle transect, about 10 miles south of the study area, are most analogous to this study (**Figure 1; Supplement 1**). The average lateral flow potential (based on heads) in the Kyle transect area (Hays County) is from the saline zone into the freshwater zone (Lambert et al., 2010). However, they conclude that the data for all the wells suggest that the interface is likely to remain stable laterally and vertically over time.

Modeling results of a USGS study (Brakefield et al., 2015) support the idea that the freshwater/saline-water interface is in fact relatively stable and has little potential for movement of significant amounts of saline water into the freshwater zone. Conversely, the risk of movement of freshwater into the saline zone is also assumed to be low. The USGS study simulated the drought of record and high rates of pumping.

Source of Saline Water

Considering that these lithologic units were deposited on a broad, shallow, carbonate shelf, lithologies of Edwards units are the same on either side of the freshwater/saline-water interface. The rocks experienced the same amount burial, diagenetic, and structural history on either side of the interface. The primary difference between Edwards units on either side of the freshwater/saline-water interface is the degree of (late) diagenesis and dissolution as the rocks on the west side became exposed to the flow of fresh (meteoric) water (Abbott, 1975; Hovorka et al., 1996). Flux of freshwater has been high in the freshwater Edwards Aquifer. This flux of slightly acidic water has dissolved a considerable amount of limestone and dolomite along faults, fractures, bedding planes, and within the matrices. Significant conduits have developed along some of these zones that facilitate flow of even greater quantities of water. In contrast the amount of water flowing through the saline Edwards Aquifer is considerably less and therefore less dissolution takes place. However, there is some dissolution, but the minerals that are dissolved from the rock are not carried away from the zone of dissolution as quickly as the area to the west, and therefore concentrations of dissolved minerals increase. The presence of evaporite minerals in the rocks may also contribute to the high values of total dissolved solids in the water east of the interface. Evaporites were once present in the Edwards units east and west of the interface, but early diagenesis has removed these much of these minerals (Hovorka et al., 1996).

One possible explanation for the high salinity of the saline zone is that the mineral constituents are from the original formation water from the time of deposition. However the chemistry of some parts of the saline Edwards is sodium-chloride water with high sulfate, which indicates that the dissolved constituents are from dissolution of the host rock, including evaporites, rather than just primary formation fluids.

Oetting et al. (1996) looked at geochemical and isotopic parameters for the origin of the saline waters. They found that the saline waters were largely a result of fluid-rock interaction and fluid mixing processes reflecting a diversity of geochemical evolution pathways. For this study area Oetting et al., (1996) describe the area as Na-Cl facies resulting from fluid mixing between meteoric water, Edwards Group brines, and saline groundwaters from the underlying Glen Rose Formation.

Groschen and Buszka (1997) present a detailed study of the hydrogeologic framework and the geochemistry of the saline-water zone. Using hydrogen and oxygen isotopes they identified two hydrological and geochemical regimes in the saline-water zone. The first one, a shallower updip regime of predominantly meteoric water recharged from the freshwater zone; and the second, a deeper downdip regime that is thermally altered, hydrologically stagant, and much older. They further describe the saline zone as hydrologically compartmentalized due (in part) to faults that impede updip and downdip flow. They conclude that substantial amounts of updip flow of saline water toward the freshwater zone is unlikely.

Another theory suggests that saline fluids from deeper in the basin have migrated into this area and have dissolved portions of the rock due to mixing of saline and freshwaters creating highly permeable rocks east of the interface (Hovorka et al., 1996). The source of salinity for the deep basinal brines in the Edwards Group is reported to be the underlying Middle Jurassic evaporites (Land and Prezbindownski, 1981). Zones of caves and karst have developed by this mechanism of dissolution in some parts of the world (Klimchouk, 2007; George Veni, personal communication).

Saline Edwards Groundwater Availability

The study area is composed of the saline Edwards Aquifer within the northern subdivision of Groundwater Management Area 10. As mandated by Texas Water Code § 36.108, districts are required to submit Desired Future Conditions (DFCs) of the groundwater resources. According to Texas Water Code § 36.108 (d-3), the district representatives shall produce a Desired Future Conditions Explanatory Report for the management area and submit it to the TWDB. A draft report was completed as of the date of this document (SWRI, 2017).

The District and other GCDs regard the saline zone as an alternative water supply that poses little threat to the freshwater Edwards—and in fact can lessen demands placed upon it. The District has rules in place (management zones and buffers) that address potential pumping projects along the interface of the saline zone. To date no permits have been requested for the saline Edwards Aquifer. The estimated modeled available groundwater (MAG) for the saline Edwards Aquifer in the region are listed in **Table 2**. The estimation was done by using a water-budget approach and assuming a closed system (SWRI, 2017).

Texas statute also requires that the total estimated recoverable storage (TERS) of relevant aquifers be determined (Texas Water Code § 36.108) by the TWDB. Total estimated recoverable storage is defined as the estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25 percent and 75 percent of the porosity-adjusted aquifer volume. **Table 3** summarizes the total estimated recoverable storage by groundwater conservation district for the saline Edwards (Balcones Fault Zone) Aquifer within the northern subdivision of Groundwater Management Area 10 (Bradley, 2016). The total estimated recoverable storage for the saline Edwards (Balcones Fault Zone) Aquifer ranges from 365,000 to 1,095,000 acre-feet.

The saline zone of the Edwards Aquifer is generally considered a closed system, especially over the time scale of groundwater availability. Accordingly, the aquifer will be mined over time. The availability numbers generated by the MAG are conservative numbers that reflect a cautious approach due to the (low) potential for negative effects on the freshwater/saline-water interface. It is likely that the DFC expression could be somewhat greater with minimal negative effects. The District requires pilot studies for projects along the interface to demonstrate low risk for negative effects. The TERS numbers represent theoretical values that do not reflect hydrogeologic reality, and are not sustainable, and thus are not useful in planning. Indeed, if those volumes were pumped, and the resulting drawdown occurred, it would likely have significant negative effects on the freshwater Edwards Aquifer.

Given the closed system of the saline Edwards Aquifer, a combination of desalinization and ASR may be a sustainable strategy.

Table 2. *Estimation of Modeled Available Groundwater (MAG; SWRI, 2017)*

	Barton Springs/Edwards Aquifer Conservation District	**Plum Creek Conservation District**	**Non-District Areas**	**Total**
Desired Future Condition	No more than 75 feet of regional average potentiometric surface drawdown due to pumping when compared to pre-development conditions			
Storage Coefficient	7.0 x 10-4			
Areal extent (acres)	72,363	15,478	75,270	163,111
Estimated Modeled Available Groundwater (acre-feet per year)	3,799	813	3,952	8,564

Table 3. *Total estimated recoverable storage (TERS) by groundwater conservation district for the saline Edwards (Balcones Fault Zone) Aquifer within the northern subdivision of Groundwater Management Area 10 (SWRI, 2017).*

Groundwater Conservation District	**Total Storage (acre-feet)**	**25% of Total Storage (acre-feet)**	**75% of Total Storage (acre-feet)**
Barton Springs/Edwards Aquifer Cons. District	690,000	172,500	517,500
Plum Creek Conservation District	150,000	37,500	112,500
Non-district Areas	620,000	155,000	465,000
Total	1,460,000	365,000	1,095,000

Saline Edwards Multiport Monitor Well

Characterization and monitoring of discrete intervals is needed to provide data that reflect the complexity of the stratigraphic units in the study area. Multiport wells are unique monitoring systems that allow recurrent measurement and sampling of discrete zones. The installation of a multiport monitor well, and the data it provides, is central to the hydrogeologic characterization of the saline Edwards Aquifer and is the focus of this report (**Figure 5**).

Figure 5. *Drilling and development of the borehole for the multiport monitor well. Photo taken on 8/11/2016.*

Stratigraphy

Geologic characterization is important to the hydrogeologic understanding of an aquifer system. The installation of the multiport well system produced valuable hydrogeologic information. The foundation is the geologic and stratigraphic information described below.

Previous Work

The Geologic Atlas of Texas (**Figure 3**) and cross sections by Brune and Duffin (1983) (**Figure 4**) provide a general geologic framework for the study area. The study area contains subsurface control shown in **Figure 1**. A test well about 1 mile to the west of the multiport well (TW on **Figure 1**) provided geologic and geophysical control of the area (Flores, 1990). In addition, an abandoned test well (T1 on **Figure 1; Supplement 2;** tracking number 190570) about 0.2 mi north of the multiport well also provided some important geologic data. Studies by the USGS (Lambert et al., 2010; Thomas et al., 2012) from the Kyle transect wells (**Supplement 1**) provided additional geologic and geophysical data.

The classic study by Rose (1972) provides the detailed stratigraphic information of the Edwards Group for the region (**Figure 2**). Subsequent work by Hovorka et al. (1996) provides further detailed information on the stratigraphy and its relationship to the porosity development within the Edwards Aquifer. Hovorka et al. (1996) describe a complex relationship between depositional facies, cyclic stacking patterns, and porosity. The porosity and permeability of the rock units in the saline Edwards Aquifer are strongly influenced by the depositional facies and subsequent early diagenesis (dolomitization, cementation, calcite replacement of evaporites) (Abbott, 1975; Hovorka et al., 1996). For example, the regional dense member (RDM), a subtidal facies is described as having low matrix porosity. Units deposited in shallow water and intertidal environments were subject to more dolomitization, especially on the San Marcos Platform (Rose, 1972; Hovorka et al., 1996). Dolomites potentially have high porosity and permeability. Abbott (1975) noted a greater percentage of dolomite within core taken from a well in the saline zone when compared to core from the freshwater zone.

Because of the depositional cyclicity vertical (unit) porosity is highly variable. High porosity zones ranging from 10-50 ft thick contain 25-35 percent porosity are interbedded with thinner beds of 10-20 percent porosity. Average porosity of the Edwards varies laterally from 16-28 percent, with an interpolated overall average of 18 percent (Hovorka et al., 1996)—however, the saline portion of the Edwards Aquifer is reported to have higher-than average porosity (Maclay and Small, 1986; Schultz, 1993). Stratiform high-porosity units were reported in the middle and upper Kainer, and upper Person. Low-porosity units include the lower Kainer (Walnut Fm), lower Person (RDM), and the Georgetown Formations (Hovorka et al. (1996).

Results: Stratigraphy

The multiport well systems installed by the District are manufactured by Westbay Instruments of Vancouver, Canada. A borehole was drilled using air-rotary drilling techniques producing boreholes with nominal 5¼ inch diameters (**Figure 5**; **Table 4**). Cuttings were collected, washed, and described (**Figure 6; Supplement 2**).

A geophysical log was run in the borehole by the U.S. Geological Survey (**Figures 9**). All borehole geophysical log data were collected according to the American Society of Testing and Materials (ASTM) borehole geophysical standard procedures. Geophysical tools include caliper, natural gamma, long/short normal resistivity, spontaneous potential, fluid temperature and conductance, EM induction conductivity/resistivity, and neutron.

Figure 6. *Travis White describes cuttings. Photo taken 8/8/2016.*

Table 4. *Basic saline Edwards multiport well Information*

State Well Number	58-58-305
Tracking Number	431923
Ddlat	30.1148889
Ddlong	-97.7815278
Land Surface Elevation (ft-msl)	658
Drilling Start Date	8/3/2016
Drilling End Date	8/16/2016
Drilling Method	Air Rotary
Blowing yield (gpm)	500
Steel Surface Casing Diameter (in)	6
Surface Casing Depth (ft)	204
Borehole diameter (in)	5.125
Well depth (ft)	1100

The geophysical logs of the borehole are provided in **Supplement 2**. The natural gamma tool was the primary tool used to determine lithologic contacts and regional correlation of the various geologic units (**Table 5**). An attempt was made to isolate the informal members of the Edwards Group defined by Rose (1972) and shown in **Figure 2**. Cuttings and thin sections indicate the majority of the Edwards Group from the borehole to be dolomite or dolomitic in composition and contain a high degree of intercrystalline and moldic porosity (**Supplement 2; Figure 7**). Notable limestone units encountered in the borehole include low porosity units of the overlying Georgetown Formation and also the regional dense member (RDM) of the Person Formation (**Figure 8**). The RDM was identified by the dense argillaceous mudstone cuttings combined with the relatively thick and constant resistivity curve.

On average, the Edwards Group has relatively low resistivity values compared with the more argillaceous limestone units of the RDM, Walnut, and Georgetown Formations. The neutron porosity log indicates the Person has the highest total porosity (average 30 percent) while the Kainer averages a total porosity of 25 percent. The RDM has the lowest at 9 percent. The low RDM value of this study is comparable to the core tests of Hovorka et al., (1996) containing 8.5 percent. The RS curves correlate well with neutron porosity, especially the lateral RS (R^2=0.62).

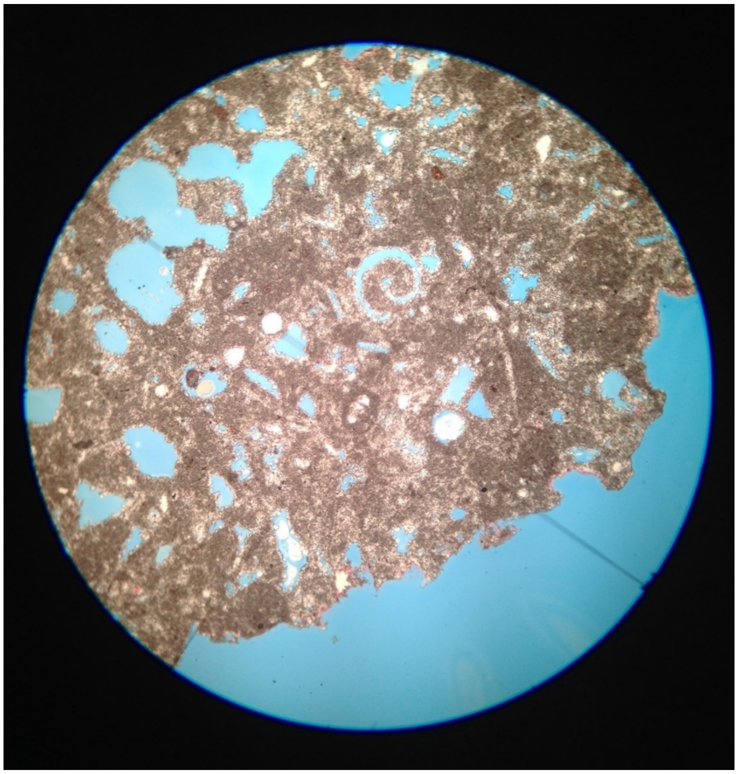


Figure 7. Photomicrograph of a dolomite from the Kainer Fm. (727 to 737 ft). This rock is very porous with intercrystalline and skeletal moldic porosity. Photograph in plain light, diameter is 5mm. This sample is comparable to a skeletal modlic porosity with 25 percent porosity reported in Hovorka et al., (1996).

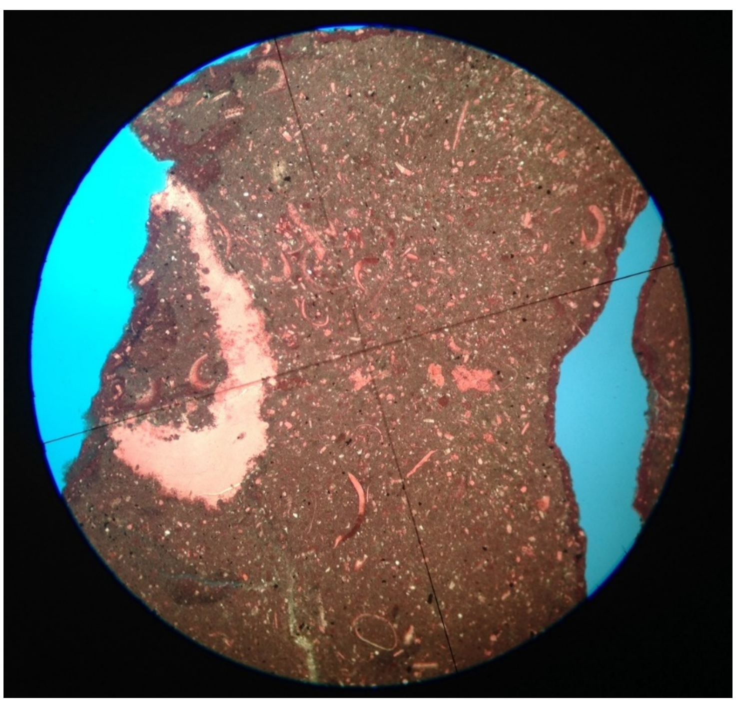


Figure 8. Photomicrograph of an argillaceous wakestone from base of the Person Fm. (regional dense member; 627 to 637 ft). This rocks has no observable porosity within the matrix. Photograph in plain light, diameter is 5mm. The geophysical porosity of 9 percent of this study is comparable to the core tests of Hovorka et al., (1996) containing 8.5 percent. Permeability of core plgs are reported to be 0.02 millidarcy (5.48E-5 ft/d) (Hovorka, et al., 1996).

Results: Multiport Well Design

The multiport well system was designed after reviewing drilling, drill cuttings, geophysical logs and considering the stratigraphy and hydrostratigraphy of the study area. A caliper log was run to measure the diameter of the borehole so that packers could be placed on relatively smooth sections where cavities were not prominent, improving the likelihood that upon inflation the packers would provide effective seals in the annular space. **Table 6** summarizes the multiport well design, stratigraphy, and average geophysical log values.

The casing of the Westbay system consists of multiple segments of 1.9 inch outer-diameter Schedule 80 PVC, which are fitted together with PVC couplings. The multiport components are laid out and numbered in the work area (**Figures 10 and 11**). The components are connected prior to insertion in the borehole and each coupling is hydraulically tested during assembly. Monitor zones are established with permanent inflatable packers (**Figure 12**) placed in the string of casing at the top and bottom of each targeted zone. A special coupling with a spring-loaded valve (sampling port) is installed between the inflatable packers. A pumping port is also installed in each zone. These are short, screened intervals through which slug tests can be conducted and permeability estimated. **Supplement 2** contains the multiport well completion report. After designing the well, its components were assembled and inserted into the well using a 3.5-in diameter steel guide tube (HQ casing). Following insertion of the components, the guide tubing was then pulled out and the packers inflated with water. Inflation of the packers provides a permanent seal of the annular space between the PVC casing and the borehole walls, thus isolating the pumping and sampling ports into discrete zones.

Discussion: Stratigraphy and Multiport Well Design

The tops of formations were primarily identified with natural gamma logs. However, the identification of the informal members (**Figure 2**) within the Edwards Group was problematic for 6 of the 8 informal members. The two informal members that were readily identified include the RDM and Walnut Fm (basal nodular member)--both of those units were isolated with packers to form zones 12 and 3, respectively. The design of the remaining Edwards zones were determined by adding in relatively numerous zones considering the caliper log and RS log. The average zone thickness is 35 ft. A total of 12 Edwards Group zones were constructed, and the well was constructed with a total of 18 zones.

The Del Rio Clay was unstable during drilling of the borehole and began to collapse and create a cavernous void. Packers were placed conservatively below and above the contact with the Del Rio so as to not inflate the packer into a void.

Key hydrostratigraphic confining, or low permeability, units were isolated with packers and include the Walnut Fm (zone 3), regional dense member (zone 12), and the overlying confining units of the Georgetown Formation and younger units (zones 15 and higher) (**Table 6**).

Figure 9. *USGS staff logging the borehole to a total depth of 1,095 ft. Photo taken 8/19/2016.*

Figure 10. *Photograph showing the work area for the installation of the multiport well. Photo taken 8/19/2016.*

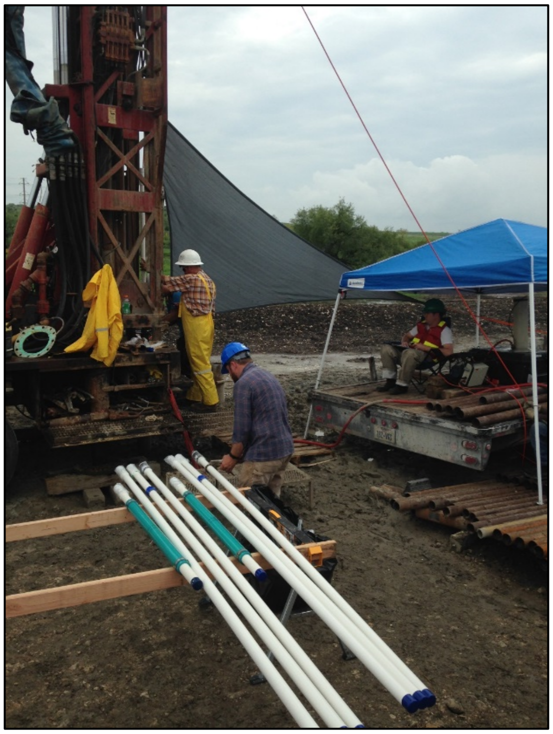


Figure 11. *Multiport well components laid out for installation. Blue items are packers. Photo taken 8/20/2016.*

Figure 12. *Photograph of assembly and testing of multiport coupling component. The coupling that connects the packer (blue, above) and the 10-ft casing section (white, below) is being pressure tested. Photo taken 8/20/2016.*

Table 5. *Depth to geologic units in the saline Edwards multiport well. The deepest geologic unit encountered in the well is the Upper Glen Rose. Older geologic units are estimated based upon other sources as indicated.*

Name	Unit	Depth to Top (ft)	Top Elevation (ft-msl)	Unit Thickness (ft)
Taylor Clay	Kta	0	658	107
Austin Chalk	Kau	107	551	274
Eagle Ford	Kef	381	277	34
Buda	Kbu	415	243	40
Del Rio	Kdr	455	203	60
Georgetown	Kgt	515	143	49
Edwards (Person Fm.)	Kep	564	94	111
Edwards (Kainer Fm.)	Kek	675	-17	292
Walnut Fm	Kwal	967	-309	48
Upper Glen Rose*	Kgru	1015	-357	400
Lower Glen Rose*	*Kgrl*	*1415*	*-757*	*250*
Hensel*	*Kh*	*1655*	*-997*	*30*
Cow Creek*	*Kcc*	*1687*	*-1029*	*90*
Hammett Shale*	*Kha*	*1775*	*-1117*	*50*
Sligo**	*Ksl*	*1825*	*-1167*	*230*
Hosston Fm.**	*Kh*	*2055*	*-1397*	*400*
Paleozoic**	*Pz*	*2455*	*-1797*	*unknown*

LSD *Thickness estimated from 5858431; **Thickness or depth estimated from Duffin and Brune, 1983

Table 6. *Summary of multiport well design, stratigraphy, and average geophysical values.*

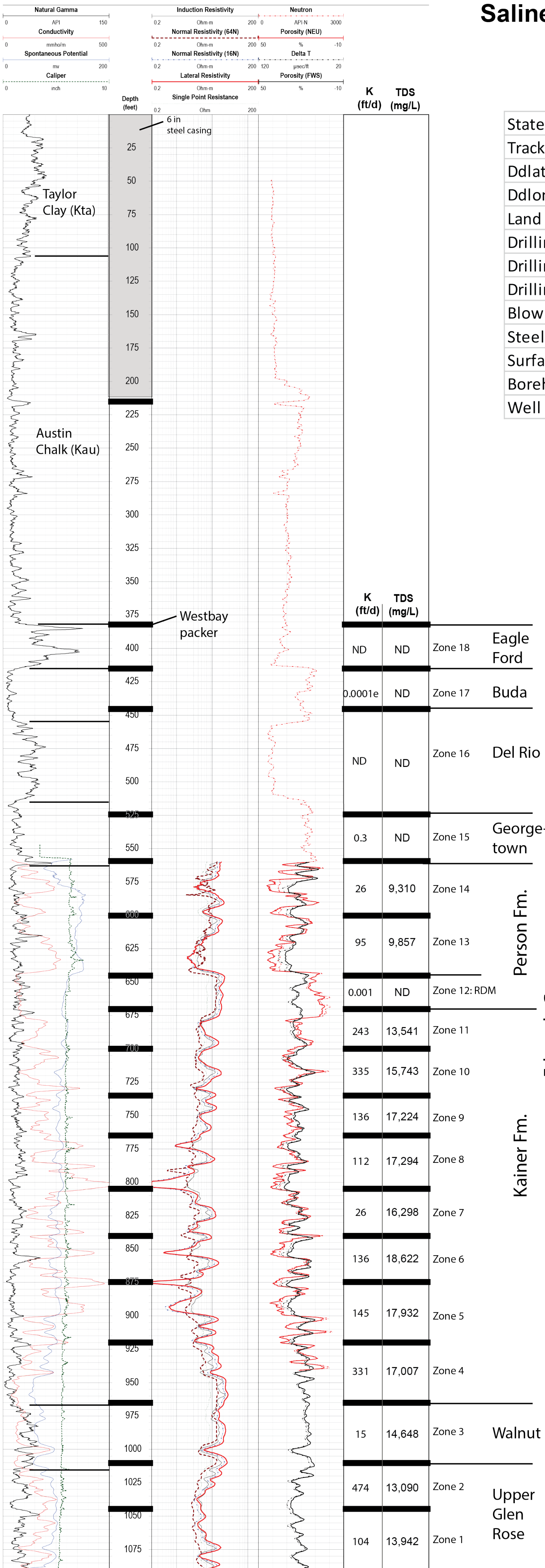
Well Design							Average Geophysical Log Values														
Zone No.	**Geologic Unit**	**Top Zone Depth (ft)**	**Bottom Zone Depth (ft)**	**Thickness Zone (ft)**	**Measurement Port Depth (ft)**	**Pumping Port Depth (ft)**	**Nat Gamma (API)**	**Fluid Cond (Ohm-m)**	**Fluid RS (Ohm-m)**	**COND (mmho/m)**	**IND_RES (Ohm-m)**	**RES (16N; Ohm-m)**	**RES (64N; Ohm-m)**	**Lateral RS (Ohm-m)**	**Single Point RS (Ohm)**	**SP (MV)**	**Caliper (in)**	**Fluid Temp (F)**	**Neutron (API-N)**	**Neutron Porosity (%)**	**Sonic Porosity (%)**
n/a	Taylor Clay	0	107	107			39.5												500		
n/a	Austin Chalk	107	384.5	278			19.4												942		
18	Eagle Ford	385	416.5	32	395	405	58.3												900		
17	Buda	420	446.5	27	430	440	11.6												1,611		
16	Del Rio	450	526.4	77	475		33.5	31,981											812		
15	Georgetown	529	561.4	32	540	550	25.2	31,485	0.3178	67	15.2	15.9	13.4	17.8	7.0	102.9	6.3	81.5	1,740	22	16
14	Edwards Person Fm.	564	601.4	37	575	585	18.2	30,532	0.3278	148	8.0	10.0	8.0	11.5	5.2	127.8	6.4	81.6	1,158	29	22
13	Edwards Person Fm.	604	646.3	42	615	625	23.2	26,436	0.3817	182	6.8	7.1	5.8	8.4	4.7	140.6	6.4	81.9	1,095	30	25
12	Edwards Person Fm--RDM	649	671.3	22*	650	660	24.3	31,924	0.3136	77	13.1	16.1	12.7	18.3	7.2	115.6	6.0	82.2	2,119	9	23
11	Edwards Kainer Fm.	674	701.3	27	685	695	21.1	31,997	0.3128	149	7.2	7.5	4.5	9.2	4.8	117.8	6.0	82.1	1,464	20	22
10	Edwards Kainer Fm.	704	736.3	32	715	725	19.0	31,231	0.3205	174	6.5	7.4	3.9	9.4	4.7	110.1	5.9	82.2	1,222	25	23
9	Edwards Kainer Fm.	739	766.3	27	750	760	23.0	31,493	0.3179	172	6.1	6.1	3.7	7.6	4.5	103.6	5.9	82.4	1,123	27	22
8	Edwards Kainer Fm.	769	806.3	37	780	790	21.9	32,447	0.3085	315	3.8	2.6	2.3	3.4	3.1	107.6	6.0	82.6	986	32	26
7	Edwards Kainer Fm.	809	841.3	32	820	830	22.1	33,083	0.3026	218	5.2	5.2	2.8	6.7	4.0	98.2	6.0	82.9	1,248	25	23
6	Edwards Kainer Fm.	844	876.3	32	855	865	21.6	33,379	0.2998	268	4.5	4.1	2.7	5.3	3.5	100.4	5.9	83.1	1,114	29	22
5	Edwards Kainer Fm.	879	921.3	42	890	900	17.6	33,587	0.2980	237	4.9	4.4	2.7	5.6	3.8	98.0	5.8	83.5	1,235	26	22
4	Edwards Kainer Fm..	924	966.3	42	935	945	16.3	33,783	0.2963	99	12.3	15.6	9.3	18.6	7.0	70.2	5.6	84.0	1,710	15	17
3	Walnut Fm.	969	1011.3	42	980	990	35.2	33,641	0.2975	93	12.4	15.8	10.8	18.5	7.2	70.6	5.6	84.7			16
2	Upper Glen Rose	1014	1046.3	32	1025	1,035	24.1	32,158	0.3114	165	6.6	7.1	3.9	8.8	4.7	93.1	5.6	85.5			22
1	Upper Glen Rose	1049	1095	46	1060	1,070	25.1	29,851	0.3386	161	6.7	7.0	3.7	8.7	5.1	92.9	5.3	86.8			21

All depths from land surface. Packers are 3 feet long and not counted in zone thickness or geophysical log values.

*Thickness is consistent with RDM described in Rose (1972).

Saline Edwards Multiport Monitor Well
Travis County, Texas

State Well Number	58-58-305
Tracking Number	431923
Ddlat	30.1148889
Ddlong	-97.7815278
Land Surface Elevation (ft-msl)	658
Drilling Start Date	8/3/2016
Drilling End Date	8/16/2016
Drilling Method	Air Rotary
Blowing Yield (gpm)	500
Steel Surface Casing Diameter (in)	6
Surface Casing Depth (ft)	204
Borehole Diameter (in)	5.125
Well depth (ft)	1100



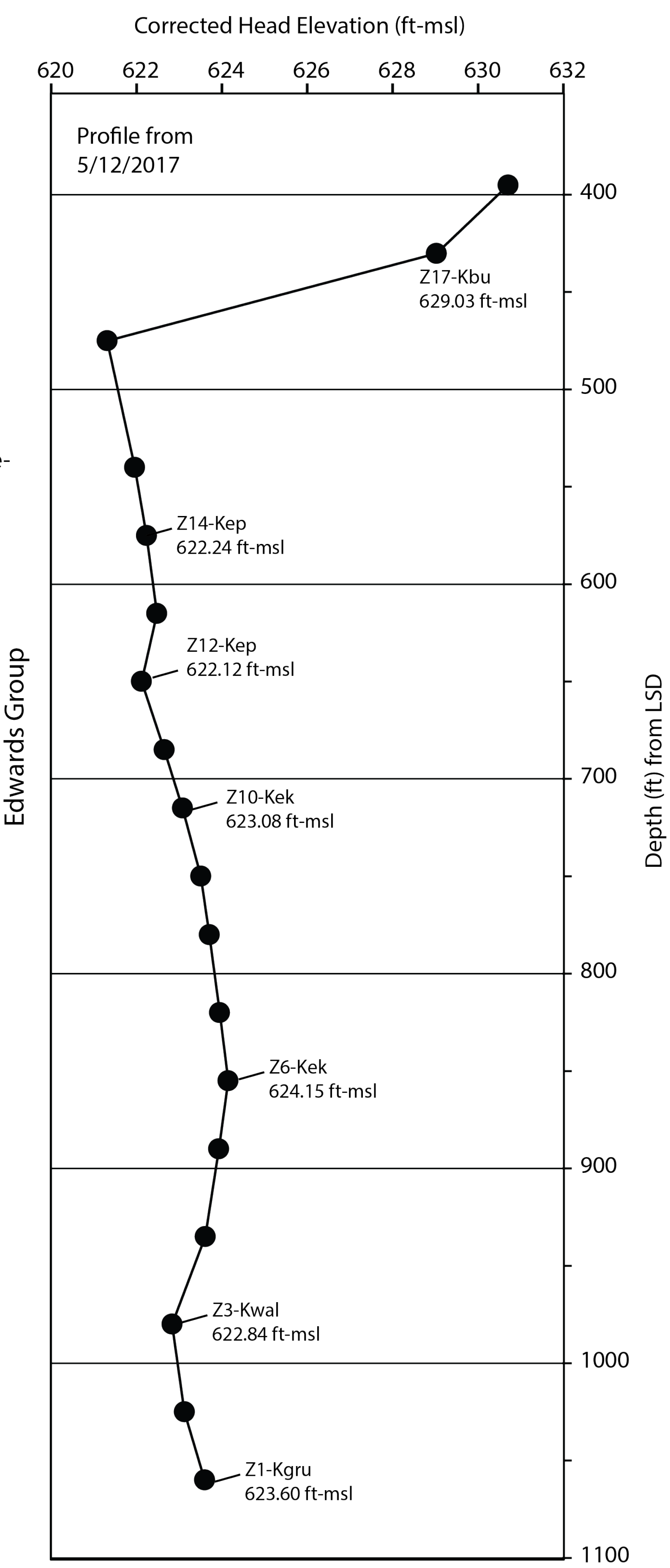


Figure 13. *Geophysical logs, well design, stratigraphy, and hydrogeologic data for multiport monitor well.*

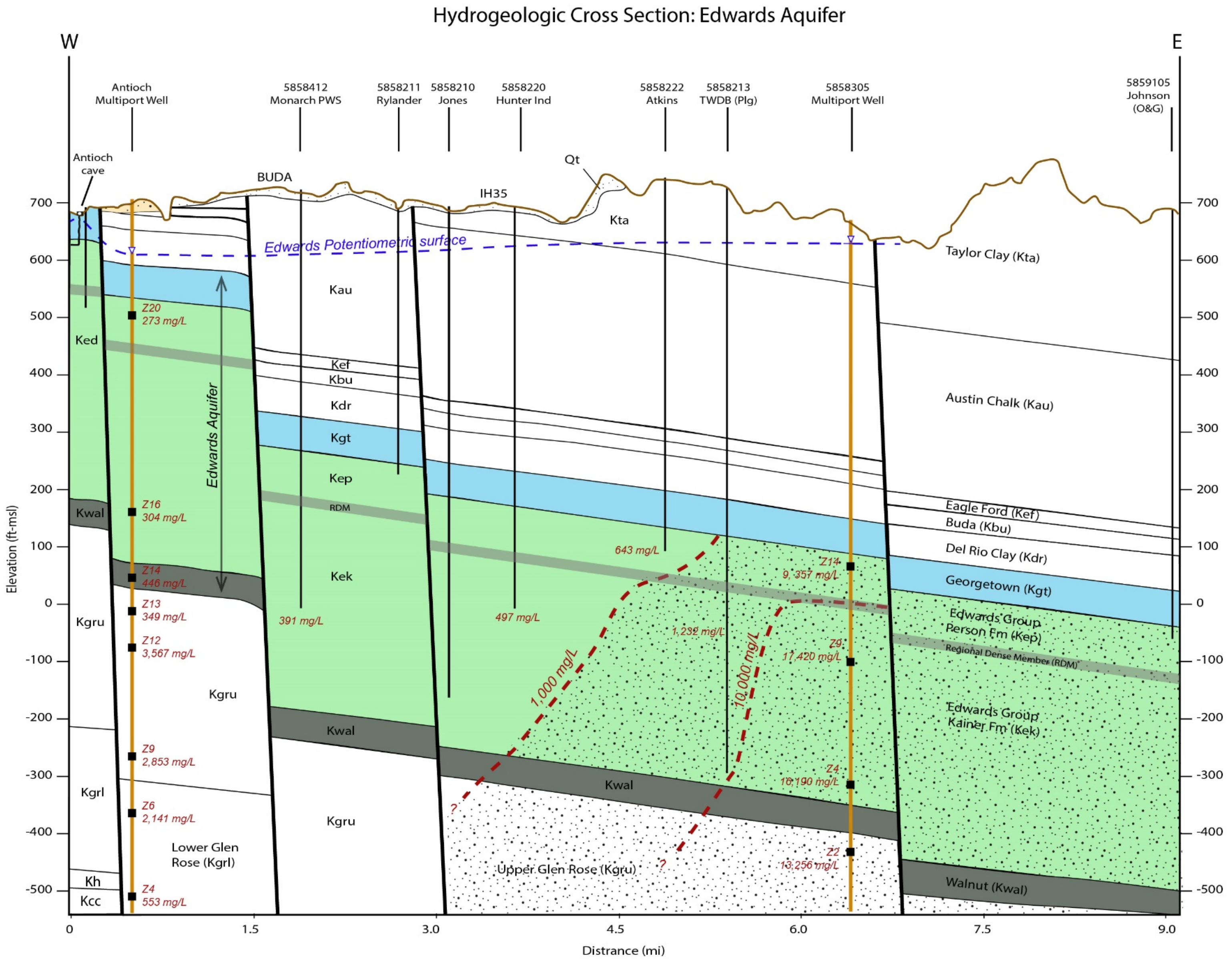


***Figure 14**. Study area cross section. Line of cross section shown on Figure 3. Pattern indicates saline zone.*

Water Levels and Hydraulic Gradients

Water level, or head data, were collected from the multiport monitor well (**Figure 15**). This information allows the assessment of the both lateral and vertical hydraulic gradients within the study area. The multiport well is unique for the assessment of hydraulic gradients as the discretely completed zones allow for the measurement of hydraulic heads for each zone.

Figure 15. *Photograph showing equipment during measurement of a profile of water-level data. The trailer contains a winch that lowers the measurement instrument into the well. Photo taken 10/6/2016.*

Previous work

Water levels in the freshwater portion of the Edwards Aquifer are well characterized with numerous continuous monitor wells and synoptic potentiometric maps (Hunt and Gary, 2014; Hunt and Smith, 2007). Water levels and gradients in the study area were investigated by Thomas et al. (2012) along the Kyle transect about 11 miles SSW of the multiport well (**Figure 1**). Key hydrogeologic data and figures from that study are provided in **Supplement 1**. Lateral-head gradients in the Kyle transect, although varied, were typically from the saline zone into the freshwater zone. In other words, heads were generally higher in the saline transect wells than in the freshwater wells. However, Thomas et al. (2012) used an EM flowmeter to measure flows within the boreholes of the Kyle transect wells. The eastern-most Kyle transect wells 3 and 4 indicated the potential for flow from the middle portion of the Edward to the lower and upper portions of the Edwards, respectively. These data suggest higher heads in the middle portion of the Edwards (**Supplement 1**).

A study by Flores (1990) included a test hole (TW, **Figure 1**) about 1 mile west of the multiport monitor well. Core and lab analyses with water-quality sampling suggest that the regional dense member (RDM) hydraulically separates the Edwards into an upper and lower unit.

Methods

A head (water-level or potentiometric) profile of a multiport monitor well consists of measuring water pressures (heads) in all of the zones in the well within a short period of time, usually over an hour or two. These values give an accurate indication of the hydraulic potential for vertical flow within the aquifer units. Pressures are measured within each zone using a sampling instrument that includes a pressure transducer. The instrument is lowered into the well using a winch to the sample port for each zone (**Figure 15**). Fluid pressure is measured in one zone at a time. The pressure transducer has a range of 2,000 psi and also measures fluid temperature. Operation of the probe and digital output are sent through a cable to the LCD display on the controller at the surface. Pressures in each zone are recorded on field sheets. Head data and the salinity density corrections are provided in **Supplement 3** and described below.

Measured pressures for each zone are converted to pressure head (Hp) and then depth to water (Dtw) and finally head (Hu) value following the calculations outlined in the equations below. Head (Hu) represents the environmental-water head and is referred to as uncorrected (for freshwater equivalent) head. Note the hydrostatic pressure gradient was calculated independently for each zone based on the fluid density in order for the pressure transducer to measure the correct Dtw. Fluid density was calculated based upon each zone's temperature (measured during profiling) and total dissolved solids (mg/L) (data from sampling) using a spreadsheet calculation derived from Maidment (1993).

Hp = (Pz-Patm)/Pgrad
Dtw = Dp-Hp
Hu = LSD – Dtw

Where:

Hp = pressure head (ft);
Pz = zone pressure (psi);
Patm = atmospheric pressure (psi);
Pgrad = hydrostatic pressure gradient (psi/ft);
Dtw = depth to water (ft)
Dp = depth of port (ft);
Hu = head or water-level elevation (ft-msl) uncorrected;
LSD = land-surface datum (ft-msl).

According to the literature, equivalent freshwater heads define horizontal gradients, while environmental-water heads define vertical gradients (Lusczynski, 1961). However, because of the unique nature of the multiport well, it was determined that equivalent freshwater heads could also define the vertical gradients in this study. Following the methods described in Thomas et al. (2010), we converted uncorrected head (Hu) values into equivalent freshwater heads (Hc). Generally, this follows the equations described below.

Hc = Hu + (lc – lu)

Hc = equivalent freshwater head (or corrected head),
Hu = environmental head (uncorrected head);
lu = length of environmental water column (lu = Dp – Dtw);
lc = length of equivalent freshwater column (lc = lu * density ratio);
density ratio = zone fluid density / 0.998

Results: Water Levels and Hydraulic Gradients

Equivalent freshwater head values are presented in **Table 7**. **Figures 13 and 16** show the vertical distribution of head values compared to the geologic units. Conversions to equivalent freshwater heads increased values from approximately 2 to 11 ft depending on the zone. **Supplement 3** contains the raw and corrected data.

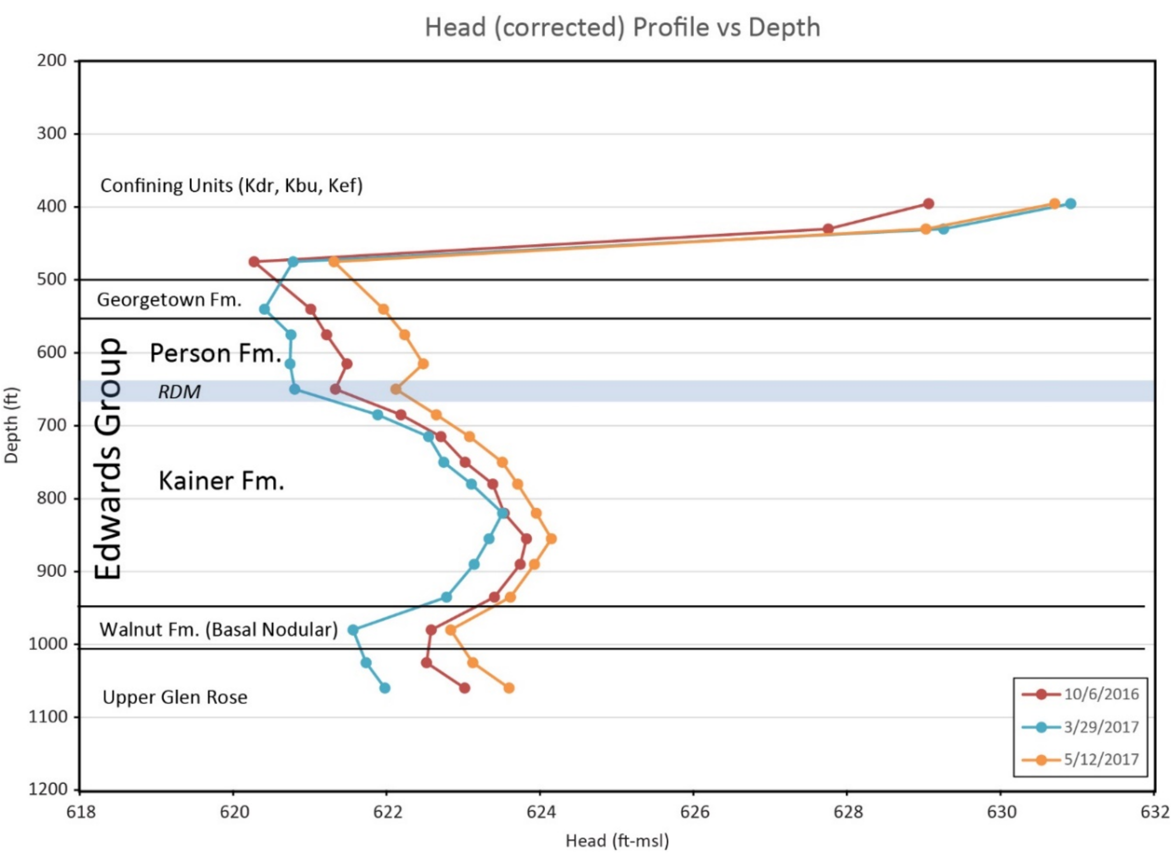


Figure 16. *Hydrograph showing head in each zone versus depth for select profiles.*

Figures 17 and 18 show the lateral distribution of equivalent freshwater head values in the multiport well compared with other freshwater and brackish water values.

Table 7. *Head profile data collected from the saline Edwards multiport well. Heads are equivalent freshwater head values. Raw data and calculations are presented in* ***Supplement 3****.*

Zone	Depth Port (ft)	8/24/2016	10/6/2016	11/14/2016	1/19/2017	3/29/2017	5/12/2017
18-Kef*	395.2		629.06	629.71	630.50	630.92	630.71
17-Kbu*	430.2	619.87	627.76	628.73	628.94	629.26	629.03
16-Kdr*	475.1	618.00	620.27	619.60	619.93	620.78	621.31
15-Kgt*	540.1	618.74	621.01	620.20	618.77	620.41	621.96
14-Kep	575.1	619.11	621.22	620.52	618.97	620.76	622.24
13-Kep	615.1	619.35	621.48	620.65	619.38	620.74	622.48
12-Kep—RDM*	650	618.98	621.33	620.48	618.86	620.80	622.12
11-Kek	685	619.76	622.19	620.08	617.74	621.89	622.65
10-Kek	715	620.30	622.71	620.49	618.10	622.55	623.08
9-Kek	750	620.69	623.02	620.78	618.46	622.75	623.51
8-Kek	780	620.95	623.38	621.19	618.92	623.11	623.71
7-Kek	820	621.03	623.53	621.31	619.21	623.51	623.95
6-Kek	855	621.23	623.82	621.51	619.38	623.34	624.15
5-Kek	890	621.08	623.74	621.41	619.32	623.14	623.93
4-Kek	935	621.11	623.41	621.39	619.43	622.78	623.61
3-Kwal	980	620.48	622.58	620.92	619.02	621.56	622.84
2-Kgru	1025	620.72	622.52	621.02	619.19	621.73	623.12
1-Kgru	1060	621.05	623.02	621.40	619.73	621.98	623.60

**head corrections are estimated based on nearest zone data.*

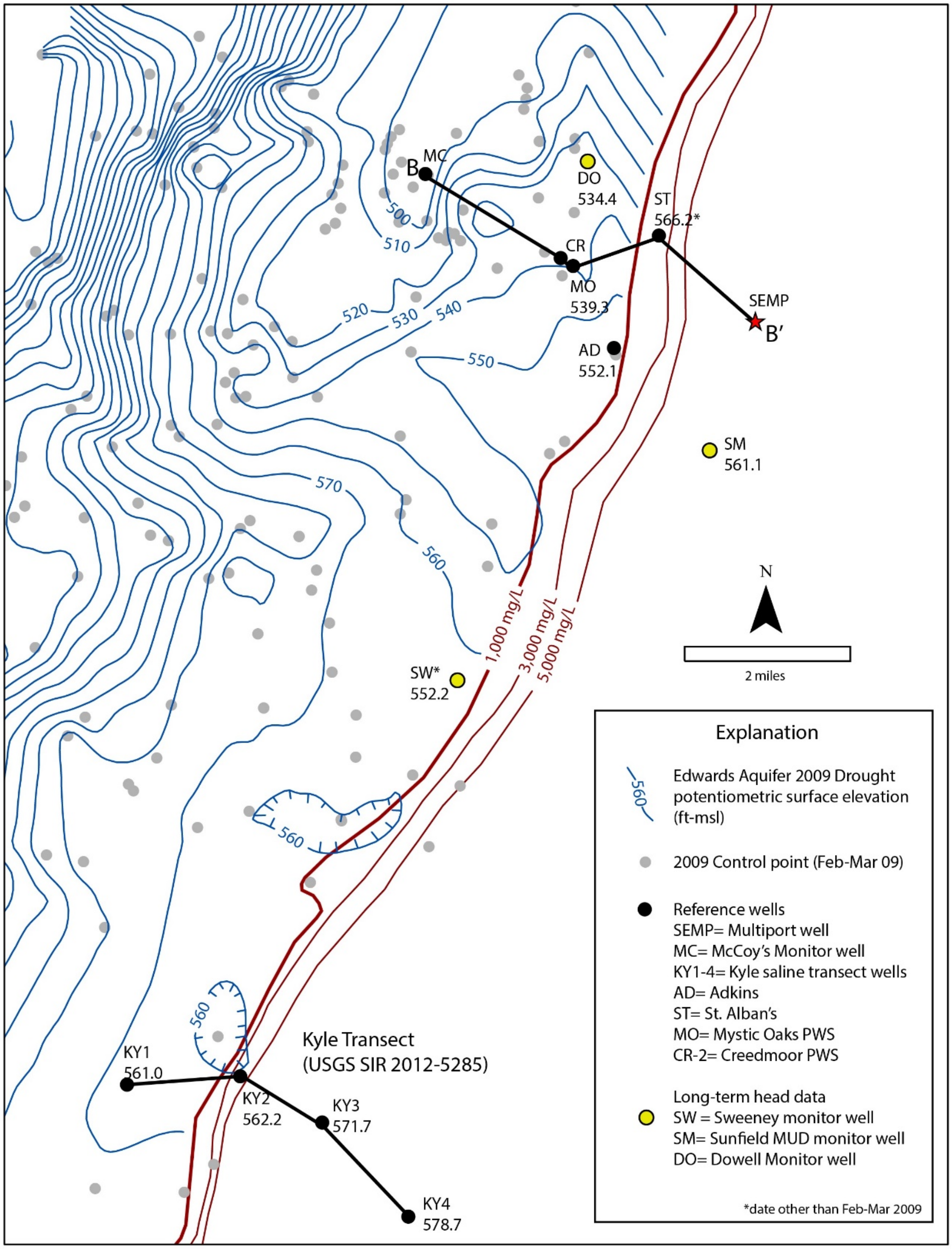


Figure 17. *Map of 2009 drought potentiometric surface and two transects across the freshwater/saline-water interface. The northern transect, B to B', is shown in the profile in Figure 18. The Kyle transect data is shown in profile in Supplement 1.*

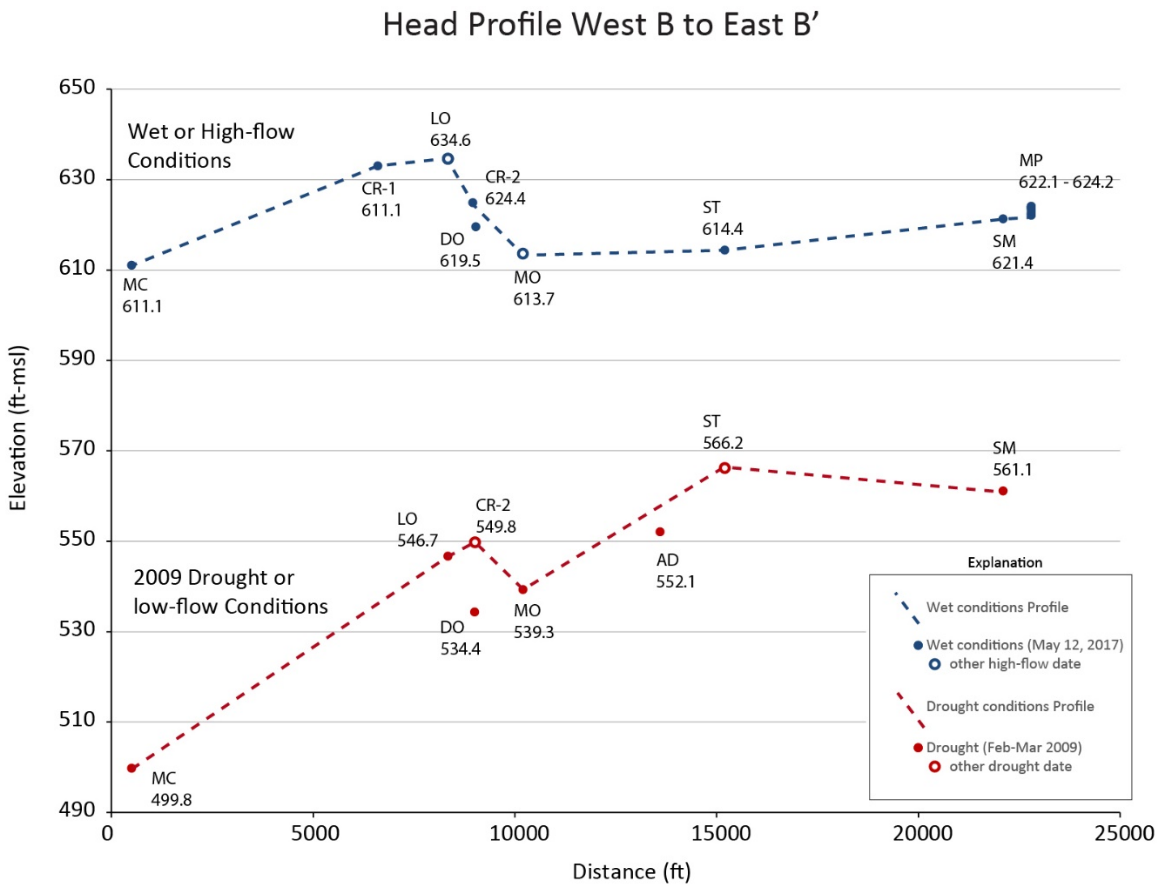


Figure 18. *Transect and profile view across the freshwater/saline-water interface for the study area. Line of section shown in Figure 17. Water-level data provided in Supplement 3.*

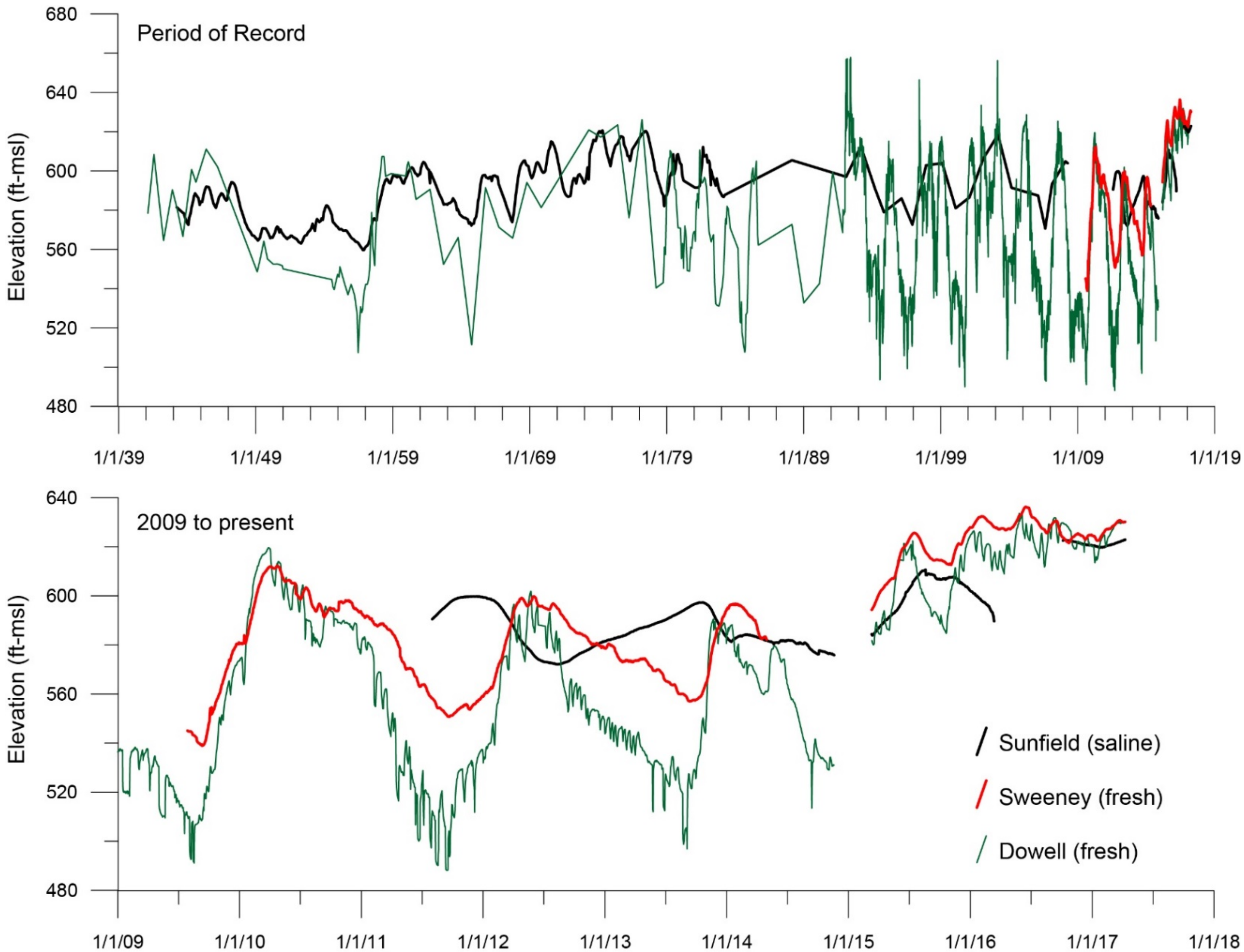


Figure 19. *(Top) Period-of-record hydrograph from three wells in the study area. (Bottom) Same wells, 2009 to present data. Wells located in Figure 17.*

Discussion: Water-Level and Gradient Data

Head data indicate several potentiometric changes in the profiles that occur where units are thought to be aquitards (**Figures 13 and 16**). Those include the Walnut Fm. (zone 3) at the base of the Edwards Group, the RDM (zone 12) between the Person and Kainer formations, and the overlying confining units of the Georgetown, Del Rio, Buda, and Eagle Ford (zones 15-18).

The highest heads within the Edwards are within the Kainer Formation (Zones 4-11) which are about 2 ft higher than the overlying Person Formation. The Kainer Formation contains the highest salinity and permeable zones. The RDM appears to be an aquitard between the two formations defining a change in heads. This is consistent with the Flores (1990) observations. This vertical distribution of heads appears to be similar to the data presented in the Kyle transect wells (Thomas et al., 2010) that has borehole flow data suggesting higher heads in the middle portion of the Edwards (**Supplement 1**).

Lateral gradients presented in **Figures 17 and 18** indicate that heads in the saline zone are higher than in the freshwater Edwards during drought conditions. This suggest the flow potential is from east (saline) to the west (fresh). However, during wet periods there is potential for the gradient to reverse and indicate a potential for flow from the west (fresh) to the east (saline). The periods of time when the heads are higher in the freshwater Edwards are much less than when heads are lower in the freshwater Edwards.

The Sunfield MUD well (SM, **Figures 18 and 19**) is in a similar setting to the multiport monitor well and is likely a good long-term proxy for heads. Long-term hydrographs (**Figure 19**) indicate that during drought periods the heads are higher in the saline zone, and under the wettest periods the gradients may reverse. However, there is a significant time lag in the saline Edwards well in response to changes in the freshwater Edwards.

Aquifer Parameters

Permeability and storativity are important variables in determining the feasibility of pumping from, or injecting into, a geologic formation. The focus of this section is on the hydraulic conductivity testing done on zones of the multiport well.

Previous work

A few studies have directly measured or estimated the permeability (transmissivity) and storativity of the saline Edwards Aquifer (Poteet et al., 1992; Pabalan et al., 2003; Lambert et al., 2010; Thomas et al., 2012). Key hydrogeologic parameters from those studies are summarized in **Table 8.**

Methods

To measure hydraulic permeability, methods for slug testing in multiport wells were followed as described in Hunt et al., 2016. For this study, slug testing was performed prior to the purging of each zone. The test was performed using a sealed 1-in diameter, 3-ft-long PVC tube as a slug. Water-level changes inside the casing were measured by placing a pressure transducer (In-Situ Level TROLL, 100 psi) below the water level after a zone's pumping port was opened. After heads equilibrated between the zone and the water inside the casing, the slug tests were performed. The slug would be quickly lowered into the water with the pressure transducer recording resulting changes in head. Following removal of the slug and pressure transducer, the pumping port would be closed. Then the procedure would be repeated for each zone. Raw data collected were adjusted to clean up early-time noise, change of sign, and correct the elapsed time to account for when the displacement occurred.

Data were analyzed with AQTESOLV software (**Figure 20**). The program calculates hydraulic conductivity values by fitting solutions to graphical representations of deviation of head (ft) from static level with respect to time (elapsed time in seconds). Data from slug tests can be classified as either overdamped or underdamped (Duffield, 2014). Overdamped slug tests occur in low to moderate hydraulic conductivity aquifers (zone 14, Figure 11). Underdamped slug tests occur in high conductivity aquifers and exhibit oscillatory behavior as shown in zone 2 of **Figures 20**. We selected the commonly-used Bouwer and Rice (1976) straight-line method for overdamped data. AQTESOLV provides suggested head ranges for the straight-line match. For overdamped data, we also selected the Hyder et al. (1994) type-curve method in AQTESOLV (also known as the Kansas Geological Survey or KGS model). For underdamped (oscillatory) data, we selected the Butler (1998) or Butler-Zhan (2004) type-curve method. All methods can be used for confined or unconfined conditions and fully- or partially-penetrating wells. No corrections to the analyses for fluid densities were performed.

Table 8. Summary of estimated aquifer parameters and well yields from published sources

Well	Well ID	Ddlat	Ddlong	Water Type	Well Depth (ft)	Open interval	LSD (ft-msl)	Static Water Depth (ft)	Discharge rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Transmissivity (ft^2/d)	Transmissivity (gpd/ft)**	Storativity*	TDS (mg/L)	Potential Well Yield (gpm)*
San Marcos B	67-01-812	29.890278	-97.928333	Saline	554[a]	495-545	581	0 to 7	n/a	2.5	nd	772	5,776	0.0002	8,810 to 12,267	1,450
San Marcos C--Person	67-01-813	29.891111	-97.929444	Saline	564[b]	505-555	581	2 to 7	70	15	nd	429	3,209	0.0002	8,900 to 11,972	860
San Marcos C--Kainer	67-01-830	29.891111	-97.929444	Saline	699[c]	640-690	581	2 to 7	70	15	nd	429	3,209	0.0002	9,928 to 12,152	nd
San Marcos D--Person	67-01-814	29.891945	-97.930833	Saline	582[d]	506-556	576	-0.40	nd	nd	nd	1,026	7,672	nd	9,160 to 11,952	nd
San Marcos D--Kainer	67-01-831	29.891945	-97.930833	Saline	742[d]	506-556	576	nd	nd	nd	nd	1,026	7,672	nd	9,400 to 12,844	nd
Kyle 2	67-02-104	29.983055	-97.871667	Transitional	975	427-975	674	76 to 134	12	5.1	2.4	472	3,530	nd	nd	nd
Kyle 3	67-02-106	29.974722	-97.857223	Saline	1100	600-1100	678	89 to 121	18	8	2.3	451	3,370	nd	17,075	nd
Kyle 4	67-02-105	29.958334	-97.842222	Saline	970	562-970	647	63 to 76	20	1.2	16.7	3,440	25,700	nd	nd	nd
Sunfield MUD #2	58-58-301	30.092222	-97.789445	Saline	639	639-643	734	119-180	nd	nd	nd	nd	nd	nd	nd	nd
TWDB Test	58-58-213	30.112223	-97.798889	Transitional	1010	515-985	740	116	8	nd	nd	nd	nd	nd	1,232	nd
TDS Test Well 2008	190570	30.120833	-97.777778	Saline	800	640-763	725	nd	300	nd	nd	nd	nd	nd	13,000	nd

TDS= total dissolved solids (mg/L)
LSD= land surface datum (ft-msl)
nd= no data
a-later plugged back from 890 ft
b-later plugged back from 920 ft
c-later plugged back from 920 ft
d-plugged back from 775
*Poteet et al., 1992; Pabalan, et al., 2003
**Lambert et al., 2010; Thomas et al. 2012

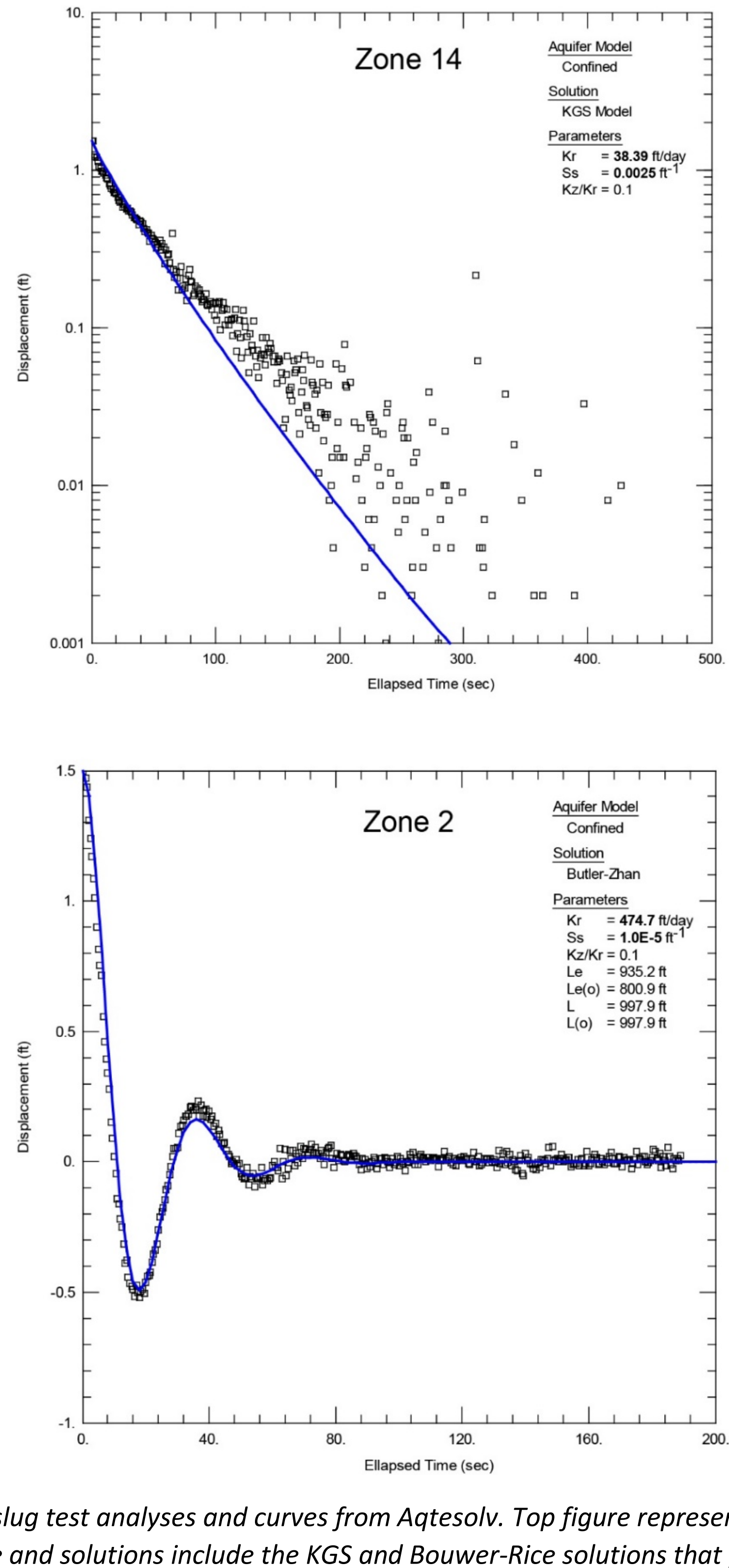


Figure 20. *Example slug test analyses and curves from Aqtesolv. Top figure represents overdamped water-level response and solutions include the KGS and Bouwer-Rice solutions that produced similar values. The lower figure represents underdamped (high permeability) water-level response and the Butler-Zhan solution to estimate permeability.*

Results: Hydraulic Conductivity

Table 9 presents the results of estimated hydraulic conductivity from slug testing for each zone tested. **Figure 13** contains hydraulic conductivity data in relation to lithologic, head, and chemistry data. **Supplement 4** contains the raw data and analyses.

Table 9. *Summary of permeability data from slug test analyses. Neutron log data from Table 6.*

Zone	Zone Thickness (ft)	Pumping Port Depth (ft)	Formation	Date	DTW (ft)*	K (ft/d)**	Transmissivity (Ft^2/d)	Transmissivity (gpd/ft)	Neutron Porosity (%)
18	32	405	Kef	ND		ND	ND	ND	22
17	27	440	Kbu	11/10/2016	45.95	0.00001***	0.00	0.00	29
16	76.9	NA	Kdr	ND		ND	ND	ND	30
15	32	550	Kgt	11/9/2016	45.4	0.34	11	81	9
14	37	585	Ked	10/14/2016	43.11	26.3	973	7,279	20
13	41.9	625	Ked	10/25/2016	45.81	95.02	3,981	29,783	25
12	22	660	Ked_RDM	10/24/2016	53.51	0.001	0.02	0.16	27
11	27	695	Ked	10/19/2016	45.51	243	6,561	49,080	32
10	32	725	Ked	11/8/2016	47.53	334.5	10,704	80,072	25
9	27	760	Ked	10/20/2016	45.63	136	3,672	27,469	29
8	37	790	Ked	11/7/2016	48.02	112	4,144	30,999	26
7	32	830	Ked	10/17/2016	40.8	240	7,680	57,450	15
6	32	865	Ked	11/4/2016	48.59	136.3	4,362	32,627	22
5	42	900	Ked	11/3/2016	46.86	145.3	6,103	45,651	29
4	42	945	Ked	10/21/2016	47.81	331	13,902	103,994	30
3	42	990	Kwal	10/31/2016	48.35	15	630	4,713	
2	32	1035	Kgru	10/18/2016	47.73	474	15,168	113,465	
1	45.7	1070	Kgru	10/26/2016	46.44	104.1	4,757	35,588	

NA = not applicable or no data; Zone 16 Kdr has no pumping port; Zones 12, 15, 17, 18 were not purged or sampled due to very low K; *DTW- depth to water, prior to purging zone; **average or select value; ***estimated

Well Yield Estimates

Estimates for potential well yields (Q, gpm) are important for an evaluation of the saline Edwards Aquifer as a potential water supply and injection target. **Table 10** provides transmissivity values for each Edwards zone and an upper and lower estimate of yield (Q) for a production well given the permeability data collected in this study, published storativity values, and certain assumptions. Transmissivities were averaged over two aquifer units—an upper Edwards Aquifer unit (zones 13 and 14), and a lower Edwards Aquifer unit (zones 4-11). Drawdowns were limited to ½ and 2/3 of the water column as outlined in Pabalan, et al. (2003). Using these parameters and assumptions, the yield was obtained using the Theis equation in AQTESOLV.

Table 10. *Estimated well yield for a potential production well.*

Zone	Pumping Port Depth (ft)	Formation	Date	DTW (ft)	K (ft/d)	Flag	Zone Thickness (ft)	Transmissivity (Ft^2/d)	TDS (mg/L)	Aquifer Interval	Combined thickness (ft)	Tavg (ft^2/d)	Storativity*	Average TDS (mg/L)	Max Drawdown (ft)**	Min Drawdown (ft)***	Qmax (gpm)	Qmin (gpm)
14	585	Ked--Person Fm	10/14/2016	43.11	26.3		37	973	9,310	Upper Edwards Zone	79	2,477	0.000198	9,094	363	179	2,750	1,300
13	625	Ked--Person Fm	10/25/2016	45.81	95.02		42	3,981	8,877									
12	660	Ked (RDM)	10/24/2016	53.51	0.001	e	22	0.02	nd									
11	695	Ked--Kainer Fm.	10/19/2016	45.51	243		27	6,561	13,541	Lower Edwards Zone	271	7,141	0.000198	16,707	435	214	9,000	4,300
10	725	Ked--Kainer Fm.	11/8/2016	47.53	334.5		32	10,704	15,743									
9	760	Ked--Kainer Fm.	10/20/2016	45.63	136		27	3,672	17,224									
8	790	Ked--Kainer Fm.	11/7/2016	48.02	112		37	4,144	17,294									
7	830	Ked--Kainer Fm.	10/17/2016	40.8	240		32	7,680	16,298									
6	865	Ked--Kainer Fm.	11/4/2016	48.59	136.3		32	4,362	18,622									
5	900	Ked--Kainer Fm.	11/3/2016	46.86	145.3		42	6,103	17,932									
4	945	Ked--Kainer Fm.	10/21/2016	47.81	331		42	13,902	17,007									

e= estimated
Pumping well construction: rc= 6 in, rw= 12 inches
Q = well yield (gpm)
*from Poteet et al., 1992
**drawdown is 33% of difference of static level to port depth of shallowest zone
***drawdown is 67% of difference of static level to port depth of shallowest zone

Discussion of Permeability

Porosity data in **Table 6** do not correlate with the direct measurements of permeability in **Table 9**. The transmissivity data of this study (**Table 9**) are similar to the data from the Kyle transect (**Table 8; Supplement 1**). Collectively, these data suggest relatively high-yielding wells are possible in the saline Edwards Aquifer (**Table 10**). Estimates of well yield (Q) in **Table 10** are relatively insensitive to order of magnitude changes in storativity. However, well yield (Q) is sensitive to changes in transmissivity. This study provides the most detailed measurements of transmissivity for the saline Edwards Aquifer.

Geochemistry

Geochemical data for each zone is an important variable in determining the feasibility for desalinization and also for understanding mixing or other geochemical processes with a desalinization and ASR system.

Figure 21. *Photograph of inertial pump during purging of a zone. Photo taken 10/14/2016.*

Previous work

Numerous studies have focused on the geochemistry of the saline Edwards to map and characterize the geochemical facies and TDS concentrations as they relate to the freshwater interface (Flores, 1990;

Schultz, 1993; Lambert et al., 2010). The most recent delineation of the freshwater/saline-water interface in the study area was completed by Hunt et al., 2014 (**Figure 1**). Other studies have focused on the origin of the saline water (section titled Saline Edwards Aquifer).

Recent geochemical studies include Mahler (2008) who presents statistical analyses of major ion and trace element geochemical data from wells that transect the freshwater/saline-water interface in the San Antonio area. Data were collected for more than 21 years from these wells. Mahler (2008) concludes that the transition zone wells (wells 1,000 to 10,000 mg/L) have relatively constant geochemistry and are not as connected to the surface hydrological conditions as the freshwater wells. Despite being less influenced by surface hydrological conditions, these wells do show some geochemical response to varying hydrologic (drought versus non-drought) conditions, although more slowly than the freshwater wells. Most of the data from these studies are derived from wells with long open-hole intervals.

Methods

After completion of the multiport well and isolation of the zones through packer inflation, each zone was individually purged. Purging of a zone was done by opening the pumping port and then using an inertial pump inside the PVC casing. Target purge volumes were calculated as four times the zone volume plus one PVC volume. Target purge volumes ranged from 215 to 320 gallons per zone. Purge rates varied based on the permeability of the zone and ranged from 0.5 to 3.5 gpm. Actual purge volumes varied from 110%-190% of the target volume. During the course of purging, a Horiba UM-50 measured field parameters and confirmed stability of values. After purging a zone, the pumping port was closed.

Westbay multiport systems offer the ability to collect discrete fluid samples. Four 250-ml stainless steel bottles are attached to the sampling instrument. Prior to insertion in the well, a vacuum is placed on the stainless steel sample bottles. The sampling instrument and sample bottles are lowered to the desired port depth. Because of the design of the multiport components, the sampling instrument can be placed at the exact port to be sampled. The instrument contains a valve through which water samples (up to 1 L) can be collected. When the instrument is in place, the valve is opened and water from the formation passes through the instrument and into the stainless steel bottles. The instrument and sample bottles are then retrieved to the surface.

Sampling, preservation, decontamination, and chain of custody procedures were generally followed as described by the Texas Water Development Board's guidelines UM 51 (Boghici, 2003). All samples were filtered in the field with disposable polyethersulfone membrane filters (QuickFilter) with 0.45 micron membranes and delivered to Environmental Laboratory Services (ELS).

All samples were analyzed for major anions and cations, deuterium, oxygen 18, and strontium 86/87. Two samples for carbon-14 analysis were collected from zones 10 and 13.

Results: Geochemistry

Samples of groundwater from 13 hydrostratigraphic zones were collected in October and November 2016. Two zones were resampled in March 2017 for confirmation of ion geochemistry and analysis of carbon 14. Results of laboratory analyses are summarized in **Table 11**. Detailed lab reports are in **Supplement 5**.

All geochemical analyses were funded by the Texas Water Development Board and data are available online (http://www2.twdb.texas.gov/apps/waterdatainteractive/groundwaterdataviewer).

Figure 22, a Durov diagram, is a graphical representation of the multiport well geochemistry compared with other waters. The basis of the Durov diagram is percentage plotting, in separate trilinear diagrams, of the major cations (calcium, magnesium, and sodium + potassium) and the major anions (bicarbonate, sulfate, and chloride) in units of millequivalents per liter (meq/L). Lines from each pair of points in the cation (left) and anion (top) trilinear fields are projected into the central square to form a common point, which represents the composition of a sample with respect to cations and anions. The points from the square field are also projected into TDS (right) and pH (bottom) fields. Similar in concept to Piper diagrams, Durov diagrams allow for more detailed comparison of samples based not only on major-ion chemistry, but also TDS and pH. The latter variables add two dimensions for interpretation that are not included with Piper diagrams.

The locations of symbols representing the multiport well in the trilinear and the square fields indicate that the overall hydrochemical signature is sodium-chloride. The points lie near symbols that represent waters of similar composition: seawater and the St. Alban's saline boundary well. Accounting for variations in the ratios of sodium-to-magnesium and chloride-to-sulfate, differences in TDS further differentiate the multiport samples from seawater and the transition-zone well.

Within the trilinear and square fields, symbols representing the multiport well form an overlapping cluster. The spread of multiport symbols in the TDS field illustrates that the concentration of dissolved solids is not uniform in the Upper Glen Rose and Walnut formations (Zones 1 – 3) and the Kainer and Person formations (Zones 4 - 14).

Edwards springs and wells, Middle Trinity springs, and Onion Creek surface water are clearly differentiated from multiport samples by the cluster of green symbols near the upper right corner of the square. The compositions are all calcium-bicarbonate (Ca-HCO3), with TDS typically less than 400 mg/L. Middle Trinity wells are distinguished from the above by the dominance of sulfate and magnesium and TDS as high as 1000 mg/L.

The variation in geochemical composition in the 13 hydrostratigraphic zones described in this report is further illustrated by depth profiles of major cations, anions.

In **Figure 23**, TDS increases from 13000 mg/L in the Upper Glen Rose (Zone 2, -1025 ft) to 18500 mg/L in the Kainer formation (Zone 6, -855 ft) and decreases to 13500 mg/L at the top of the Kainer (Zone 12, -685 ft). Above the Regional Dense Member aquitard (Zone 12), TDS is less than 9400 mg/L in the Person formation (Zones 13 and 14, -615 ft and -575 ft, respectively). The chloride depth profile mimics that of TDS, an indication that chloride is a primary component of dissolved solids.

In **Figure 24**, the profile of sulfate does not follow that of chloride. The lowest concentrations are in the Upper Glen Rose, Walnut and lower Kainer formations (Zones 1 -7), and the highest are in the Upper Kainer (Zone 9) and Upper Person (Zone 14) formations.

There is also marked conformance between the depth profiles of the concentrations of sodium and chloride (**Figure 25**), and calcium + magnesium and bicarbonate (**Figure 26**). **Figures 24** - **26** underscore that the hydrochemical profile, although relatively uniform with respect to overall composition, varies with regard to stratigraphy, with the highest TDS occurring in the Kainer formation. A more detailed assessment of geochemical factors accounting for hydrochemical signatures will be developed in a separate report on the inorganic and isotope geochemistry of the Edwards and Trinity Aquifer systems.

Equilibrium Chemistry

Effect of Mixing Injectate with Groundwater of the Edwards Aquifer (Person Formation)

Groundwater mixing models were developed with Geochemist's Workbench© v. 11 to illustrate the effect of mixing groundwater of the Person formation (14-Kep and 13-Kep) with two potential sources of injected water: (1) desalinated groundwater of the Kainer formation (11-Kep – 4-Kep), and (2) fresh groundwater from the Creedmoor Water Supply Corporation. Such models are a means of assessing the compatibility of injectate and native groundwater and to ascertain whether groundwater in the mixing zone is oversaturated or undersaturated with respect to key mineral species. This is especially important if arsenic-bearing minerals are disseminated within the matrix of the receiving formation. In situations in which there are marked differences between the hydrochemical compositions of injectate and groundwater, mixing models also illustrate the degree to which higher-TDS water of the storage zone will dominate the composition of water in the mixing zone.

The ratios of the Person-Kainer and the Person-Creedmoor models were 1:99, 2:98, 5:95, 25:75, and 50:50. The composition of Person groundwater was modeled as a 50:50 mixture of groundwater from zones 14-Kep and 13-Kep. The composition of desalinated Kainer groundwater was based on Carollo's estimated concentration of dissolved solids, and the composition of Creedmoor groundwater was taken from data on the Creedmoor WSC well as found in the groundwater data base of the Texas Water Development Board. Dissolved oxygen (DO) concentrations for Person and treated Kainer were set to 0.1 mg/L, and to 2.1 mg/L for Creedmoor. The Creedmoor estimate was based on data from a BSEACD study of DO concentrations in groundwater (Lazo-Herenca et al., 2011). The compositions of Person, treated Kainer, Creedmoor, and the modeled mixtures are listed in **Table 12**. The results of the mixing models are illustrated by two Schoeller diagrams (**Figure 27**). The Schoeller format was selected because it better illustrates changes in composition based on the mixing ratios used in this assessment.

Carollo's estimated composition of treated Kainer water required adjustment to eliminate a large negative charge imbalance (-54 percent) and to force electroneutrality, a fundamental requirement of geochemical modeling of aqueous systems. The adjustment was made by specifying charge balance on sodium. This increased the estimated TDS from 7 mg/L to 16 mg/L.

The compositions of the endmembers are: Person (Na-Cl-SO4), treated Kainer (Na-OH), and Creedmoor (Ca-HCO3). There are also large differences in TDS (Person, 9487 mg/L; treated Kainer, 16 mg/L; and Creedmoor, 484 mg/L) and in ionic strength (Person, 0.1744 mol/L; treated Kainer, 0.0004 mol/L; and Creedmoor, 0.0087 mol/L).

The models illustrate that the saline groundwater of the Person formation strongly dominates the composition of all mixtures with treated Kainer groundwater and four of the five mixtures with Creedmoor groundwater. The dominance of Person groundwater in the mixtures is clearly illustrated by the Schoeller diagrams of **Figure 27**. All Person-Kainer mixtures are Na-Cl, and the TDS of the mixtures ranges from 110 at a 1:99 Person-Kainer ratio to 4823 at 50:50. The TDS of mixtures with Creedmoor groundwater ranges from 574 at 1:99 to 4984 at 50:50. Mixtures consisting of 5 percent or more Person groundwater are Na-Cl. At lower percentages of Person groundwater, the mixtures are Ca-HCO3.

Selected saturation indices are listed in columns below the table of concentrations (**Table 12**). Positive values indicate oversaturation with respect to a mineral species, and negative values are interpreted to indicate undersaturation. It is important to note that oversaturation does not signify that a mineral will precipitate, only that it has the potential to form. Negative indices indicate the potential for dissolution.

The negative indices for pyrite indicate the potential for dissolution of the mineral. At this time, the presence of pyrite in the matrix of the Person formation has not been verified. Pyrite is a mineral with which arsenic is often associated. Concentrations of arsenic in zones 14 and 13 are 3.68 μg/L and 3.79 μg/L, respectively. The occurrence of arsenic in the samples indicates that arsenic is available within the formation. The mineralogical association, however, is not known.

It is important to note that DO of Creedmoor groundwater might drive the oxidation of any pyrite in the Person formation. Oxygenated waters injected at early ASR sites in Florida were the key factors that led to the release of arsenic in concentrations greater than the 10-μg/L MCL (Arthur et al., 2002; Price and Pichler 2006; Jones and Pichler 2007), primarily from pyrite (FeS_2) and arsenopyrite (FeAsS). The occurrence of arsenic in groundwater at ASR sites in Florida was not observed until the early stages of cycle testing, and the mineral associations were discovered only after investigators examined cores and cuttings from the storage zone (Suwannee Limestone).

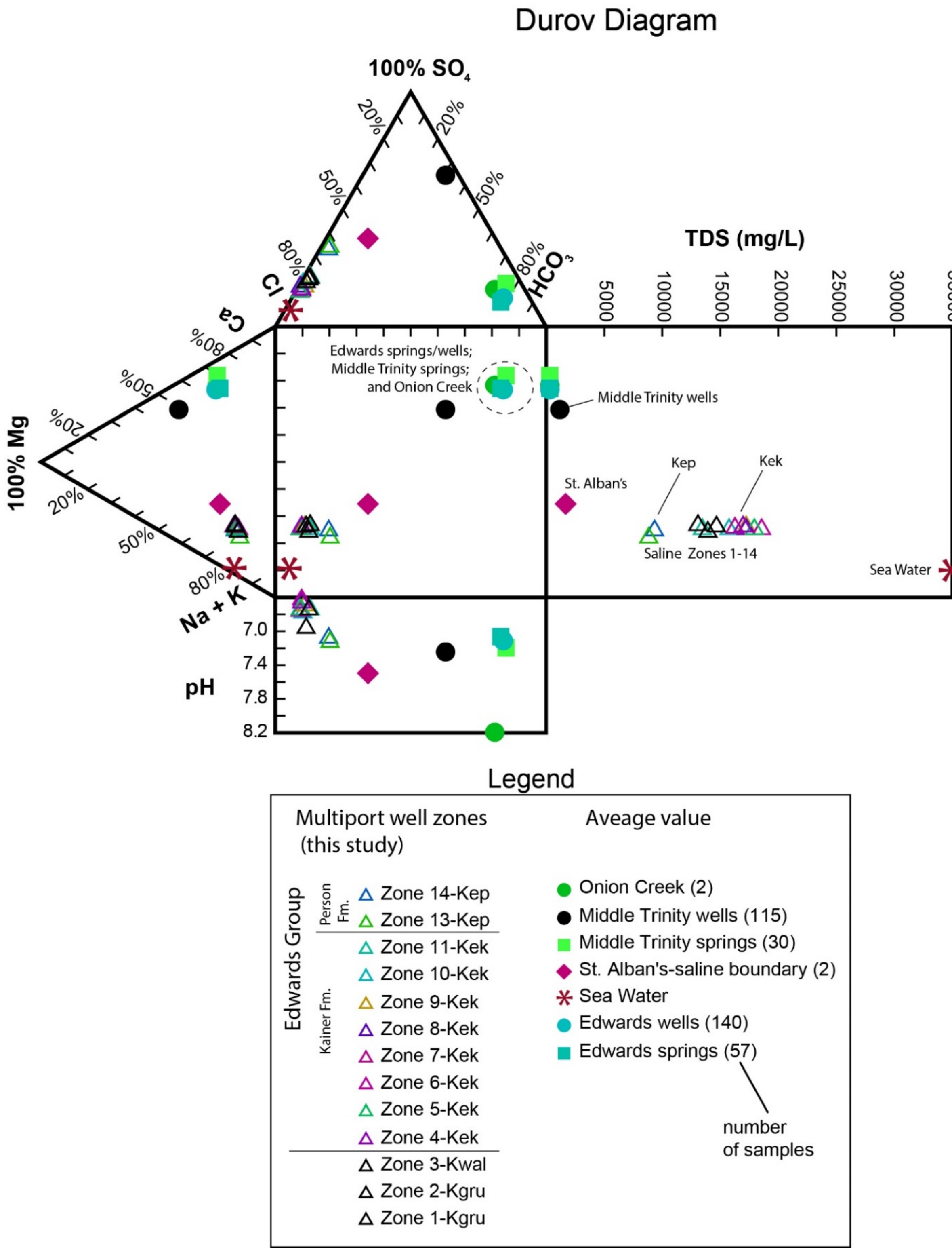


Figure 22. *Durov diagram showing geochemistry of the multiport zones compared to other source waters. Results indicate all the multiport zones have a sodium-chloride water type.*

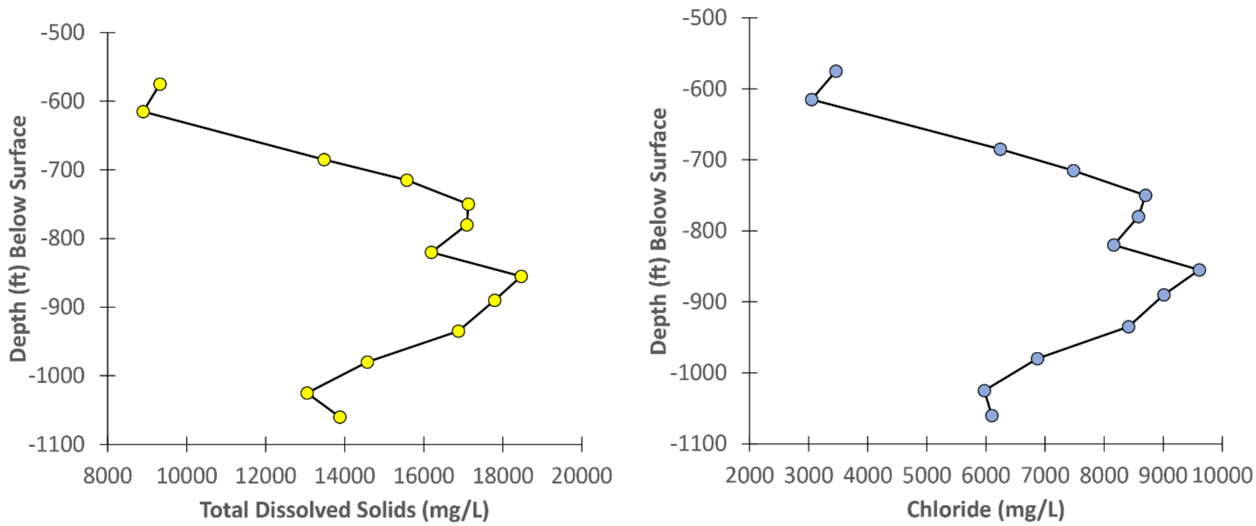


Figure 23. *Depth profile of total dissolved solids (mg/L) and chloride (mg/L).*

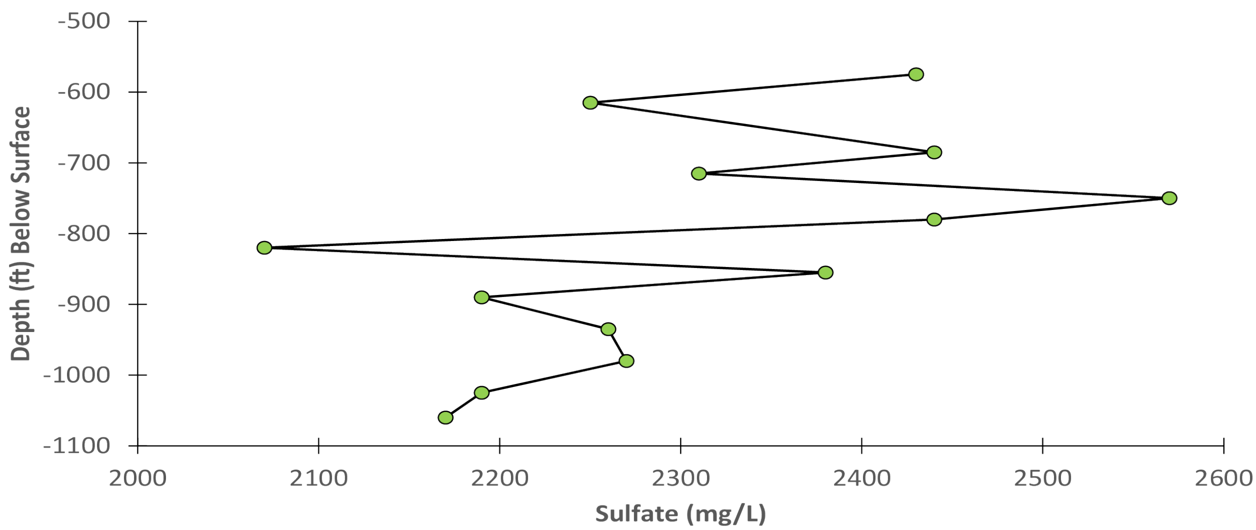
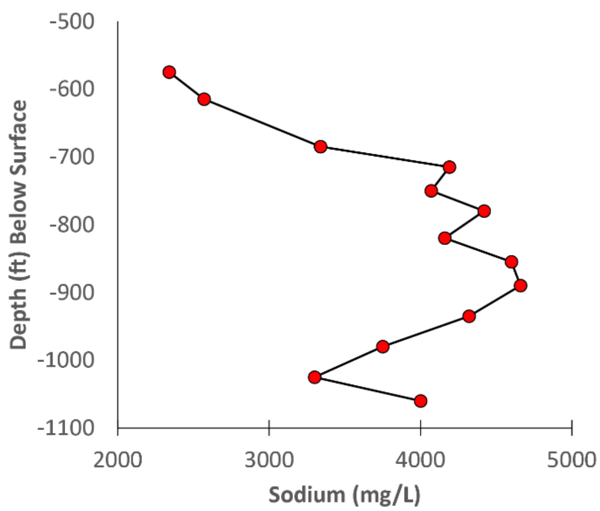


Figure 24. *Depth profile of sulfate (mg/L).*



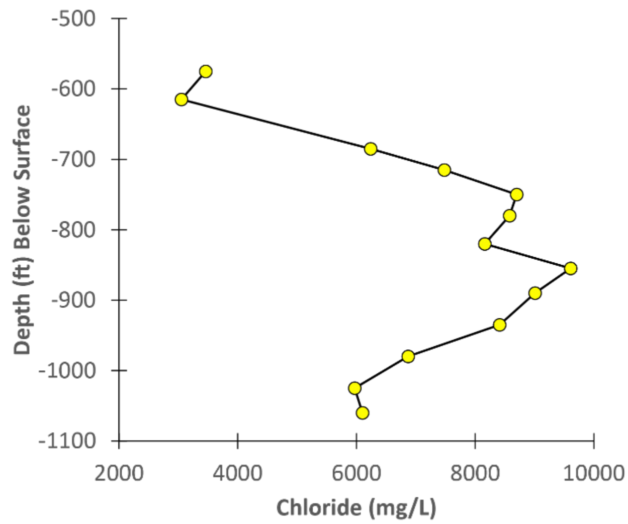
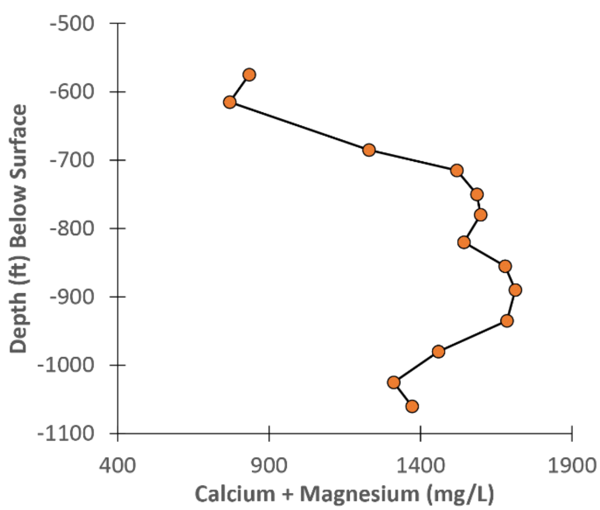


Figure 25. *Depth profile of sodium (mg/L) and chloride (mg/L).*



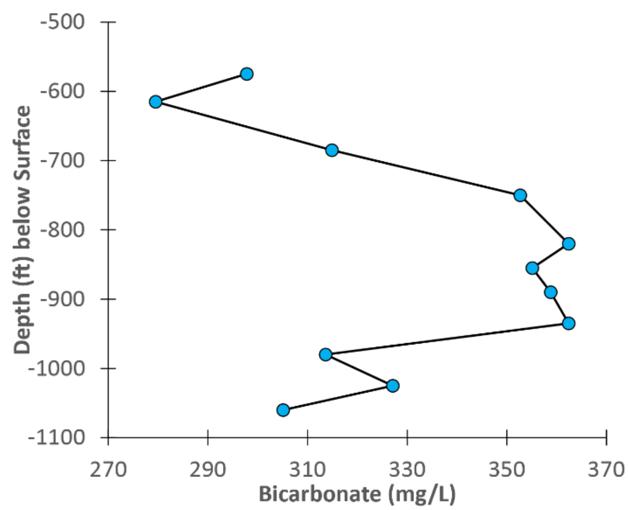


Figure 26. *Depth profile of Calcium + Magnesium (mg/L) and Bicarbonate (mg/L).*

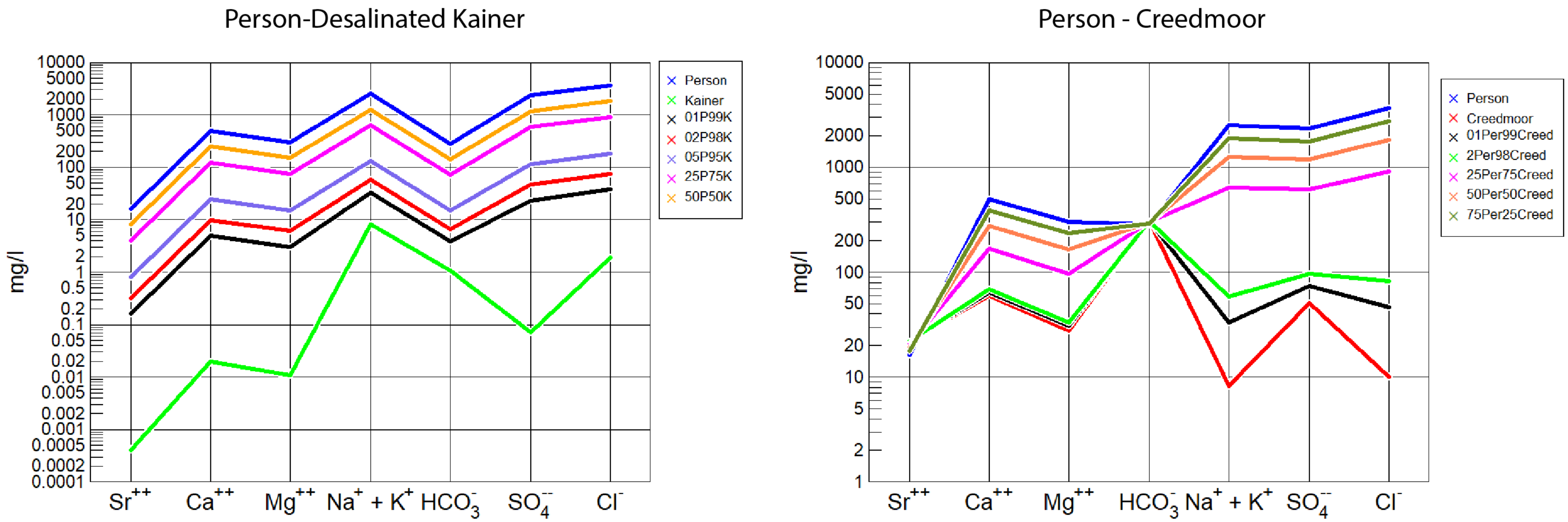


Figure 27. *Schoeller diagrams illustrating results of mixing groundwater of Person formation with desalinated injectate and with fresh groundwater from Creedmoor WSC. Person:Injectate and Person:Creedmoor mixing ratios are 1:99, 2:98, 5:95, 25:75,and 50:50.*

Table 11. *Summary of geochemistry data.*

Zone	Geologic Unit	Sample Port Depth (ft)	Purge Volume*	Sample Date	Purge Water Conductivity (uS/cm)	Temp C	TDS (mg/L)	An/Cat Charge Balance (%)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SO4 (mg/L)	HCO3 (mg/L)	Cl (mg/L)	AS (ug/L)	Fl (mg/L)	Sr (mg/L)	Si (mg/L)	Br (mg/L)	B (ug/L)	Mn (ug/L)	Fe (ug/L)	Nitrite/Nitrate (mg/L as N)	pH	Deut (PERMIL VSMOW)	O-18 (PERMIL VSMOW)	Sr-86/87	Delta Carbon 13 C13/C12 per mil	PMC
18	Eagle Ford	395	NA	NS																										
17	Buda	430	NA	NS																										
16	Del rio	475	NA	NS																										
15	Georgetown	540	NA	NS																										
14	Edwards--Person Fm	575	122%	10/14/2016	14,200	24.22	9,310	-0.82	518	316	2,340	69	2,430	298	3,460	3.68	3.1	15.90	11.6	32.40	4,840	44.90	221	<0.02	7.1	-28.1	-4.73	0.7086722		
13	Edwards--Person Fm	615	140%	10/25/2016	14,300	24.78	8,877	-8.15	478	292	2,570	70	2,250	279	3,050	3.79	5	16.60	13.1	33.60	4,170	30.60	99	<0.04	7.1	-30.0	-4.57	0.7086857		
13	Edwards--Person Fm	615	n/a	3/29/2017		24.12	9,857	-4.85	569	322	2,660	70	2,590	256	3,460	3.97	3.12	17.20	12.5	30.10	4,290	11.40	<50	<0.02	nd	nd	nd	nd	0.0	< 0.0044
12	Edwards--Person (RDM)	650		NS																										
11	Edwards--Kainer Fm	685	190%	10/19/2016	22,200	2440	13,541	1.69	773	457	3,340	98	2,440	315	6,240	7.7	2.88	18.90	16.2	51.55	6,750	140.00	1,020	<0.02	6.7	-28.7	-4.27	0.7087400		
10	Edwards--Kainer Fm	715	140%	11/8/2016	23,200	24.23	15,743	-3.23	972	548	4,190	120	2,310	175	7,480	8.81	<10	22.00	14.8	53.30	7,870	<2.00	60	<0.1	6.8	-27.4	-3.88	0.7088100		
10	Edwards--Kainer Fm	715	n/a	3/29/2017		24.75	15,642	1.64	970	520	3,820	116	2,480	283	7,520	10.3	2.75	22.20	21.4	59.20	7,210	1.67	<50	<0.08	nd	nd	nd	nd	0.1	< 0.0044
9	Edwards--Kainer Fm	750	166%	10/20/2016	23,800	25.4	17,224	4.46	1,010	576	4,070	115	2,570	353	8,700	9.84	2.8	20.80	15.8	69.20	7,530	<2.00	<1000	<0.1	6.7	-28.0	-4.08	0.7088310		
8	Edwards--Kainer Fm	780	120%	11/7/2016	25,200	24.06	17,294	0.26	1,030	568	4,420	129	2,440	179	8,580	9.62	<10	22.70	15.9	63.00	8,430	<2.00	<50	<0.1	6.8	-27.5	-3.83	0.7088495		
7	Edwards--Kainer Fm	820	154%	10/17/2016	25,500	26.12	16,298	0.00	1,000	543	4,160	133	2,070	362	8,160	10.4	3.79	22.30	27.8	61.80	7,910	4.81	183	<0.04	6.6	-27.4	-3.99	0.7088500		
6	Edwards--Kainer Fm	855	122%	11/4/2016	25,400	24.65	18,622	3.08	1,090	589	4,600	134	2,380	355	9,610	9.76	<5	24.10	19.9	72.20	8,850	2.92	<50	<0.1	6.8	-27.7	-3.89	0.7088755		
5	Edwards--Kainer Fm	890	117%	11/3/2016	26,200	25.45	17,932	-1.00	1,110	603	4,660	137	2,190	359	9,010	9.66	<5	24.80	20.3	68.30	8,780	2.58	<50	<0.1	6.7	-27.3	-3.79	0.7088816		
4	Edwards--Kainer Fm	935	163%	10/21/2016	24,600	25.95	17,007	-0.86	1,070	615	4,320	117	2,260	362	8,410	11.10	2.90	22.30	11.2	58.20	5,130	5.06	<2500	<0.1	6.7	-27.4	-3.93	0.7088526		
3	Walnut Fm	980	110%	11/2/2016	21,300	24.86	14,648	-1.97	936	523	3,750	105	2,270	314	6,870	7.03	<5	22.80	16.8	56.60	6,300	9.19	<50	<0.1	7.0	-27.8	-4.07	0.7087874		
2	Upper Glen Rose Mbr	1025	132%	10/18/2016	20,300	26.82	13,090	-1.69	848	463	3,300	107	2,190	327	5,970	6.29	3.90	18.40	28.6	49.20	6,730	14.60	68	<0.04	nd	-29.8	-4.26	0.7088380		
1	Upper Glen Rose Mbr	1060	147%	10/28/2016	21,900	26.29	13,942	-8.16	881	491	4,000	114	2,170	305	6,100	6.68	<10	20.90	15.2	55.60	6,760	8.14	<50	<0.04	6.7	-28.2	-4.07	0.7088300		

*100%=4 x zone volume and 1 x pipe volume.

Table 12. *Modeled results of mixing groundwater from Person formation with desalinated injectate and with groundwater from Creedmoor WSC. Person:Injectate and Person:Creedmoor mixing ratios are 1:99, 2:98, 25:75, 50:50, and 75:25*

SAMPLE ID	UNIT	PERSON	KAINER	01P99K	02P98K	05P95K	25P75K	50P50K	CREEDMOOR	1P-99C	2P-98C	5P-95C	25P-75C	50P-50C
TEMPERATURE	C	24.5	25	25	24.99	24.98	24.88	24.75	24	24	24.01	24.02	24.13	24.25
PH	pH	7.093	10.41	10.32	10.26	9.989	8.615	7.483	7.1	7.097	7.095	7.087	7.07	7.068
SIO2(AQ)	mg/l	12.35	0.0013	0.1242	0.2471	0.6159	3.077	6.161	10.9	10.92	10.93	10.97	11.26	11.63
O2(AQ)	mg/l	0.05	0.05	0.05	0.05	0.05	0.05	0.05	2.1	2.079	2.059	1.998	1.589	1.077
CA++	mg/l	498	0.0195	4.976	9.933	24.81	124.1	248.4	60	64.36	68.72	81.82	169.2	278.6
MG++	mg/l	304	0.011	3.037	6.062	15.14	75.74	151.6	27.9	30.65	33.4	41.65	96.73	165.7
SR++	mg/l	16.25	4.00E-04	0.1621	0.3239	0.8092	4.048	8.106	22	21.94	21.88	21.71	20.57	19.13
NA+	mg/l	2448	8.264	32.55	56.83	129.7	616	1225	7	31.32	55.64	128.6	615.5	1225
K+	mg/l	69.75	0.0343	0.7282	1.422	3.504	17.4	34.81	1.2	1.883	2.566	4.615	18.29	35.41
HCO3-	mg/l	283.9	1.065	3.879	6.695	15.14	71.52	142.1	309.6	309.3	309.1	308.3	303.2	296.8
SO4--	mg/l	2340	0.0713	23.36	46.65	116.5	583	1167	51	73.8	96.61	165	621.6	1193
CL-	mg/l	3650	1.904	38.21	74.53	183.5	910.7	1822	10	46.26	82.53	191.3	917.4	1826
BR-	mg/l	33	0.0155	0.3438	0.6721	1.657	8.232	16.47	0.01	0.3387	0.6673	1.653	8.234	16.47
F-	mg/l	2.8	0.0023	0.03015	0.05799	0.1416	0.6992	1.398	0.9	0.9189	0.9378	0.9946	1.374	1.848
B	mg/l	4.505	0.0849	0.1289	0.1729	0.3049	1.186	2.29	0.1	0.1439	0.1877	0.3194	1.198	2.298
FE	mg/l	0.1600		0.0016	0.0032	0.0080	0.0399	0.0798	0.1000	0.1006	0.1012	0.1030	0.1150	0.1299
MN	mg/l	0.0378		0.0004	0.0008	0.0019	0.0094	0.0188	0.1000	0.0994	0.0988	0.0969	0.0845	0.0689
AS	mg/l (as As)	0.0037		0.0000	0.0001	0.0002	0.0009	0.0019	0.0000	0.0000	0.0001	0.0002	0.0009	0.0019
TDS	mg/l	9487	16.06	110.1	207.2	494.2	2416	4823	483.7	573.7	663.8	946.8	2735	4984
WATER TYPE		Na-Cl	Na-OH	Na-Cl	Na-Cl		Na-Cl	Na-Cl	Ca-HCO3	Ca-HCO3	Ca-HCO3	Na-Cl	Na-Cl	Na-Cl
IONIC STRENGTH	mol/l	1.74E-01	3.73E-04	2.39E-03	4.36E-03	1.01E-02	4.65E-02	9.01E-02	8.71E-03	1.05E-02	1.22E-02	1.75E-02	5.17E-02	9.33E-02
QUARTZ	log Q/K	0.3446	-4.3840	-2.3770	-2.0590	-1.4900	-0.3218	0.0262	0.2800	0.2809	0.2814	0.2834	0.2969	0.3135
CALCITE	log Q/K	0.2430	-2.7900	-0.0042	0.4153	0.8812	0.8923	0.2237	-0.0742	-0.0705	-0.0651	-0.0505	0.0468	0.1279
DOLOMITE	log Q/K	1.4950	-4.7160	0.9013	1.7490	2.6960	2.7480	1.4310	0.6527	0.6734	0.6958	0.7521	1.0260	1.2260
GYPSUM	log Q/K	-0.4380	-8.0950	-3.3080	-2.7900	-2.1490	-1.1530	-0.7812	-2.1190	-1.9630	-1.8490	-1.6200	-1.0350	-0.7402
FLUORITE	log Q/K	0.2730	-9.2690	-4.7270	-3.9210	-2.8670	-1.1000	-0.3951	-0.8432	-0.8237	-0.8038	-0.7435	-0.4077	-0.1150
GOETHITE	log Q/K	5.8900		3.1870	3.5360	4.1300	5.3220	5.6340	5.7120	5.7140	5.7150	5.7200	5.7570	5.8030
HALITE	log Q/K	-3.8510	-9.3370	-7.4660	-6.9500	-6.2300	-4.9430	-4.3950	-8.7560	-7.4480	-6.9530	-6.2420	-4.9480	-4.3970
PYRITE	log Q/K	-230		-249	-248	-246	-238	-233	-240	-240	-240	-239	-238	-237

Origin of Salinity

The origin of salinity in the eastern reaches of the Edwards Aquifer has been a subject of research for many years. The results of several prominent investigations are summarized in an earlier section of this report. There is not universal agreement among researchers, and the matter of salinity sources remains one of great interest. This section of the report considers key major ions and ionic ratios, as wells as oxygen and hydrogen isotope ratios as indicators of source(s) of salinity.

Saline groundwaters are derived from many sources: seawater, evaporated seawater, residual brines derived from the precipitation of halite, evaporated fresh waters, oil field waters, dissolution of halite and gypsum, and interaction between water and rocks other than evaporites. The concentrations of dissolved solids are affected by each source, and ratios of selected ions are often used as indicators of a source or sources of salinity.

The ratio of sodium to chloride in seawater is approximately 0.86, and in freshwater that has dissolved halite (NaCl), the ratio is 1.0 – a reflection of the equimolar ratio of sodium to chloride in the halite lattice. In addition to Na/Cl molar ratios, the ratio of chloride to bromide (Cl/Br) is often considered to be an indicator of source (Davis et al., 1997; Acala' and Custodio, 2008), and the stable isotope ratios $\delta^{18}O$ and $\delta^{2}H$ are indicators of processes such as evaporation and rock-water interaction (Sharp, 2007, p. 88 - 91).

The concentrations of sodium and chloride are strongly correlated in groundwater samples from the 13 hydrostratigraphic zones, as illustrated by **Figure 28**. The coefficient of determination (R^2) of the regression equation is 0.92, a measurement of the degree to which the variability of the concentration of sodium is explained by the association with the predictor variable, chloride. Molar ratios of sodium-to-chloride, however, are neither consistent with halite dissolution nor a seawater-only source (**Figure 29**), as most of the ratios and all of the chloride concentrations are below those of seawater.

Chloride-bromide ratios do not support a halite source or a seawater source (**Figure 30**). Chloride and bromide are conservative ions, and few processes other than dissolution or precipitation of halite, interaction with other lithic sources, or mixing of groundwaters significantly affect their concentrations (Hem, 1985). The magnitude of the chloride-bromide ratio is sensitive to the origin of water as marine, as a second-cycle solution of marine salt, or as a residual brine from the precipitation of halite. In seawater the weight ratio of chloride to bromide is 290, and the molar ratio is 650 (Davis et al., 1998; Alcala' and Custodio, 2008). During evaporation, the ratio remains constant up to the point at which halite begins to precipitate. Because of its larger radius, the bromide ion is excluded from the halite lattice, so that the residual brine is enriched in bromide relative to chloride. This causes the chloride-bromide ratio to decrease in the residual brine. Because halite is deficient in bromide, the ratio increases substantially as halite is later dissolved by other waters.

Figure 30 illustrates that the weight ratios are much lower than the seawater ratio of 290 (or 650 molar). This could be an indication that the waters are derived from residual brine, or that higher bromide concentrations are related to very long-term interaction with unidentified lithic sources of bromide. The water-rock interaction hypothesis is supported by at least one other line of data, abundances of the stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H).

Oxygen-18 and deuterium are incorporated into the water molecule. Although naturally occurring, they are much less abundant than the more common stable isotopes oxygen-16 (^{16}O) and protium (^{1}H). The abundances are reported in per mil units as $\delta^{18}O$ and $\delta^{2}H$. Waters derived from precipitation will characteristically have $\delta^{18}O$ and $\delta^{2}H$ values that lie along or subparallel to the global meteoric water line (GMWL). The GMWL describes the association between $\delta^{18}O$ and $\delta^{2}H$, measured from samples of precipitation collected from locations around the planet. The equation of the GMWL is (Craig, 1961):

$\delta 2H = 8\delta^{18}O + 10$

Figure 31 shows the GMWL along with $\delta^{18}O$ and $\delta^{2}H$ measurements from samples of water from springs discharging from the Edwards Aquifer in southern Travis, Hays, and Comal counties. The data are found in the groundwater chemistry data base of the Texas Water Development Board (http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp). Also plotted on the figure are the $\delta^{18}O$ and $\delta^{2}H$ measurements from the groundwater samples listed in Table 11 of this report.

The spring water samples generally lie on or slightly subparallel to the GMWL. The variability in the measurements is related to factors such as season of recharge and evaporation. Accounting for that variability, the measurements are consistent with water derived entirely from precipitation in the central Texas region.

The samples from **Table 11** (listed as Saline Edwards on the figure) form a distinct linear pattern extending to the right of the GMWL. Such patterns are characteristic of waters that have become enriched in ^{18}O through contact with carbonates and silicates, rocks with heavier $\delta^{18}O$ values than unevaporated surface waters. This is a common feature of thermal waters (Faure, 1986, p. 451) as well as basinal brines and saline formation waters (Clayton et al., 1966). It is apparent that the 13 samples collected from the multiport well display the plotting pattern common to waters that have been in contact with ^{18}O-enriched rocks. Such enrichment typically occurs under higher temperature environments than is the case with respect to this area of the Edwards Aquifer. If the enrichment occurred in a higher-temperature environment, then a reasonable hypothesis might be that the saline waters of the Glen Rose, Walnut, Kainer, and Person formations might have originated as deep-basin brines and then migrated in a high geopressured system to shallower formations of the Gulf Coast Basin. That hypothesis has been proposed by Hoff and Dutton (2017) in their evaluation of brackish Edwards Group water and measurements of geopressured in oil and gas wells of south-central Texas:

> *Brackish water in the Edwards Aquifer in south-central Texas is hypothesized to occur in a zone of convergent flow with hydrodynamic and transient mixing mainly between hydropressured freshwater moving downdip by gravity and saline water migrating updip from depth by a geopressure drive. Another source of water and dissolved mass is upward-directed cross-formational flow into the Edwards Group.*
>
> *And*

The presence of geopressure conditions in the deep Edwards Group is indicated by fluid-pressure data from oil and gas wells, but has not been verified using field information. Geopressure in the superjacent Cenozoic section might have induced high fluid pressure in the Edwards Group. A regime of geopressure or 'subgeopressure' within the Edwards Group, however, seems required to drive saltwater updip toward the freshwater zone and to account for high hydraulic head in fault-bounded saline rocks adjacent to the freshwater aquifer.

The geochemical data considered in this report do not support halite dissolution as a source of salinity in the Glen Rose – Person formations. This inference is based, first, on sodium-chloride ratios and chloride-bromide ratios that are inconsistent with ratios that would have been derived from the dissolution of halite. Furthermore, the prominent horizontal trajectory of $\delta^{18}O$ values to the right of the GMWL is strongly indicative of groundwater that has been enriched in ^{18}O under higher temperatures. All considered, the data support the hypothesis that the salinity is derived from long-term rock-water interaction in deeper formation of the central Texas Gulf Coast Basin.

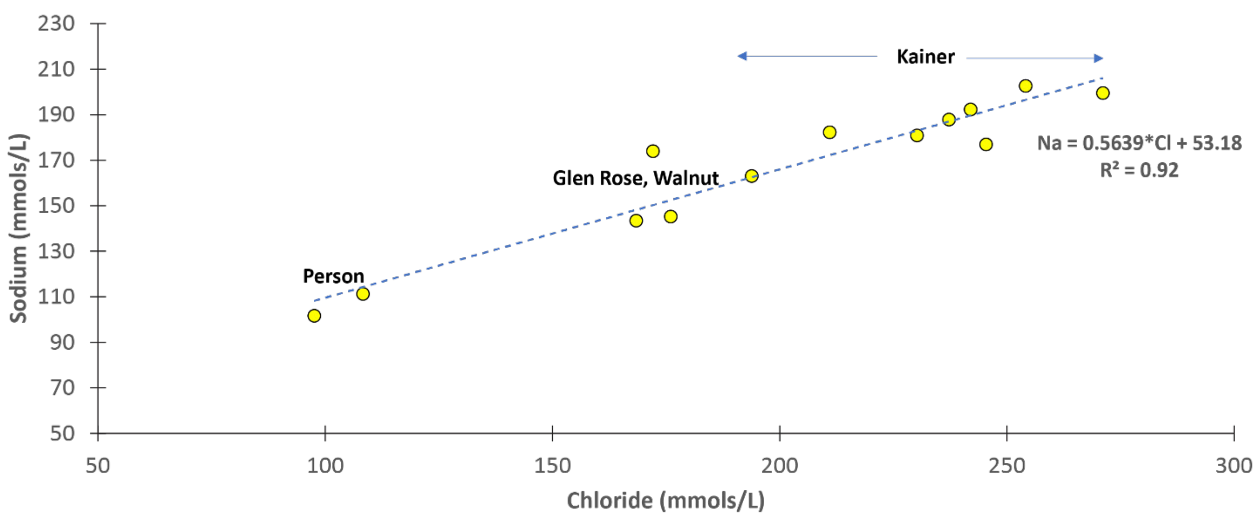


Figure 28. *Graph of sodium and chloride concentrations in groundwater from the Glen Rose, Walnut, Kainer, and Person formation. The regression model illustrates a high degree of correlation between the ions, on the basis of the R2 statistic, which is interpreted to mean that 92 percent of the variability of sodium concentrations is accounted for by the association with chloride.*

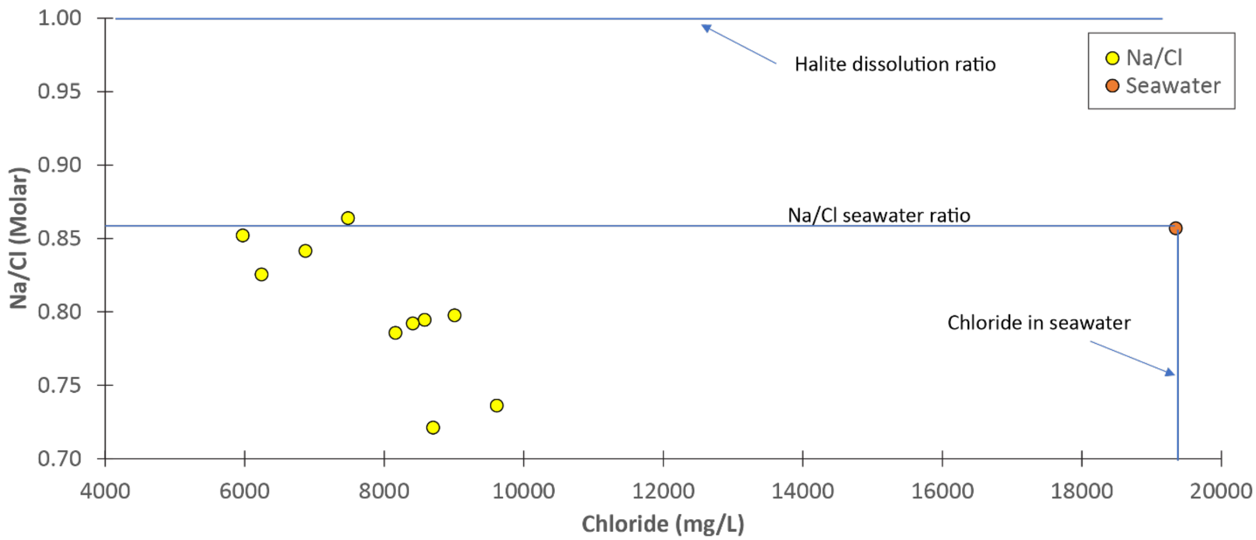


Figure 29. *Sodium-chloride molar ratios in samples of groundwater from the Glen Rose, Walnut, Kainer, and Person formations. Ratios derived entirely from the dissolution of halite should fall on or very near to the halite line. Seawater-derived ratios should cluster around a ratio of approximately 0.86.*

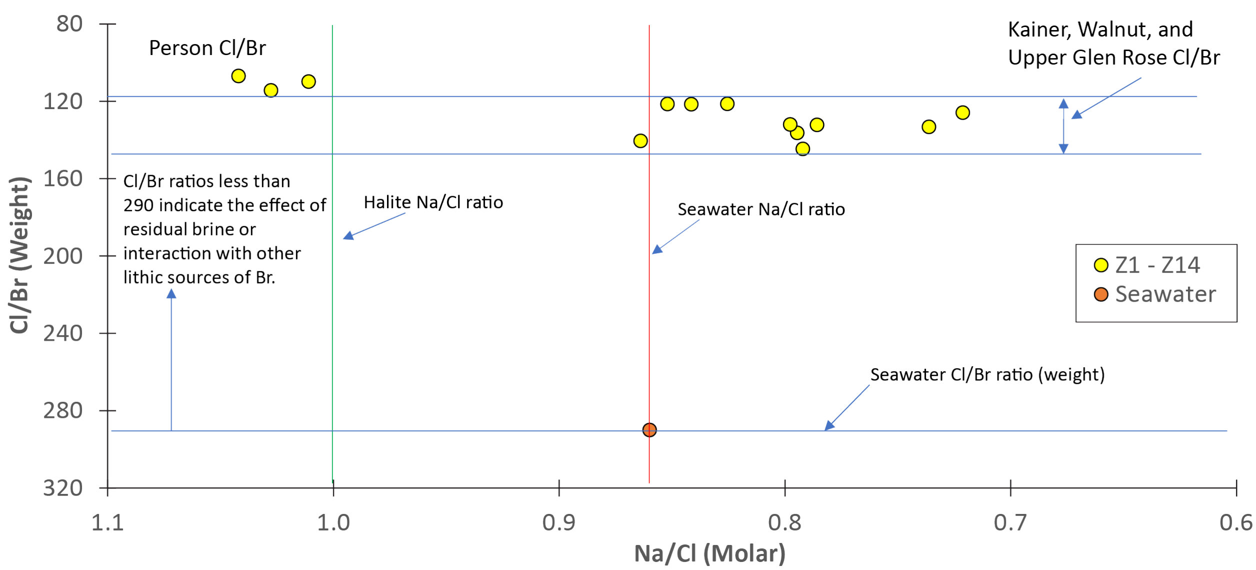


Figure 30. *Plot of chloride-bromide weight ratios and sodium-chloride molar ratios. The ratios are significantly lower than the seawater ratio, 290. This indicate that the waters are derived either from residual brines or from contact with lithic sources enriched in bromide.*

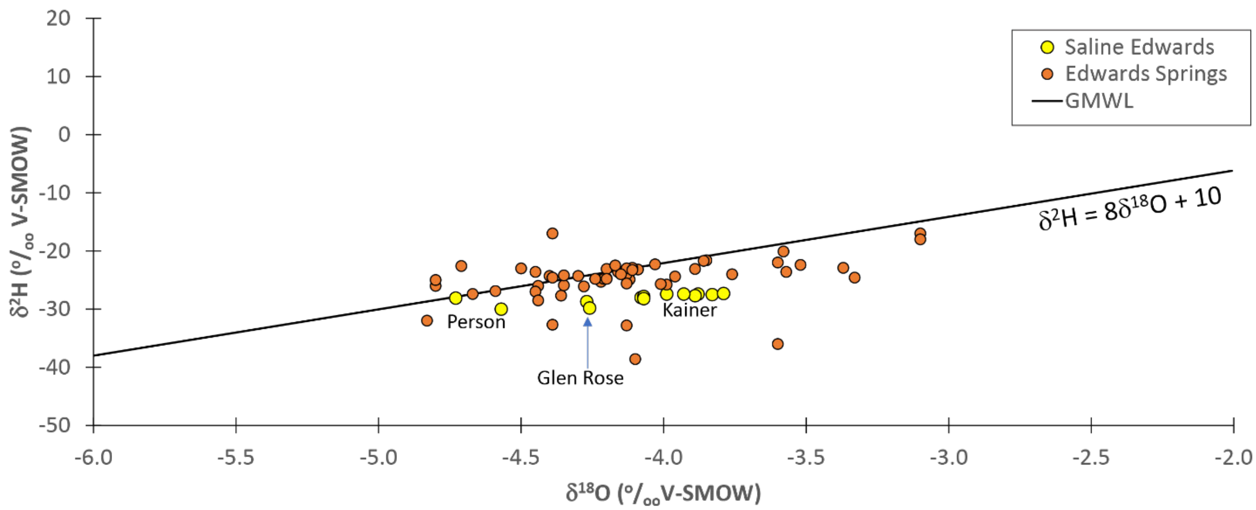


***Figure 31**. Global Meteoric Water Line along with d18O and d2H values from Edwards springs and zones 1 – 14. The horizontal deflection to the right of the GNWL formed by the Glen Rose, Walnut, and Kainer samples is a pattern consistent with enrichment of water in 18O in thermal systems and in basinal brines and formation waters.*

Discussion of Geochemistry Data

Geochemical data compiled for this investigation illustrate that the composition of groundwater from hydrostratigraphic zones 1 – 11, 13 and 14 is sodium-chloride, with variable concentrations of total dissolved solids. TDS increases from 13000 mg/L in the Upper Glen Rose (Zone 2, -1025 ft) to 18500 mg/L in the Kainer formation (Zone 6, -855 ft) and decreases to 13500 mg/L at the top of the Kainer (Zone 11, -685 ft). Above the Regional Dense Member aquitard (Zone 12), TDS is less than 9400 mg/L in the Person formation (Zones 13 and 14, -615 ft and -575 ft, respectively). Although the origin of salinity remains unknown, the geochemical data appear to allow for the elimination of at least two potential sources of salinity: seawater (or residual seawater), and halite dissolution.

Ratios of sodium to chloride are not consistent with ratios derived from a seawater-only source or from the dissolution of halite. Most sodium-chloride ratios are less than that of seawater, 0.86. The sodium-chloride ratio of halite-dissolution brines is 1.0 or very close to that because of the equimolar concentrations of sodium and chloride in the halite lattice. Chloride-bromide ratios are not close to that of seawater (290) but are low enough (150) to be consistent with that expected for residual brines. The samples are enriched in bromide, compared with the concentration of bromide in seawater, but the greatest TDS of the 13 samples is far below that of residual brines, and less than the TDS of seawater, 35,000 mg/L.

An alternative hypothesis to explain the low chloride-bromide ratios is the interaction of groundwater and unidentified lithic sources of bromide, perhaps in deeper formations of the Gulf Coast. An indication of such interaction is the plotting pattern of δ^{18}O and δ^2H values along a horizontal trajectory to the right of the global meteoric water line. Such patterns are characteristic of groundwaters that have become enriched in ^{18}O through interaction with carbonates or silicates in high-temperature environments. A recent study of the occurrence of saline water in the Edwards Group of south-central Texas posits migration of deep formation brines to shallower formations of the Gulf Coast by geopressured systems that drive brine upward along pathways along fault-bounded blocks. This is a reasonable hypothesis to account for the occurrence of saline water along the saline and freshwater boundary and more concentrated brines in deeper formations to the east.

Mixtures of desalinated groundwater from the Kainer formation or of fresh Edwards groundwater from the Creedmoor WSC will be strongly dominated by the sodium-chloride receiving water of the Person formation. All mixtures of treated Kainer and Person will be sodium-chloride in composition, and mixtures of freshwater Edwards and Person will be sodium-chloride at Person-Edwards mixtures of 5:95. There is potential for the release of arsenic within the storage zone. The occurrence of arsenic in samples from zones 13 and 14 indicates that arsenic is available and mobile. The mineralogical associations of arsenic in the matrix of the Person formation are unknown; but there remains a probable association with ferrous iron, perhaps in the form of pyrite. Injection of Edwards water with measurable concentrations of dissolved oxygen could drive the dissolution of pyrite and to the release of arsenic. If freshwater Edwards is the injectate, it will be advisable to monitor arsenic concentrations in recovery water, especially over long periods of storage.

Conclusions

The multiport well provides detailed hydrogeologic data that are critical for characterizing the saline Edwards Aquifer in the study area. Some conclusions from this study include:

- Heads are generally higher in the saline Edwards than the freshwater Edwards Aquifer, with a potential for flow toward the freshwater/saline-water interface.
- Vertical flow potential is variable. There is downward flow potential from the upper Edwards (Person) to the lower Edwards (Kainer Fm), and there is upward flow potential from the Upper Glen Rose to the lower Edwards (Kainer Fm).
- The overlying geologic units (Georgetown, Del Rio, Buda, Eagle Ford) confine the underlying saline Edwards Aquifer.
- The Person (111 ft thick) and Kainer Formations (292 ft thick) of the Edwards Group appear to be hydrologically isolated from each other due to the regional dense member (22 ft thick), as determined by this study and as noted in other publications. The regional dense member is likely to provide confinement between the Person and Kainer Formations over a large area.
- The upper Edwards (Person Fm) has an average transmissivity of 2,400 ft2/d. The Kainer has an average of 7,100 ft2/d.
- Estimates indicate relatively high-yielding wells are possible in the saline Edwards, with yields greater than 1,000 gpm. This is consistent with other studies.
  Saline waters are sodium-chloride waters with a range in TDS of 9,000 to 17,900 mg/L. The Kainer Formation had the highest TDS, followed by the Upper Glen Rose and then the Person Formation.
- Although the origin of salinity remains unknown, the geochemical data appear to allow for the elimination of at least two potential sources of salinity: seawater (or residual seawater), and halite dissolution. Isotope data suggest a potential source of the saline water is from interaction with

carbonates or silicates in high-temperature environments, such as deeper formations of the Gulf Coast.

- Mixtures of the injectate with receiving groundwaters of the Person formation will be dominated by the sodium-chloride groundwater. There is potential for the release of arsenic within the storage zone. The occurrence of arsenic in samples from zones 13 and 14 indicates that arsenic is available and mobile. It will be advisable to monitor arsenic concentrations in recovery water.
- Results from this hydrogeologic study suggest that the saline Edwards Aquifer can serve as a source of water for a desalination facility and potentially a reservoir for ASR.

Future Studies

A test well for production of the saline Edwards Aquifer that is relatively close to the multiport well is needed for additional evaluations. Data from the production well and observations from the multiport well will help provide storativity and transmissivity values representative of a larger area. In addition, the data would help confirm the confining characteristics of the RDM.

Acknowledgements

There are many that contributed to this project. We would like to thank all the partners that contributed. Specifically we would like to thank and acknowledge the Texas Water Development Board for recognizing value and supporting the project. TWDB staff Janie Hopkins and Chris Muller supported the analytical costs for geochemistry samples. Texas Disposal Systems, Inc. granted access and supported the installation of the multiport well with key monitor well infrastructure. C&C Groundwater drilled and helped with installation of multiport monitor well casing materials. Westbay Instruments (Canada) provided multiport well materials and technicians Tony Kim and Anthony Morgan installed the multiport well. Travis White assisted with drilling collection of cuttings and observing drilling activities. Dillon Johns assisted with purging, slug testing, and sampling of the multiport well. Justin Camp (BSEACD) assisted with installation of the multiport well and data collection throughout the life of the project. Since 2008 Dr. Brann Johnson (retired Texas A&M University) has provided equipment for the installation of the District's multiport wells.

Photograph of the installation of the last Westbay casing piece in the multiport well. Photograph taken on 8/20/2016.

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Photograph of completed Multiport well on 9/13/2016.

Supplemental Information Available Upon Request

Supplement 1. Kyle Transect: Excerpted Figures from Lambert et al., 2010.

Supplement 2. Drilling and well completion reports

- Drilling notes, cuttings, and thin section descriptions;
- Geophysical log
- Westbay completion report
- State of Texas Well Reports

Supplement 3. Water Levels

- Digital spreadsheet of data

Supplement 4. Permeability Testing

- Digital slug data
- Aqtesolve solutions

Supplement 5. Sampling and Chemistry results

- Table 11 in spreadsheet
- PDF files of laboratory results