Brackish Groundwater Resources of the Northern Trinity Aquifer, Texas

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ABSTRACT

The Trinity Aquifer is a Texas Water Development Board (TWDB) designated major aquifer and underlies all or parts of 70 counties in Texas as well as extending into portions of Oklahoma and Arkansas. In Texas, the aquifer extends uninterrupted from the Oklahoma border to south-central Texas. We define the Northern Trinity Aquifer as that portion of the Trinity Group in Texas which lies north of the Colorado River. We utilized the hydrostratigraphic zonation from the groundwater availability model (GAM) developed for the TWDB (Kelly et al., 2014) which subdivided the Trinity Group into five distinct hydrostratigraphic units; Hosston, Pearsall, Hensell, Glen Rose, and Paluxy. These Lower Cretaceous units are predominantly composed of interbedded sands, shales, and carbonates with minor evaporate beds present. The combined saturated thickness of the Northern Trinity Aquifer averages between 600 and 1900 feet.

In 2009, the 81st Texas Legislature provided funding to the TWDB to establish the Brackish Resources Aquifer Characterization System (BRACS). The goal of the program is to map and characterize the brackish portions of the aquifers in Texas in sufficient detail to provide useful information and data to regional water planning groups and other entities interested in using brackish groundwater as a water supply. House Bill 30, passed by the 84th Texas Legislative Session in 2015, requires the TWDB to identify and designate brackish groundwater production zones in the aquifers within the state. The Trinity Aquifer was one of the aquifers selected for study in House Bill 30.

In this study we combined the hydrostratigraphic units of the Northern Trinity Aquifer GAM with groundwater salinity values measured from groundwater samples and calculated from geophysical well logs. The geophysical well log measurements used in calculating groundwater salinity were mainly induction resistivity run primarily in oil and gas wells. Salinity zones were then mapped based upon the combined sampled and calculated total dissolved solids concentrations of the groundwater for each of the five hydrostratigraphic units. The four salinity zones mapped for each hydrostratigraphic unit are based upon total dissolved solids concentrations: these are (1) fresh (0 to 1000 milligrams per liter); (2) slightly saline (1000 to 3000 milligrams per liter); (3) moderately saline (3000 to 10,000 milligrams per liter); and (4) very saline (10,000 to 35,000 milligrams per liter). Groundwater volumes were calculated for each mapped salinity zone for each of the five hydrostratigraphic units. All data and analysis techniques were documented and will be made publicly available.

INTRODUCTION

To better formulate groundwater management strategies, planners and decision makers need reliable estimates of the available fresh, brackish, and saline groundwater in Texas. House Bill 30 passed by the 84th Texas

Legislative Session requires the Texas Water Development Board (TWDB) to identify and designate brackish groundwater production zones in the aquifers of Texas. Specifically, the legislation directed the TWDB to conduct studies on four aquifers and report the results of the studies to the legislature by December 31, 2016. Studies and reports on the remaining aquifers are to be completed by December 31, 2022. To meet this requirement, the TWDB let contracts to conduct studies of brackish groundwater in six Texas aquifers. The Trinity Aquifer was one of the aquifers selected for study as a result of House Bill 30.

This report utilizes the contracted work performed for the Trinity Aquifer and documents the brackish resources of the northern section of the Trinity Aquifer, hereafter referred to as the Northern Trinity Aquifer. The Northern Trinity Aquifer in Texas roughly corresponds to the area of Groundwater Management Area 8. All or portions of 53 Texas counties lie within the study area covering a total area of 30,861 square miles (Fig. 1).

The Northern Trinity Aquifer was extensively studied during the development of the updated groundwater availability model (GAM) developed by Kelley et al., (2014). The hydrostratigraphic framework developed for the GAM provided the geological structure that we used for aquifer determination and for defining salinity zones. The GAM study utilized 1302 geophysical well logs in order to define the vertical and lateral extents of the five hydrostratigraphic units that compose the Northern Trinity Aquifer.

Northern Trinity Aquifer groundwater quality data for this study was sourced in part from water quality data from the TWDB groundwater database. In the deeper downdip portions of the aquifer, it was necessary to augment observed water quality data, so we used petrophysical analysis techniques to analyze geophysical logs for water quality. Calculations of Northern Trinity Aquifer water quality as measured by total dissolved solids were made using geophysical logs to provide the additional data needed to better define the groundwater salinity zones within the Northern Trinity Aquifer.

We defined groundwater quality using the total dissolved solids concentration which has been divided into groundwater salinity zones corresponding to: (1) fresh water with total dissolved solids concentration less than 1000 milligrams per liter; (2) slightly saline groundwater defined as groundwater with total dissolved solids concentration between 1000 to 3000 milligrams per liter; (3) moderately saline groundwater with total dissolved solids concentration between 3000 and 10,000 milligrams per liter; and (4) very saline groundwater with total dissolved solids concentration between 10,000 to 35,000 milligrams per liter (Winslow and Kister, 1956). Based upon the mapping of the salinity zones, we calculated the volume of groundwater in place for the entire Northern Trinity Aquifer represented by the five hydrostratigraphic units defined for the Trinity Group, Figure 2. The results show that the Northern Trinity Aquifer contains approximately 2,068,912,000 acre-feet of groundwater. Of the approximate 2 billion acre-feet of groundwater, 520,080,000 acre-feet is fresh groundwater, 580,677,000 acre-feet is slightly saline groundwater, 498,840,000 acre-feet is moderately saline and 469,315,000 acre-feet is very saline. Due to the geological complexities and relatively low porosity and permeability of large portions of the Trinity Group, the vast majority of the groundwater volume in the Northern Trinity Aquifer would likely be uneconomical to produce.

The TWDB makes all of the digital data and information used in the generation of this study available to the public. The Brackish Resources Aquifer Characterization System (BRACS) includes a Microsoft Access database that contains references to the well and geology information used for this study.

GEOLOGIC SETTING

We utilized six of the correlation surfaces defined by Kelly et al. (2014) to subdivide the Trinity Group within the study area into a consistent and continuous set of hydrostratigraphic units. The six surfaces used are from oldest to youngest shown in Figure 2: (1) Base of Cretaceous sediments; (2) top of the Hosston Formation; (3) top of the Pearsall Formation; (4) top of the Hensell Formation; (5) top of the Glen Rose Formation; and (6) top of the Paluxy Formation. These surfaces were mapped in the subsurface throughout the study area using 1302 geophysical well logs and correlated to known surface outcrops. To some extent these surfaces adhere to the associated named stratigraphic units, but it must be recognized that the predominant use of geophysical well logs for correlation is an allostratigraphic approach (Bhattacharya and Walker, 1991) that tends to better reflect the depositional units rather than the named lithostratigraphic units.

There are significant structural controls on the extents of the various hydrostratigraphic units of the Trinity Aquifer, these are shown in Figure 1. The most significant is the Mexia-Talco Fault Zone, which is a complex set of individual faults that have offsets of up to 700 feet and mark the downdip southeastern extent of the Northern Trinity Aquifer. In the southern portion of the study area, the Balcones Fault Zone extends into the study area; individual faults have offsets generally less than 400 feet. The Balcones Fault Zone has been found to offset Trinity Group strata in such a way as to cause both isolation and communication between different hydrostratigraphic units (Klemt et al., 1975). The Preston anticline extends southeast into northern Grayson County along with the corresponding Sherman syncline (Bullard, 1931). The impact of the various structural features on the
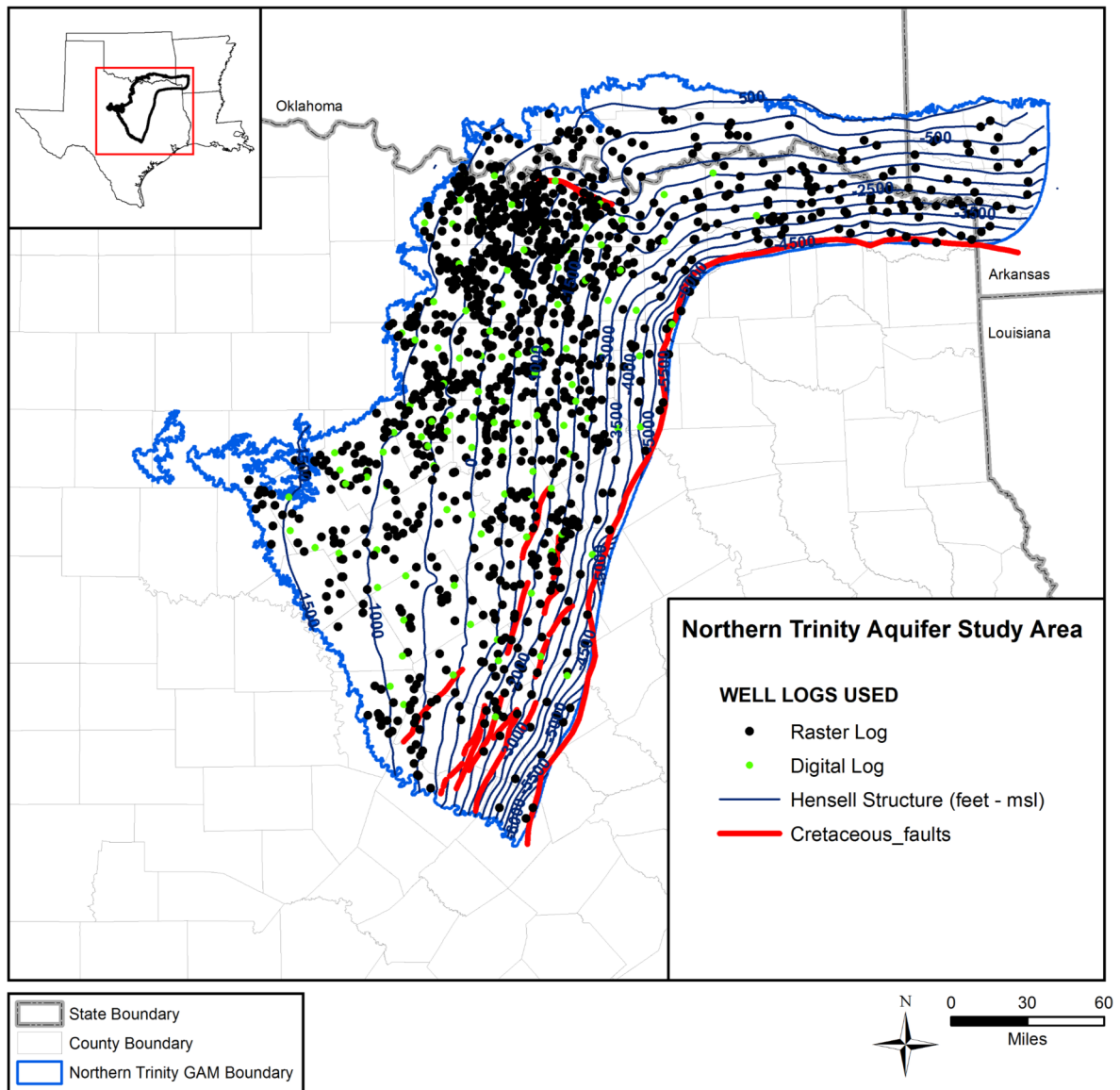
Figure 1. Location of the Northern Trinity Aquifer study area. Also shown are the geophysical well logs used (1193 image logs and 109 digitized logs), structure contours on the top of the Hensell hydrostratigraphic unit, and the major Cretaceous faults.

occurrence and movement of groundwater in the Northern Trinity Aquifer is not considered in any detail by this study.

SALINITY DETERMINATION

There are numerous methods for estimating the salinity of groundwater using geophysical data from well logs and many have been used with success for evaluations of brackish water resources in Texas. Examples of these techniques are included in studies such as Alger (1966), Hamlin (1988), Estepp (1998), and Meyer (2012).

Age m.y.	System	Group	Formations			Hydrostratigraphic Units
			North and West	Central	South	
65	Upper Cretaceous		Eagle Ford			
			not present	undifferentiated	undifferentiated	
			Woodbine			
			not present	undifferentiated	undifferentiated	
		Washita	Grayson	Buda Del Rio Georgetown	Buda Del Rio Georgetown	
			Mainstreet Pawpaw Weno Denton Fort Worth Duck Creek			
100	Lower Cretaceous	Fredericksburg	Kiamichi	Kiamichi Edwards Comanche Peak Walnut	Kiamichi Edwards Comanche Peak Walnut	
			Goodland Walnut			
		Trinity	Antlers	Paluxy Glen Rose	Paluxy Glen Rose	Paluxy
						Glen Rose
				Hensell	Hensell	Hensell
				Pearsall	Pearsall	
					Cow Creek	Pearsall
				Twin Mountains	Travis Peak / Hammett	
					Sligo	
				Hosston	Hosston	Hosston
			Pre-Cretaceous			

Figure 2. Stratigraphic column showing Cretaceous stratigraphy in various portions of the study area with the hydrostratigraphic units used in this study shaded (modified after Fisher and Rodda, 1967; Salvador and Muneton 1989; Walker and Geissman, 2009).

Most of these methods have been developed and evaluated for the unconsolidated sediments of the Gulf of Mexico Basin. Examples of techniques used specifically in the consolidated units of the Trinity Aquifer are rare although Estepp (1998) does have specific examples of calculations performed in the Northern Trinity Aquifer system.

In general, these methods rely on three main assumptions: (1) that the resistivity value of formation water can be determined from resistivity, spontaneous potential, and other parameters recorded by geophysical well logs; (2) that the calculated water resistivity can be corrected for variances in formation temperature and water chemistry; and (3) that an appropriate relationship between corrected water resistivity and the concentration of total dissolved solids can be determined. As such, this evaluation of potential brackish water resources in the Northern Trinity Aquifer requires development of an understanding of the distribution of the salinity in water producing units of the Northern Trinity Aquifer and application of geophysical well log data to estimate total dissolved solids concentrations where direct water quality measurements are not available.

Estimating the total dissolved solids concentration of groundwater in an area where few water quality samples are available requires the use of a proxy measurement for water quality (i.e., the resistivity of water $[R_w]$) within a subsurface formation). As a result, R_w is often calculated using values measured by geophysical well log tools. Under most conditions, R_w is inversely related to the concentration of total dissolved solids.

Geophysical logging tools collect data on a number of physical properties. The types of tools and specific properties being measured by geophysical well logs have varied significantly over time, but a few measurements relevant to calculating R_w are fairly common. These measurements include spontaneous potential, deep and shal-

low resistivity (R_{deep} and $R_{shallow}$, respectively), and porosity (ϕ). Ideally, the measured R_{deep} value is equivalent to the true formation resistivity (R_t) value. R_t represents the resistivity of the formation with no influence from invaded mud or other drilling fluids. Depending on the type of geophysical well log tool used, some corrections to the R_{deep} value may be needed to make it more representative of the formation R_t value (Estepp, 2010). When a formation is fully saturated with water, as is the case for aquifers, the true formation resistivity (R_t) is equal to the water-saturated formation resistivity (R_0).

Archie (1942) developed a relationship between R_w and the R_0 expressed as Equation 1:

$$F = \frac{R_0}{R_w} \tag{1}$$

F is the formation factor, which is related to porosity by Equation 2:

$$F = \frac{a}{\phi^m} \tag{2}$$

In Equation 2, ϕ is the formation porosity, m is the cementation exponent, and a is the tortuosity factor, which is commonly assumed to equal 1 (Archie, 1942). Combining Equation 1 and Equation 2 produces Equation 3:

$$R_w = R_0 \times \phi^m \tag{3}$$

This provides the basis for development of several methods to calculate R_w from the measured geophysical well log values. It is important to note that the relationships developed by Archie (1942) and the measurements of R_{deep} and R_{xo} are based on the presence of saline groundwater composed of sodium chloride, which is common for deep groundwater associated with petroleum deposits. Fresh and brackish groundwater varies widely in chemical compositions that are often very different from sodium chloride solutions. As a result, the calculated R_w in Equation 3 is more correctly called the resistivity of the water equivalent (R_{we}) because it represents an assumption of sodium chloride groundwater composition. Values of R_{we} must be corrected to account for the differences in chemical composition before a valid R_w can be determined.

Because of the variability of the formation factor and the inability to identify and subsequently predict its variability it is difficult to predict the formation factor in Archie's (1942) resistivity relationships (Equations 1–3). An alternative method for calculating total dissolved solids of groundwater using geophysical well logs is the resistivity ratio or modified Alger-Harrison technique (Estepp, 2010; Alger and Harrison, 1989). Application of this technique only requires values from well logs for deep resistivity and shallow resistivity, resistivity of the mud filtrate, and the temperatures of the mud filtrate and the formation water.

For the flushed zone immediately adjacent to the wellbore, the resistivity of the mud filtrate, R_{mf}, is defined as follows in Equation 4:

$$R_{mf} = \phi^m \times R_{xo} \tag{4}$$

where R_{xo} = the resistivity of a 100 percent mud filtrate-saturated formation.

The resistivity ratio method allows calculation of R_{we} by substituting Equation 3 into Equation 4 to produce Equation 5.

$$R_{we} = R_{mf} \times \frac{R_0}{R_{xo}} \tag{5}$$

Advantages of the resistivity ratio method are that specific formation factor parameters do not need to be measured or estimated and that once R_{mf} is corrected for temperature to 25°C, formation temperatures are not needed. R_{mf} temperature corrections were conducted using the Arps (1953) equations. Thus, after temperature correction the final R_{we} calculation becomes Equation 6.

$$R_{we25} = R_{mf25} \times \frac{R_0}{R_{xo}} \tag{6}$$

where R_{we25} is the equivalent formation water resistivity at 25°C and R_{mf25} is the mud-filtrate resistivity at 25°C.

We are therefore able to correct the measured resistivity values to formation temperature using Equation 5. It is also necessary to convert the resistivity of the mud filtrate at surface temperature to the resistivity of mud filtrate at the formation depth temperature using Equation 7. It was determined that the most representative dataset would be the surface temperature and bottom hole temperature recorded on the log header.

There are issues with this dataset that should be considered when it is used for calculating the mud-temperature gradient. The return of the borehole temperature to ambient conditions is sensitive to the contrast between the thermal properties of the drilling fluid and of the surrounding rock and the duration of the borehole drilling disturbance (Luheshi, 1982). Equilibrating the temperature in the borehole to the natural geothermal gradient can take up to a few months in some cases (Luheshi, 1982) and standard practices in the oil and gas industry negate waiting until the temperature returns to ambient conditions before measuring the mud temperature. Therefore, in calculating the mud-temperature gradient, it is assumed that the borehole was continually circulated up to the point that the mud-temperature/resistivity measurement was made and the geophysical well logging was performed. We further decided to use the surface temperature determined with the PRISM Climate Group (2016) average annual surface-temperature dataset and bottom-hole temperature determined from the geophysical log header (Equation 7):

$$T_m(z) = T(z_1) + \frac{T(z_2) - T(z_1)}{z_n - z_1}(z - z_1) \tag{7}$$

where $T_m(z)$ is the temperature (degrees Fahrenheit) of mud at depth of interest, $T(z_1)$ is the temperature (degrees Fahrenheit) at depth one, which corresponds to the temperature of the mud filtrate recorded by the logging engineer on the log header, $T(z_2)$ is the temperature (degrees Fahrenheit) at depth two, which corresponds to the bottom hole temperature recorded on the log header, z is the depth at which $T_m(z)$ is being calculated, z_1 is the depth at which $T(z_1)$ was taken, which usually corresponds to ground surface, and z_2 is the depth at which $T(z_s)$ was taken, which usually corresponds to the total depth of the log run.

As discussed previously, the calculated R_{we25} value is also impacted by variations in chemistry within the brackish- and fresh-water zones. Techniques for correcting R_{we25} (and R_{mf25}) for the effects of chemistry are found in Estepp (2010) and Collier (1993a, 1993b). In general, the presence of ions such as calcium, magnesium, bicarbonate, and sulfate can have a significant impact on measured resistance values. The variations in the groundwater chemical composition of the Northern Trinity Aquifer require the use of non-constant correction factors to convert R_{we25} to R_{w25}.

Our approach to correcting for chemistry was to calculate the sodium chloride (NaCl)-equivalent total dissolved solids (TDS_{NaCl}) (estimated total dissolved solids value if the groundwater was a simple sodium chloride solution) for known water wells using measured water-quality data. Water-quality data from the Northern Trinity Aquifer region was used to calculate TDS_{NaCl} values using the ionic concentration of the groundwater and the conversion scheme provided in Schlumberger's GEN–4 Chart (Fig. 3) (Desai and Moore, 1969; Collier, 1993a, 1993b; Schlumberger, 2013). The curves for each ion constituent in the GEN-4 chart are used with the calculated total dissolved solids for the water sample to produce a multiplier for each ion. This multiplier is then applied to the measured concentrations of each ion to give, when summed, an equivalent TDS_{NaCl}. To apply the GEN–4 Chart corrections, the correction curves for each ion were digitized and fit using various polynomial-rational equations. The parameters for the curve fits were then integrated into the water-quality data sheets to calculate the appropriate multipliers.

The correlation between total dissolved solids and TDS_{NaCl} for each hydrostratigraphic horizon was determined by fitting the data using a linear regression approach. The resulting equations were used as a chemistry correction factor to convert the total dissolved solids values determined from borehole geophysics data to an estimate of total dissolved solids for the groundwater.

The R_{we25} calculated from the resistivity ratio method (Equation 6) is converted into a TDS_{NaCl} value using the equation of Bateman and Konen (1977) (Equation 8):

$$TDS_{NaCl} = 10^{\left(\frac{3.562 - \log_{10}[R_{we25} - 0.0123]}{0.955}\right)} \tag{8}$$

where TDS_{NaCl} is the equivalent sodium chloride total dissolved solids in mg/L and R_{we25} is the equivalent formation water resistivity in ohm-m.

This calculated TDS_{NaCl} value is then converted into an appropriate $TDS_{AquiferUnit}$ (estimated total dissolved solids of the hydrostratigraphic unit groundwater) value using the TDS_{NaCl} correlation equation for that particular hydrostratigraphic unit.
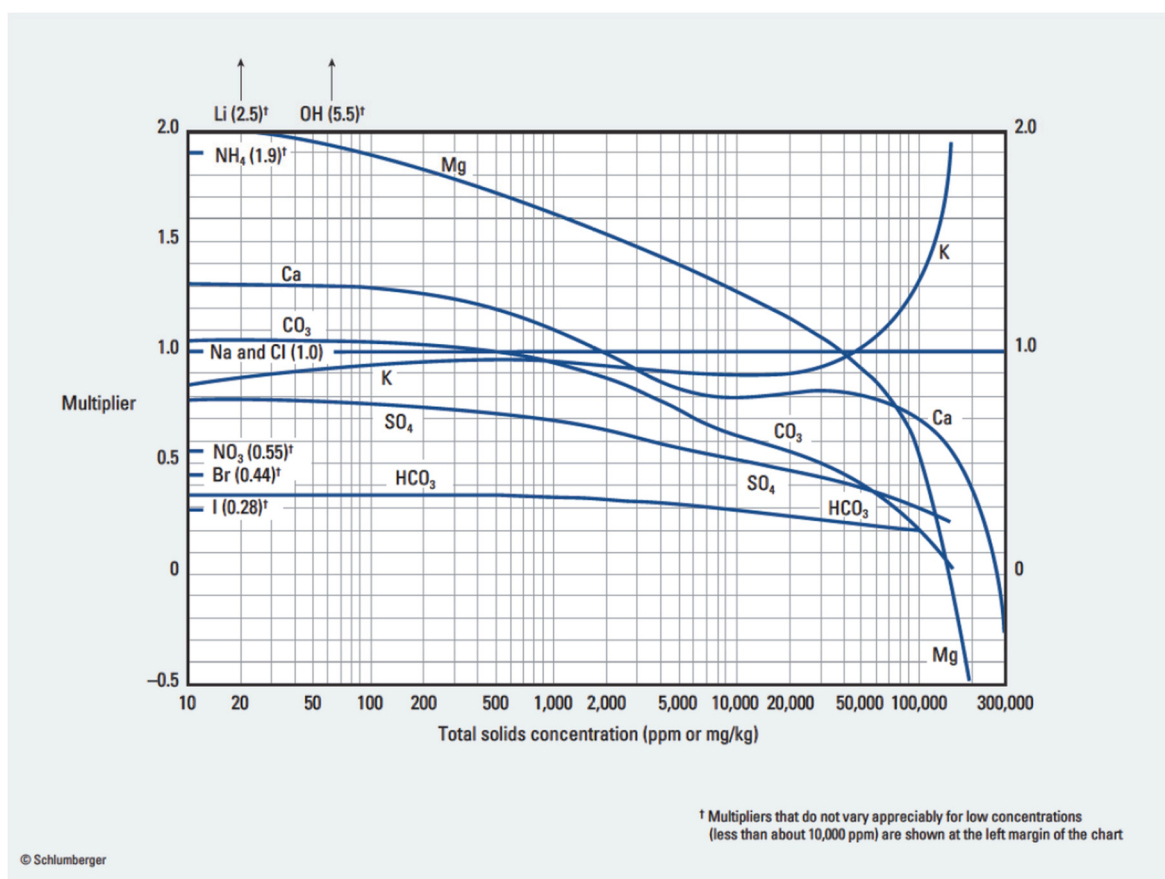
Figure 3. Schlumberger chart GEN–4 (Schlumberger, 2009) used to calculate equivalent sodium chloride total dissolved solids from a known water chemistry sample. ppm = parts per million; mg/kg = milligrams per kilogram.

To evaluate this approach, Northern Trinity Aquifer water wells screened exclusively in the Hosston hydrostratigraphic unit, which also have a geophysical log with relevant header parameters, screen information, and water-quality samples were examined. In total, there were 32 wells that fit the criteria. For the 32 wells, there were a total of 113 screened sand intervals. Average calculated total dissolved solids values from the resistivity ratio technique were plotted against sampled total dissolved solids values for all the wells (Fig. 4). As can be seen from the plot, the measured and estimated total dissolved solids values are somewhat poorly correlated. The poor correlation observed for the test calculations may be due to the relatively small range over which the measured data is available. That is, there are only four sample measurements that exceed 2000 mg/L, and most of the measurements cluster between 500 and 1500 mg/L total dissolved solids. Because this technique has a sound theoretical basis, we would expect it to be broadly applicable over a wide water-quality range.

To assess the performance of the technique over wider total dissolved solids ranges, additional water-quality samples from other hydrostratigraphic units that exceed 3000 mg/L total dissolved solids were plotted versus the calculated value from the nearest resistivity log along strike. There were only 10 pairs of data that met this criterion. The results are shown on Figure 4, having been added to the existing Hosston dataset. Figure 4 indicates that the approach shows scatter around the 1:1 line but that the expanded total dissolved solids range improves significantly at 3000 to 10,000 mg/L total dissolved solids. Because the 1000 mg/L total dissolved solids line can largely be determined based on sampled water quality, the improvement in the resistivity ratio approach at higher total dissolved solids ranges allows for a complementary approach; i.e., the resistivity ratio method allows estimates of the location of the 3000 mg/L total dissolved solids and 10,000 mg/L total dissolved solids transition lines, while sampled water quality is considered to be the best data source for estimating the location of the 1000

mg/L total dissolved solids transition line. When the approach was applied more broadly to other formations in the Northern Trinity Aquifer, a discernable trend of increasing calculated total dissolved solids with depth along dip was observed. This trend generally matched the conceptual model of the extent of fresh water delineated by Kelley et al. (2014).

The TDS–TDS$_{NaCl}$ equations for the five hydrostratigraphic units modeled for the Northern Trinity Aquifer are listed in Equation 9 through Equation 13 below. The data and regression lines are shown in Figure 5A through Figure 5E.

$$TDS_{Paluxy} = 1.0559(TDS_{NaCl\ Paluxy}) + 67.946 \tag{9}$$

$$TDS_{Glen\ Rose} = 1.2238(TDS_{NaCl\ Glen\ Rose}) - 21.92 \tag{10}$$

$$TDS_{Hensell} = 1.0272(TDS_{NaCl\ Hensell}) + 67.404 \tag{11}$$

$$TDS_{Pearsall} = 1.0879(TDS_{NaCl\ Pearsall}) + 36.409 \tag{12}$$

$$TDS_{Hosston} = 1.1597(TDS_{NaCl\ Hosston}) - 3.5185 \tag{13}$$

The water quality (TDS) for every sand and limestone unit for the Paluxy, Glen Rose, Hensell, Pearsall, and Hosston hydrostratigraphic units in the Northern Trinity Aquifer were calculated using this methodology. These calculated water-quality values were averaged by formation and subsequently plotted on maps of the study area along with sampled water quality and used to divide each hydrostratigraphic unit into salinity zones

GROUNDWATER SALINITY ZONES

The salinity zones for the hydrostratigraphic units were developed from the sampled water quality data and geophysical log interpretations of water quality. The sampled water quality dataset from Kelley et al. (2014), including formation designations, was used without modification. These data were plotted on a series of maps along with the average calculated water quality values derived from the geophysical log analyses. These posted values were contoured by hand to produce 1000, 3000, and 10,000 mg/L TDS contour lines. The 1000 mg/L TDS lines were generally similar to those from Kelley et al. (2014), and were modified where additional estimates from geophysical logs were available.

The poorest agreement between the sampled and calculated values in the fresh water area occurred in the Hosston hydrostratigraphic unit. This poor agreement may be because the majority of these wells are water wells and were likely not circulated as long as deeper oil and gas wells; the longer a well is circulated, the more opportunity there exists for the mud filtrate to replace the formation water in the near wellbore zone. Additionally, higher density muds are used when drilling the deeper oil and gas wells, which would increase the pressure on the wellbore wall. This increased pressure could be responsible for a more complete replacement of the formation fluid with the mud filtrate. If the mud filtrate replacement is incomplete but the equation used assumes that there is complete mud filtrate replacement, then the resulting calculated water quality will be different from the sampled water quality.

In areas where both sampled and calculated (resistivity-derived) estimates of water quality were available, the sampled water quality estimates were considered to have the higher confidence than the calculated estimates. In some areas, local variability in the calculated water quality data required expert judgement to determine which values to use when determining the contours. On Figures 6A through 6E, calculated estimates of water quality that were generally not considered when contouring are marked with an "X" through the posted location of the well. On the whole, this approach produces moderate agreement with the sampled water quality data and good agreement with the assumed trend of increasing TDS with depth and the degradation of water quality near the Mexia-Talco Fault Zone.
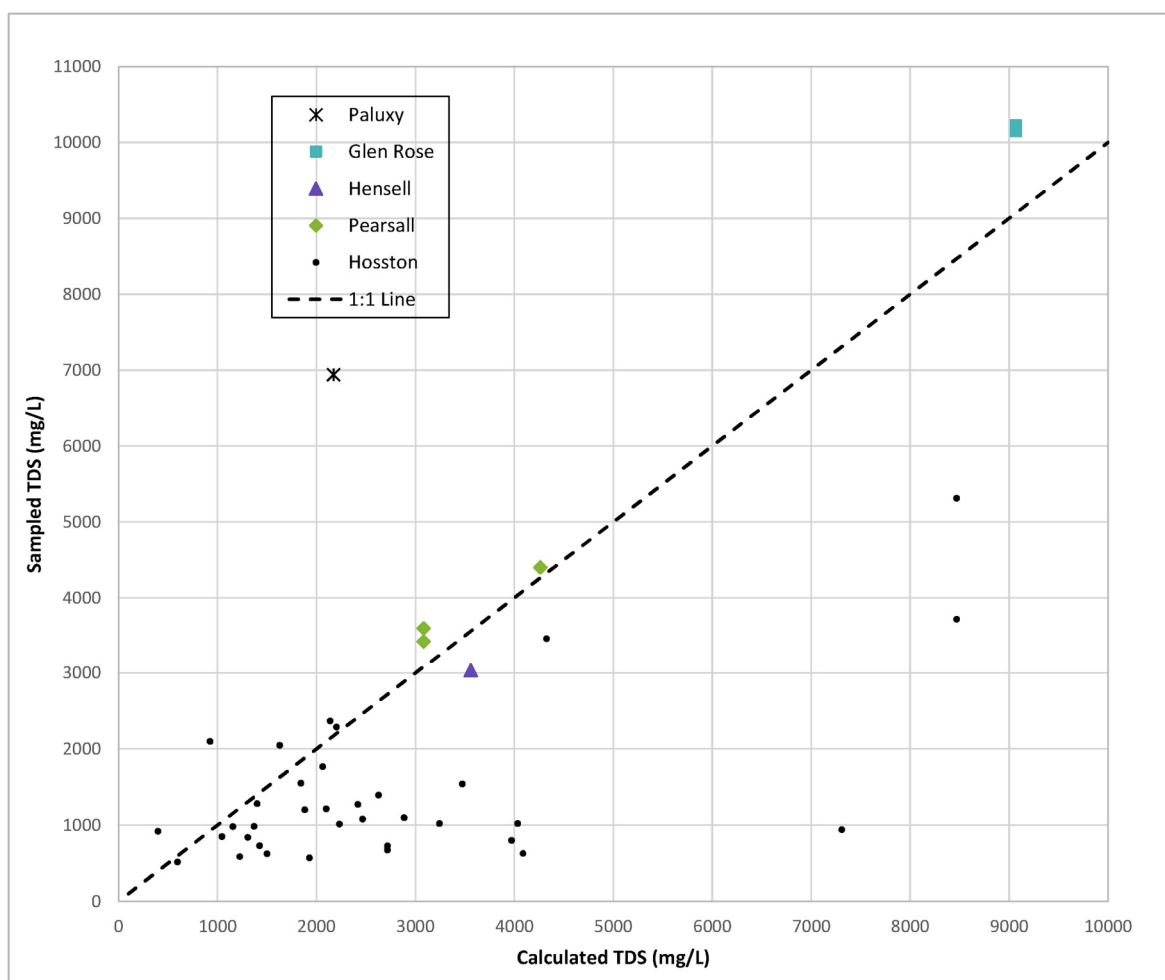
Figure 4. Sampled total dissolved solids (TDS) plotted against calculated total dissolved solids using the resistivity ratio method.

AQUIFER HYDRAULIC PROPERTIES

Aquifer hydraulic properties refer to the physical characteristics that govern flow of groundwater through an aquifer. This section introduces several important terms and concepts associated with characterization of aquifer hydraulic properties, such as horizontal and vertical hydraulic conductivity, transmissivity, and specific storage, as well as aquifer structure, aquifer lithology, depositional environment, and the presence of fractures and faults.

Groundwater volume calculations described below require input values for aquifer properties such as aquifer thickness, static water level, and specific yield. These values for the Northern Trinity Aquifer are described below. For volume calculations in the five hydrostratigraphic units of the Trinity Aquifer, the member unit thickness and the elevations of unit tops and bottoms are based upon the structure in the updated Northern Trinity and Woodbine Aquifer GAM (Kelley et al., 2014). Water levels used to calculate aquifer volumes are based upon the last year of calibration (beginning of 2010) from the updated Northern Trinity and Woodbine Aquifer GAM (Kelley et al., 2014). Specific yield values were assigned based on the Northern Trinity and Woodbine Aquifer GAM (Bené et al., 2004), where:

Paluxy specific yield = 0.15,
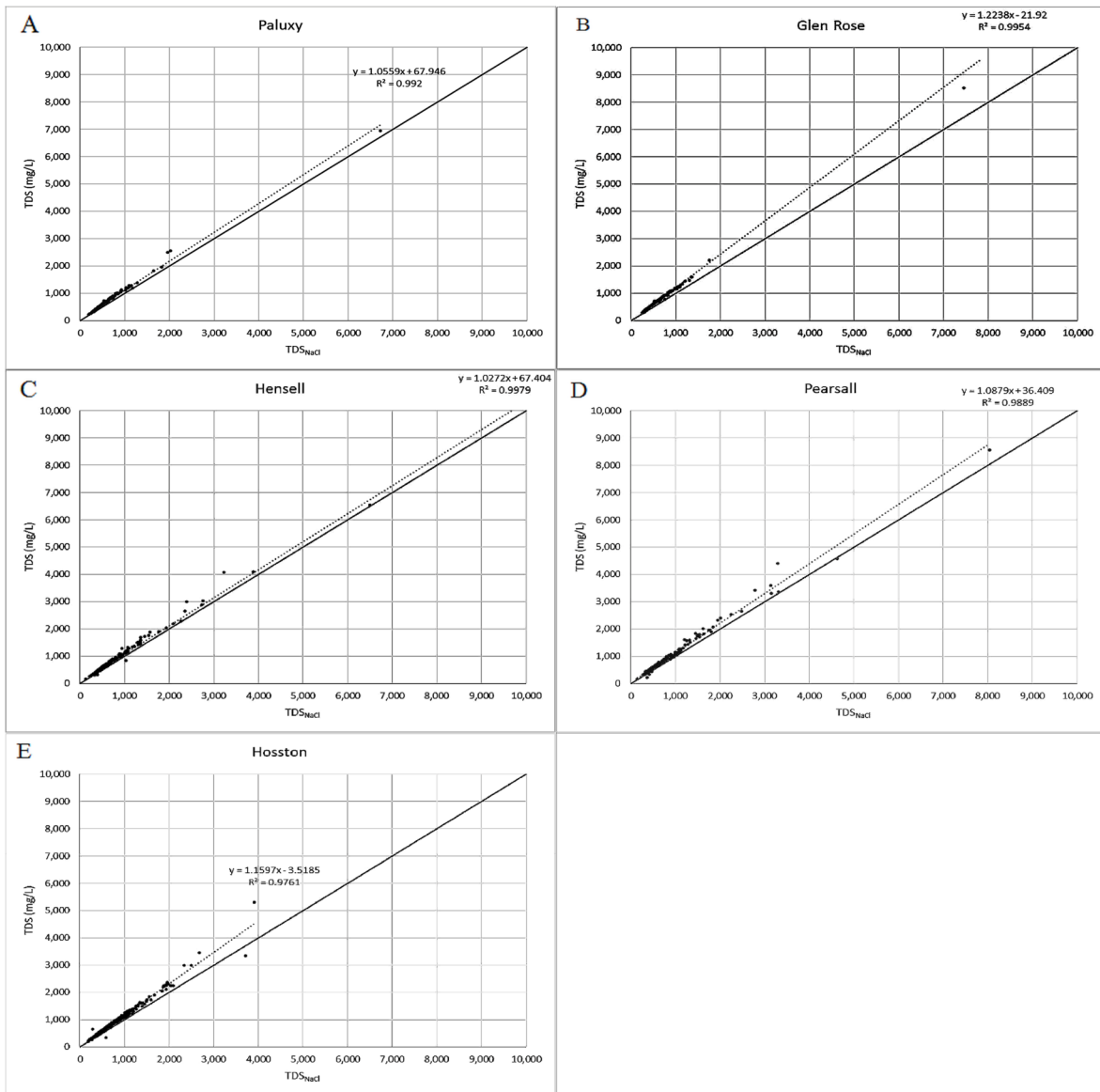Glen Rose specific yield = 0.05,

Figure 5. Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the studied hydrostratigraphic units: (A) Paluxy, (B) Glen Rose, (C) Hensell, (D) Pearsall, and (E) Hosston. Solid line indicating 1:1 relationship is shown for comparison.

Hensell specific yield = 0.15,
Pearsall specific yield = 0.05, and
Hosston specific yield = 0.15.

GROUNDWATER VOLUME CALCULATION

Estimates of groundwater volumes were generated for each hydrostratigraphic unit based on the defined groundwater salinity zones. Shi et al. (2014) provided a good overview of the calculation of the volume of
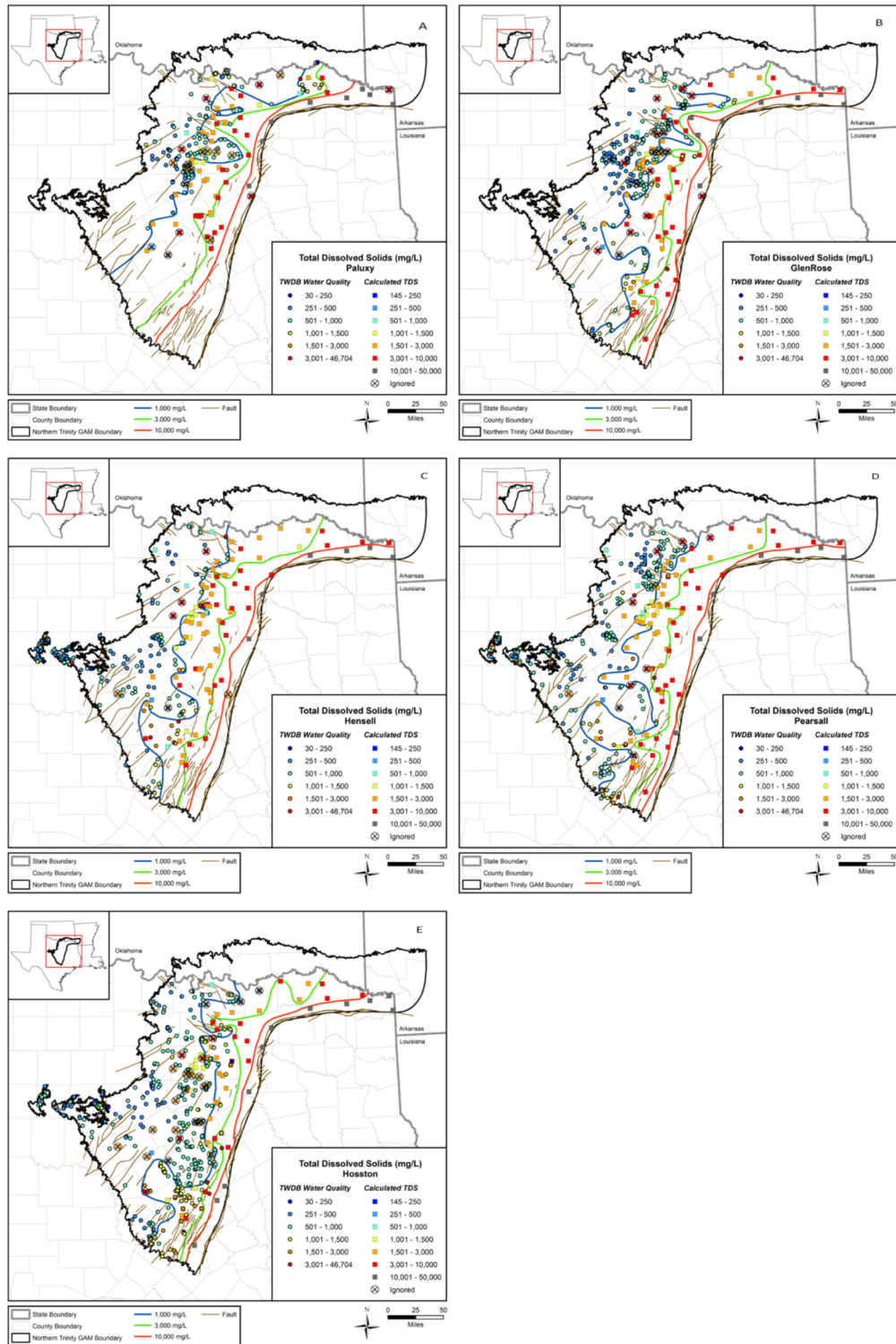
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Figure 6. Maps of salinity zones derived from sampled and calculated water salinity values for the studied hydrostratigraphic units: (A) Paluxy, (B) Glen Rose, (C) Hensell, (D) Pearsall, and (E) Hosston.

groundwater stored in an aquifer. The approach we used to calculate aquifer groundwater volumes is essentially the same as the process used by the TWDB to estimate "total estimated recoverable storage." The method used to calculate groundwater volume in both Shi et al. (2014) and in this report is dependent on whether or not the aquifer is confined or unconfined.

In general, the Northern Trinity Aquifer is a dipping aquifer that is unconfined updip and confined downdip. The term "unconfined" refers to the portion of the aquifer where the water level occurs below the top of the aquifer. This generally coincides with the outcrop area and area immediately downdip of the outcrop. In the Northern Trinity Aquifer, the formations generally dip south-southeast. Therefore, the unconfined portions of the Northern Trinity Aquifer hydrostratigraphic units fall along the northern and western edge of the outcrop area. The term "confined" refers to the portion of the aquifer where the static water level occurs above the top of the aquifer. The Northern Trinity Aquifer hydrostratigraphic units become confined south and east of their outcrops, as the units dip deeper and are overlain by younger units.

The major part of groundwater storage is sourced from actual dewatering of the aquifer as the water level in the aquifer falls below the top of the aquifer and ultimately to the bottom of the aquifer. This portion of aquifer storage is referred to as the unconfined aquifer storage. Given the same aquifer area and water level decline, the amount of water released from unconfined storage is much greater (orders of magnitude) than that released from confined storage. The parameters that quantify these physical differences are storativity of a confined aquifer and specific yield of an unconfined aquifer. Aquifer storativity typically ranges from 0.00001 to 0.001 for most confined aquifers, while specific yield values typically range from 0.01 to 0.3 for most unconfined aquifers. The TWDB makes a distinction between the total volume of groundwater in unconfined aquifer storage versus that portion that is considered drainable. The equations for calculating the total groundwater volume are presented below.

For unconfined aquifers (Equation 14):

$$\text{Total Volume} = \text{Vdrained} = \text{Area} * \text{Sy} * (\text{Water Level} - \text{Bottom}) \tag{14}$$

For confined aquifers (Equation 15):

$$\text{Total Volume} = \text{Vconfined} + \text{Vdrained} \tag{15}$$

Volume for confined part (Equation 16):

$$\text{Vconfined} = \text{Area} * [\text{S} * (\text{Water Level} - \text{Top})] \tag{16}$$

Or:

$$\text{Vconfined} = \text{Area} * [\text{Ss} * (\text{Thickness}) * (\text{Water Level} - \text{Top})] \tag{17}$$

Volume for unconfined part (Equation 18):

$$\text{Vdrained} = \text{Area} * [\text{Sy} * (\text{Thickness})] \tag{18}$$

where,
     Vdrained = storage volume due to water draining from the formation (acre-feet),
     Vconfined = storage volume due to elastic properties of the aquifer and water (acre-feet),
     Area = area of aquifer (acre),
     Water Level = static groundwater elevation (feet above mean sea level),
     Top = elevation of aquifer top (feet above mean sea level),
     Bottom = elevation of aquifer bottom (feet above mean sea level),
     Thickness = thickness of aquifer (feet),
     Sy = specific yield (no units),
     Ss = specific storage (per foot), and
     S = storativity or storage coefficient (no units).

The groundwater volume calculations for groundwater storage are implemented on a quarter-mile grid scale coincident with the Groundwater Availability Model Grid (Kelley et al., 2014). Where present, both confined storage and unconfined drained storage have been calculated for each of the five hydrostratigraphic units. We have calculated the unconfined drained groundwater storage for each unit using Equation 14 and the confined groundwater storage for each unit using Equation 17. The variable "Top" is the top elevation of the hydrostratigraphic unit in question while the variable "Bottom" is the bottom elevation of that unit. The variable

"Thickness" is calculated specifically for each hydrostratigraphic unit based on the difference between the variable "Top" and "Bottom." The calculations were developed using a Python code.

The calculations are rounded to the nearest 1000-acre foot per year. Table 1 summarizes the volumes of groundwater, by salinity classification, in the five hydrostratigraphic units of the Trinity Aquifer: the Paluxy, the Glen Rose, the Hensell, the Pearsall, and the Hosston. The total volume of groundwater calculated is 2,068,912,000 acre-feet of groundwater. The Pearsall has the smallest volume of the units. The groundwater in the Northern Trinity Aquifer is split nearly evenly between the water quality classifications with approximately 25% of the groundwater classified as fresh, approximately 28% as slightly saline, approximately 24% as moderately saline, and approximately 23% as very saline.

CONCLUSIONS

In order to estimate water quality from geophysical logs in this study, the modified Alger-Harrison (1989) resistivity ratio method has been used. This method requires resistivity values of mud filtrate (R_{mf}) from the log header and deep (R_t) and shallow resistivities (R_{xo}) from the borehole data. The method generally requires adjustments of resistivity values due to tool differences and calculated resistivities must be adjusted for the influence of variable chemistry. This study has documented that the calculation and analysis of water quality from geophysical logs in the Trinity Aquifer is very complex and requires advanced petrophysical techniques to accurately derive water quality (total dissolved solids) estimates. This study provides a foundation for these techniques.

Total dissolved solids concentrations estimated from 123 geophysical well logs along with measured TDS concentrations from 2519 water wells were used to define the TDS boundaries across the study area. These boundaries allowed us to delineate the geometry of five salinity classes in each hydrogeologic formation: freshwater, slightly saline, moderately saline, very saline, and brine waters.

One of the challenges is the general lack of hydrogeologic data in the brackish portions of the Northern Trinity Aquifer. The absence of data is significant and especially limiting in the downdip area of the Northern Trinity Aquifer.

The volume of the Northern Trinity Aquifer defined for this study contains approximately 2 billion acre feet of groundwater. Out of the 2 billion acre feet of groundwater, 520 million acre feet is freshwater, 581 million acre feet is slightly saline groundwater, 499 million acre feet is moderately saline groundwater, and 469 million acre feet is very saline groundwater.

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REFERENCES CITED

Alger, R. P., 1966, Interpretation of electric logs in fresh water wells in unconsolidated sediments: Society of Professional Well Log Analysts 7th Annual Logging Symposium Transactions, Tulsa, Oklahoma, 25 p.

Alger, R. P., and C. W. Harrison, 1989, Improved fresh water assessment in sand aquifers utilizing geophysical well logs: The Log Analyst, January-February issue, p. 31–44.

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 146, p. 54–62.

Arps, J. J., 1953, The effect of temperature on the density and electrical resistivity of sodium chloride solutions: Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 198, p. 327–330.

Bateman, R. M., and C. E. Konen, 1977, Wellsite log analysis and the programmable pocket calculator: Society of Professional Well Log Analysts 7th Annual Logging Symposium, Houston, Texas, p. B1–B35.

Table 1. The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Northern Trinity Aquifer in acre-feet.

Aquifer Unit	Total Volume (acre-feet)				
	Fresh	Slightly saline	Moderately	Very saline	Total
Paluxy	114,748,000	80,676,000	64,503,000	81,312,000	341,239,000
Glen Rose	107,622,000	137,657,000	114,292,000	79,875,000	439,446,000
Hensell	94,766,000	63,080,000	34,648,000	20,647,000	213,141,000
Pearsall	31,834,000	52,494,000	52,433,000	31,124,000	167,885,000
Hosston	171,110,000	246,770,000	232,964,000	256,357,000	907,201,000
Total	520,080,000	580,677,000	498,840,000	469,315,000	2,068,912,000

Bené, J., B. Harden, D. O'Rourke, A. Donnelly, and J. Yelderman, 2004, Northern Trinity/Woodbine groundwater availability model: Prepared for the Texas Water Development Board, Austin, by R.W. Harden & Associates, Inc., with Freese and Nichols, Inc., HDR Engineering, Inc., LBG Guyton Associates, USGS, and Dr. Joe Yelderman, Jr., <http://www.twdb.state.tx.us/groundwater/models/gam/trnt_n/TRNT_N_Model_Report.pdf> Accessed April 30, 2018.

Bhattacharya, J., and R. G. Walker, 1991, Allostratigraphic subdivision of the Upper Cretaceous Dunvegan, Shaftesbury, and Kaskapau formations in the subsurface of northwestern Alberta: Bulletin of Canadian Petroleum Geology, v. 39, p. 145–164.

Bullard, F. M., 1931, The geology of Grayson County, Texas: University of Texas at Austin Bulletin 3125, 72 p., 1 plate.

Collier, H. A., 1993a, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas, volume I: Texas Water Development Board Report 343, Austin, 414 p., 1 Appendix, 5 plates.

Collier, H. A., 1993b, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas, volume II: Texas Water Development Board Report 343, Austin, 216 p.

Desai, K. P. and E.J. Moore, 1969, Equivalent NaCl determination from ionic concentrations: The Log Analyst, May-June issue, p. 12–21.

Estepp, J. D., 1998, Evaluation of ground-water quality using geophysical logs: Texas Natural Resource Conservation Commission unpublished report, Austin, 516 p.

Estepp, J. D., 2010, Determining groundwater quality using geophysical logs: Texas Commission on Environmental Quality unpublished report, Austin, 85 p.

Fisher, W. L., and P. U. Rodda, 1967, Lower Cretaceous sands of Texas; stratigraphy and resources: Bureau of Economic Geology Report of Investigations 59, Austin, Texas, 116 p.

Hamlin, H. S., 1988, Depositional and ground-water flow systems of the Carrizo–Upper Wilcox, South Texas: Bureau of Economic Geology Report of Investigations 175, Austin, Texas, 61 p.

Kelley, V. A., J. Ewing, T. L. Jones, S. C. Young, N. Deeds, and H. S. Hamlin, 2014, Updated Groundwater Availability Model of the Northern Trinity and Woodbine aquifers: Prepared for the Texas Water Development Board, Austin, 942 p.

Klemt, W. B., R. D. Perkins, and H. J. Alvarez, 1975, Ground-water resources of part of Central Texas with emphasis on the Antlers and Travis Peak formations: Texas Water Development Board Report 195, Austin, v. 1, 63 p.

Luheshi, M. N., 1982, Estimation of formation temperature from borehole measurements: Journal of Geophysical Research, v. 74, p. 747–776.

Meyer, J. E., 2012, Geologic characterization of and data collection in the Corpus Christi Aquifer Storage and Recovery Conservation District and surrounding counties: Texas Water Development Board Open File Report 12–01, Austin.

PRISM Climate Group, 2016, Prism temperature data raster map: Oregon State University, Corvallis, <http://prism.oregonstate.edu> Accessed April 30, 2018.

Salvador, A., and J. M. Q. Muneton, 1989, Stratigraphic correlation chart the Gulf of Mexico Basin, *in* A. Salvador, ed., The geology of North America, v. J: The Gulf of Mexico Basin: Geological Society of America, Boulder, Colorado.

Schlumberger, 2009, Log interpretation charts: Houston, Texas.

Schlumberger, 2013, Log interpretation charts: Houston, Texas.

Shi, J., R. G. Bradley, S. Wade, I. Jones, R. Anaya, and C. Seiter-Weatherford, 2014, GAM TASK 13–031: Total estimated recoverable storage for aquifers in Groundwater Management Area 8: Texas Water Development Board report, Austin, 41 p.

Walker, J. D., and J. W. Geissman, 2009, Geologic time scale: Geological Society of America, Boulder, Colorado.

Winslow, A. G., and L. R. Kister, 1956, Saline-water resources of Texas: U.S. Geological Survey Water Supply Paper 1363, 105 p.

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