Utilizing resistivity logs and the R_{wa} Method to map salinity zones in the Eocene Queen City Aquifer, central Texas

Presentation 4-1
T18. Unconventional Aquifers and Aquifer Management
Monday March 25, 2019
2019 GSA South-Central/North-Central/Rocky Mountain Section Meeting

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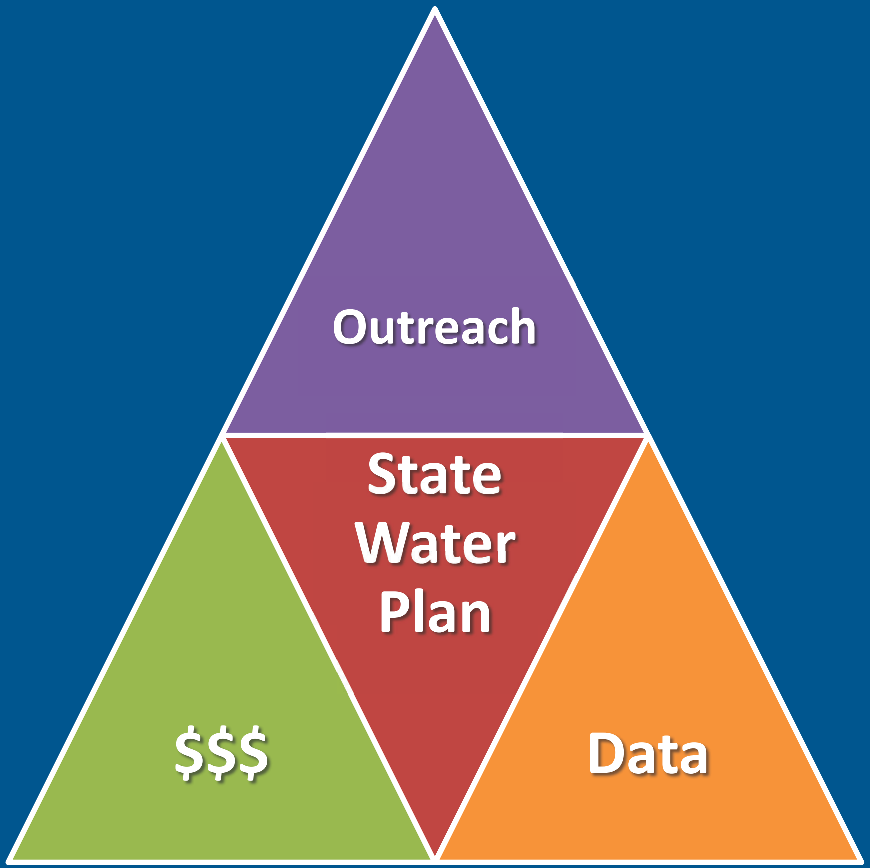
Texas Water Development Board (TWDB)



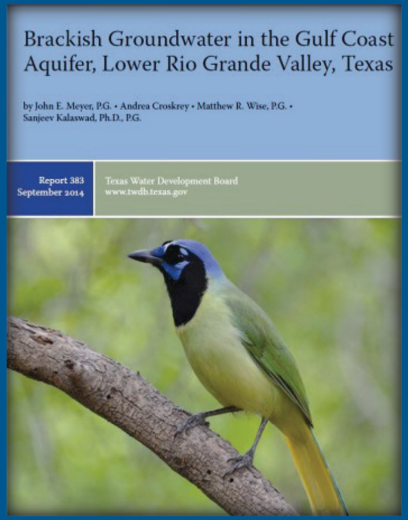
Create a 50-year State Water Plan every 5 years!

Brackish Resource Aquifer Characterization System (BRACS)

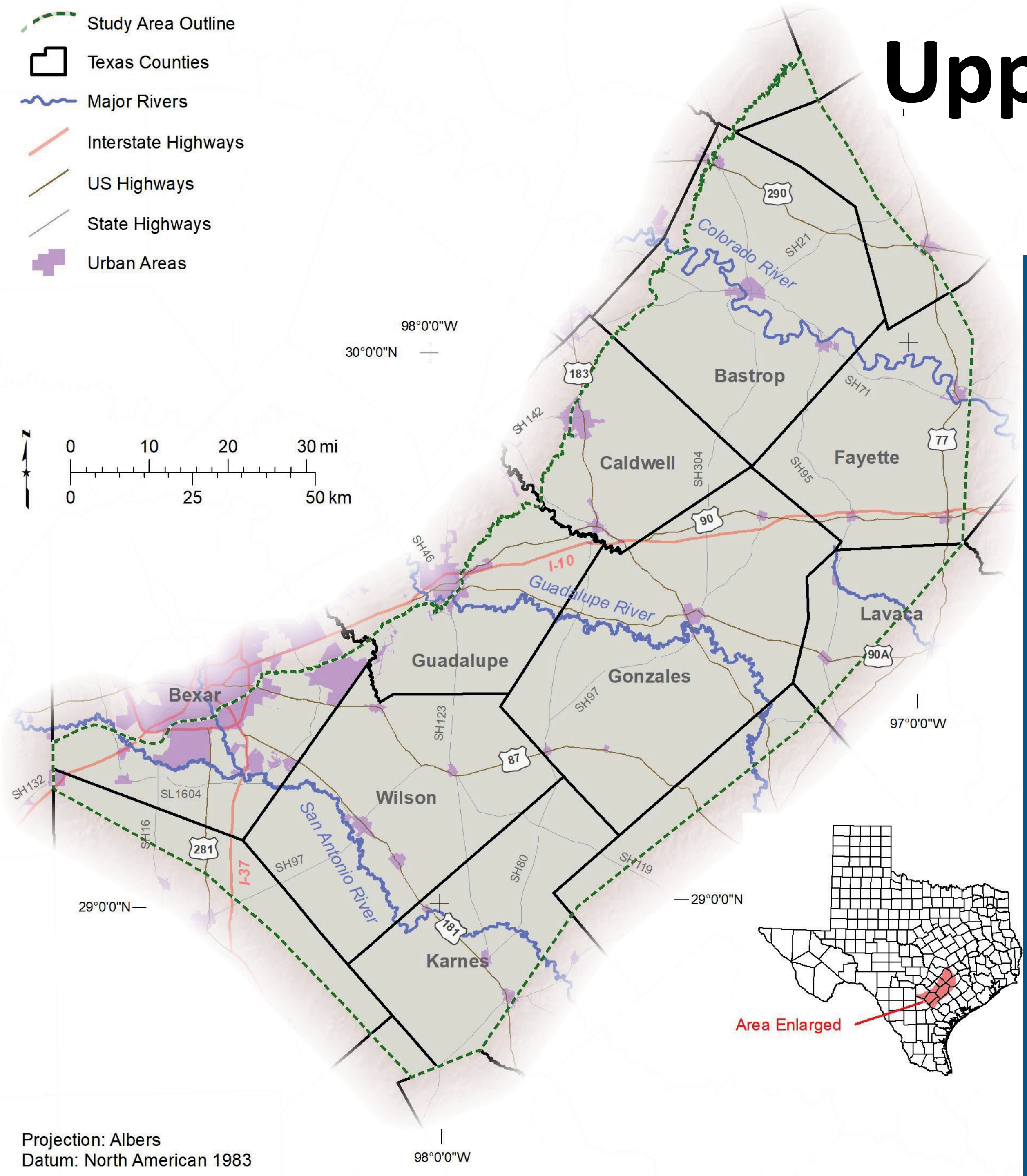
http://www.twdb.texas.gov/innovativewater/bracs/studies.asp

Map brackish groundwater!

1. Stratigraphy
2. Lithology
3. Water Quality



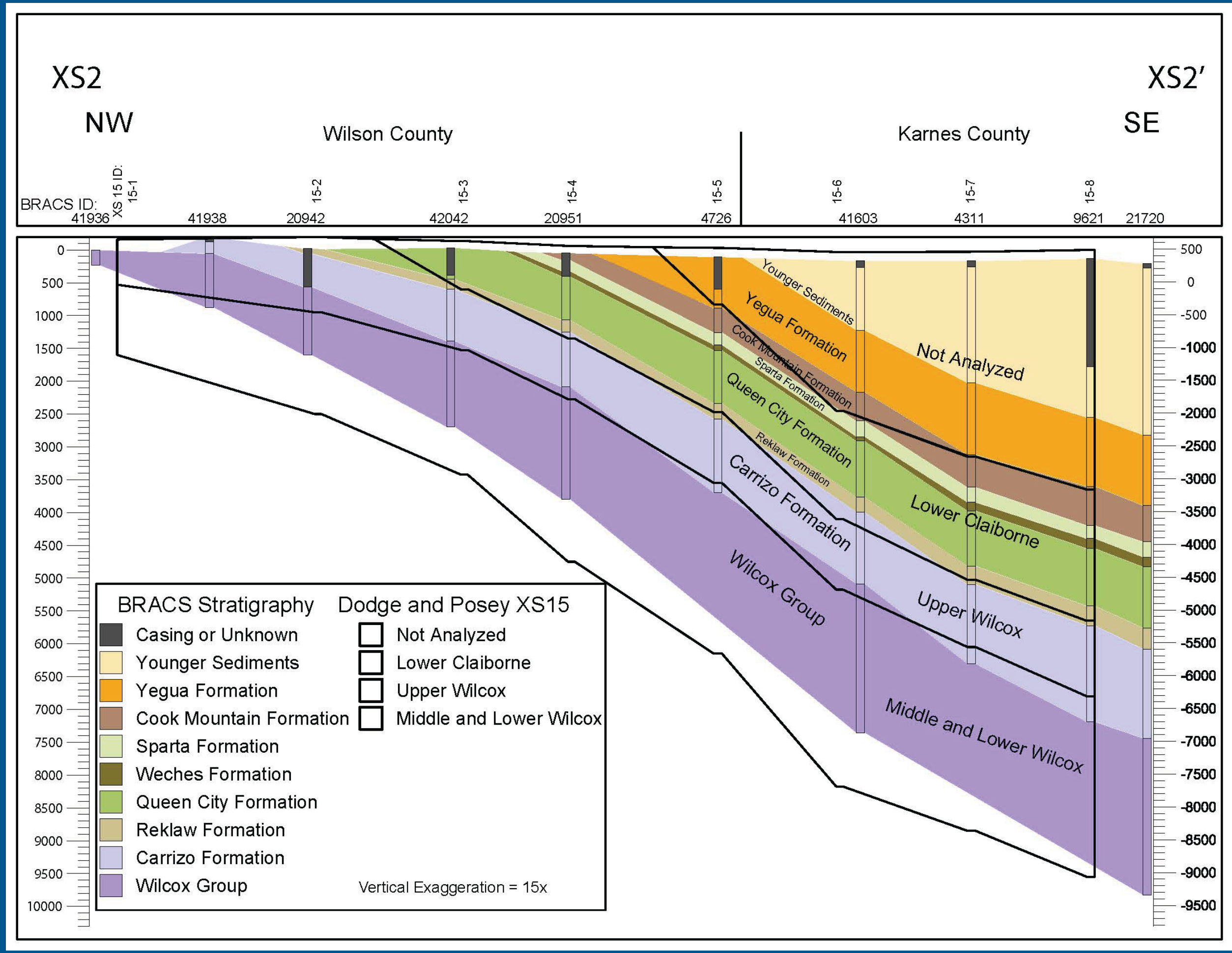
All this data is managed in an MS Access Database (available for download!!!)



Upper Coastal Plains – Central Study Overview

- Parts of 14 counties in central Texas
- 5 aquifers
  - (Yegua, Sparta, Queen City, Carrizo, Wilcox)
- 8 Eocene stratigraphic units mapped
  - (Yegua, Cook Mountain, Sparta, Weches, Queen City, Reklaw, Carrizo, Wilcox)
- Thousands of lithologic picks
  - (sand, sand with clay, clay with sand, clay)

Epoch	Group	Formation	USGS nomenclature	Texas Hydrogeologic unit
Eocene	Jackson	Caddell	Vicksburg-Jackson confining unit	Yegua-Jackson Aquifer
Eocene	Jackson	Moodys Branch	Vicksburg-Jackson confining unit	Yegua-Jackson Aquifer
Eocene	Claiborne	Hiatus	Vicksburg-Jackson confining unit	Yegua-Jackson Aquifer
Eocene	Claiborne	Yegua	Upper Claiborne Aquifer	Yegua-Jackson Aquifer
Eocene	Claiborne	Cook Mountain	Middle Claiborne Confining unit	Confining unit
Eocene	Claiborne	Hiatus	Middle Claiborne Confining unit	Confining unit
Eocene	Claiborne	Sparta	Middle Claiborne Aquifer	Sparta Aquifer
Eocene	Claiborne	Weches	Middle Claiborne Aquifer	Confining unit
Eocene	Claiborne	Hiatus	Middle Claiborne Aquifer	Confining unit
Eocene	Claiborne	Queen City	Middle Claiborne Aquifer	Queen City Aquifer
Eocene	Claiborne	Reklaw	Lower Claiborne confining unit	Confining unit
Eocene	Claiborne	Hiatus	Lower Claiborne confining unit	Confining unit
Eocene	Wilcox	Carrizo	Lower Claiborne – upper Wilcox Aquifer	Carrizo-Wilcox Aquifer
Eocene	Wilcox	Hiatus	Lower Claiborne – upper Wilcox Aquifer	Carrizo-Wilcox Aquifer
Eocene	Wilcox	Sabinetown	Lower Claiborne – upper Wilcox Aquifer	Carrizo-Wilcox Aquifer
Eocene / Paleocene	Wilcox	Rockdale	Lower Claiborne – upper Wilcox Aquifer / Middle Wilcox Aquifer	Carrizo-Wilcox Aquifer
Paleocene	Wilcox	Seguin	Middle Wilcox Aquifer	Carrizo-Wilcox Aquifer
Paleocene	Midway	Wills Point	Midway confining unit	Confining unit



Stratigraphic column showing relationship between the epochs, formations, and hydrogeologic units. The United States Geological Survey (USGS) nomenclature is based on Ryder (1996). Texas hydrogeologic units are based on TWDB (2007a) and George and others (2011). This table does not reflect the entire Jackson or Midway group stratigraphy. This table is not scaled vertically in uniform units of time.

Cross-section comparing the stratigraphic nomenclature and picks between this study and Dodge and Posey (1981)

Salinity Mapping

Groundwater Salinity Classification	Salinity Zone Code	Total Dissolved Solids (milligrams per liter)
Fresh	FR	0 to 1,000
Slightly Saline	SS	1,000 to 3,000
Moderately Saline	MS	3,000 to 10,000
Very Saline	VS	10,000 to 35,000
Brine	BR	Greater than 35,000

BRACKISH

PWS →

BUQ →

USDW →

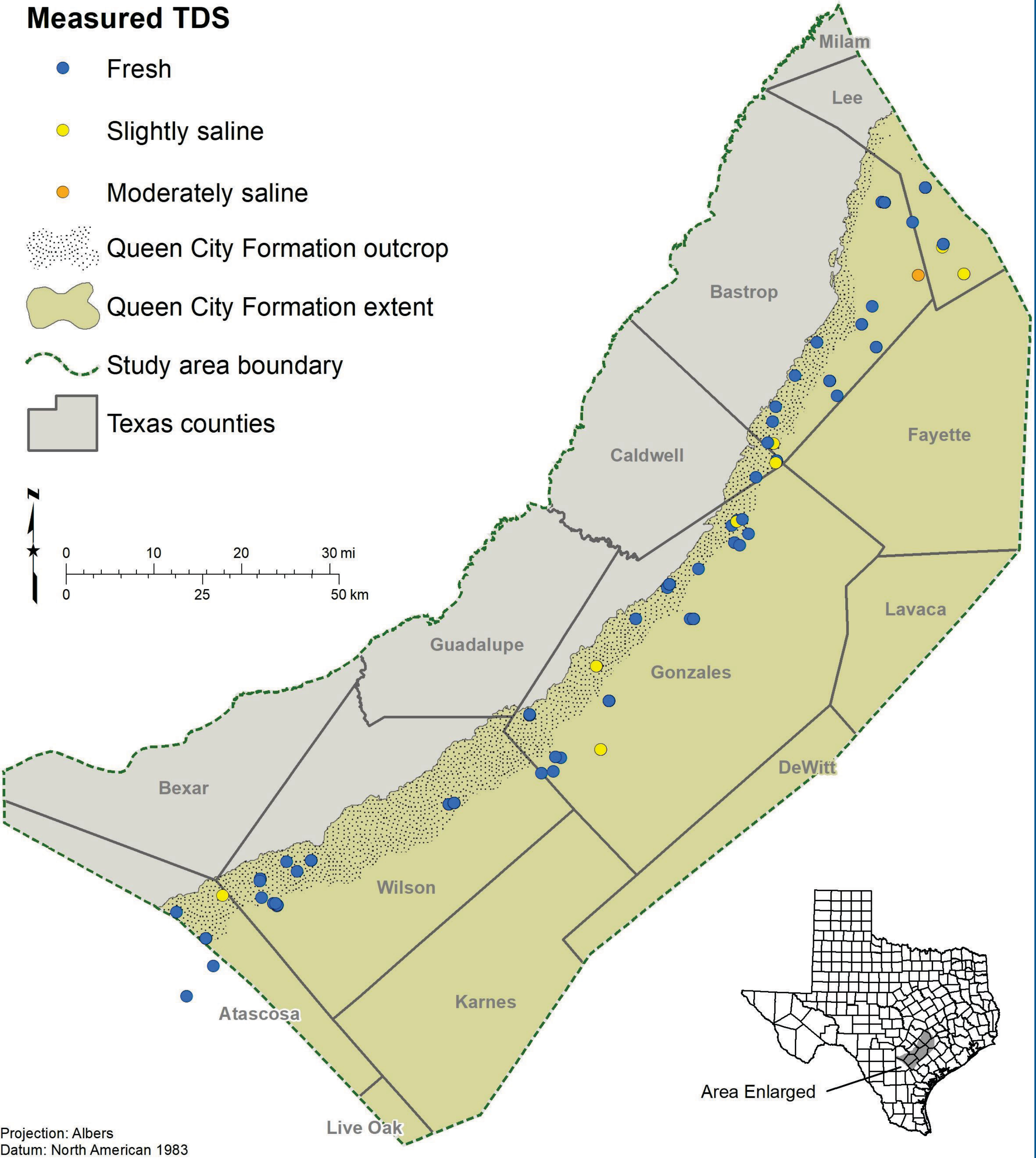
← Most Texas Major/Minor Aquifer Mapped Limit

← Seawater

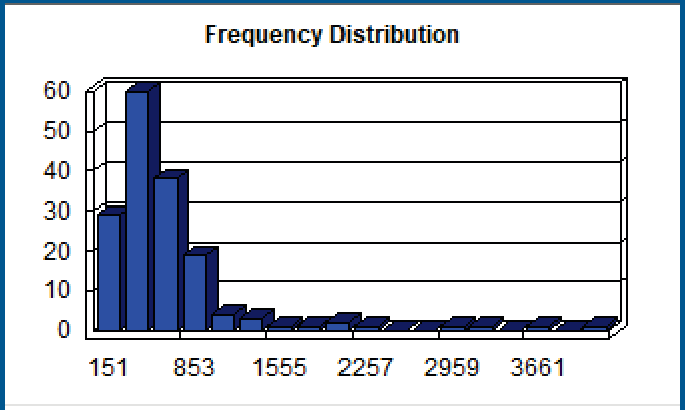
PWS: Public Water System threshold for fresh water, TX Commission on Environmental Quality
BUQ: Base Useable Quality water, TX Railroad Commission
USDW: Underground Source Drinking Water, US Environmental Protection Agency

modified from Winslow and Kister (1956) USGS WSP 1365

Measured Water Quality (TDS_{meas})



- 61 water wells, 146 measurements identified using aquifer determination
- Limited to where people drill wells (shallow & fresh)
- Min: 151, Max: 4,345, Mean: 729
- Sources: TWDB Groundwater Database, San Antonio Water System, Gonzales Underground Water Conservation District, U.S. Geological Survey Produced Water Database, published reports, raw-water sample reports from the Texas Commission on Environmental Quality public drinking water system program



Calculating Water Quality (TDS_{calc})

- 348 oil & gas wells with 538 TDS_{calc} values
- The R_{wa} Minimum Method (Resistivity Water Apparent) is based on the relationship between water salinity and resistivity.

- A simplified version of Archie's equation (1942) assumes 100% water saturation and Winsauer factor = 1 :

$$R_w = R_o \cdot \phi^m$$

where:

	R_o	= resistivity of the formation (units: ohm-meter)
	R_w	= resistivity of water (units: ohm-meter)
	ϕ	= porosity (units: percent)
	m	= cementation exponent (units: dimensionless)

- Resistivity → specific conductance → total dissolved solids.
- Let's look at the details…

Parameters (1/3)

Depth and Temperatures

(D_t, D_f, T_s, T_{bh})

- Temperature effects resistivity
- We assume a constant temperature gradient from the surface to bottom of the well hole to calculate the formation temperature

D_t: total depth of the well

D_f: depth of the formation

T_s: surface temperature

T_{bh}: bottom hole temperature

Deep Resistivity

(R_o)

- Avoid the mud infiltrate “invaded zone”
- Take value from a clean, shale-free sand >10ft thick
- Units are in ohm-m

Parameters (2/3)

"ct" factors

TDS low	TDS high	Number records	TDS	ct	R_{wcRw}	Ca	Mg	Na	HCO_3	SO_4	Cl
0	499	35	335	0.54	1.23	39	9	72	183	55	63
500	999	61	686	0.56	1.22	69	21	146	282	181	122
1,000	1,999	6	1,224	0.62	1.25	110	41	245	279	504	179
2,000	2,999	2	2,272	0.52	1.25	190	75	497	395	876	438
3,000	3,999	3	3,420	0.57	1.11	140	48	1,050	205	623	1,450
4,000	4,999	1	4,345	0.5	1.14	15	12	1,607	682	704	1,654
>5,000		0									

- 108 TDS_{meas} correlated with specific conductance

$$ct = \frac{TDS}{C_w}$$

ct = ct conversion factor

TDS = interpreted total dissolved solids (milligrams per liter)

Cw = conductivity water at 77°F (microsiemens centimeter)

Porosity (ϕ)

Geological formation	Total porosity
Yegua Formation	39
Sparta Formation	34
Queen City Formation	y = -0.0023x + 41.657
Carrizo Formation	y = -0.0015x + 38.465
Wilcox Group	y = -0.0019x + 39.839

- 15 wells with 20 measurements
- If a nearby measurement was not available, we used a depth regression to estimate ϕ

Parameters (3/3)

Cementation exponent (m)

- Function of grain size, grain size distribution, grain sorting, pore tortuosity, and grain lithology
- No core analysis
- Therefore assumed m = 1.75
- 1.75 is within the range of slightly to moderately cemented sandstones

Water quality correction factor (RwcRw)

- Logs were developed for oil & gas exploration and assume NaCl dominated H_2O
- Ions have different resistivities
- Factor calibrates solution to an equivalent NaCl concentration for analysis
- We used weighting multipliers from Chart Gen-8, Resistivities of Solutions (Schlumberger, 1979; 1985)

Math is Fun!

1. **Determine the temperature of the formation being investigated.**
2. Determine resistivity of water equivalent.
3. Correct resistivity water based on groundwater type correction factor.
4. Convert resistivity water at formation temperature to 77°F using Arp's Equation.
5. Convert resistivity water at 77°F to conductivity water at 77°F.
6. Calculate interpreted total dissolved solids.

$$G_g = \frac{(T_{bh} - T_s)}{D_t}$$

$$T_f = (Gg \cdot Df) + Ts$$

where:

G_g = geothermal gradient (°F/foot)
T_{bh} = temperature bottom hole (°F)
T_s = temperature surface (°F)
D_t = depth total (feet)
T_f = temperature formation (°F)
D_f = depth formation (feet)

Math is Fun!

1. Determine the temperature of the formation being investigated.
2. **Determine resistivity of water equivalent.**
3. Correct resistivity water based on groundwater type correction factor.
4. Convert resistivity water at formation temperature to 77°F using Arp's Equation.
5. Convert resistivity water at 77°F to conductivity water at 77°F.
6. Calculate interpreted total dissolved solids.

$$R_w = \phi^m \cdot Ro$$

where:

R_w	= resistivity of water equivalent (ohm-meter)
ϕ	= porosity of the formation evaluated (dimensionless)
m	= cementation exponent (dimensionless)
R_o	= resistivity of water from geophysical log (ohm-meter)

Math is Fun!

1. Determine the temperature of the formation being investigated.
2. Determine resistivity of water equivalent.
3. **Correct resistivity water based on groundwater type correction factor.**
4. Convert resistivity water at formation temperature to 77°F using Arp's Equation.
5. Convert resistivity water at 77°F to conductivity water at 77°F.
6. Calculate interpreted total dissolved solids.

$$R_{wc} = \frac{R_w}{R_{wcRw}}$$

where:

Rwc = resistivity water, corrected (ohm-meter)
Rw = resistivity water equivalent (ohm-meter)
RwcRw = sodium chloride equivalent correction factor (dimensionless)

Math is Fun!

1. Determine the temperature of the formation being investigated.
2. Determine resistivity of water equivalent.
3. Correct resistivity water based on groundwater type correction factor.
4. **Convert resistivity water at formation temperature to 77°F using Arp's Equation.**
5. Convert resistivity water at 77°F to conductivity water at 77°F.
6. Calculate interpreted total dissolved solids.

$$R_{w77} = R_{wc} \cdot \frac{(T_f + 6.77)}{(77 + 6.77)}$$

where:

T_f = temperature formation (°F)

R_{wc} = resistivity water, corrected (ohm-meter)

R_{w77} = resistivity water at 77°F (ohm-meter)

Math is Fun!

1. Determine the temperature of the formation being investigated.
2. Determine resistivity of water equivalent.
3. Correct resistivity water based on groundwater type correction factor.
4. Convert resistivity water at formation temperature to 77°F using Arp's Equation.
5. **Convert resistivity water at 77°F to conductivity water at 77°F.**
6. Calculate interpreted total dissolved solids.

$$C_w = \frac{10{,}000}{R_{w77}}$$

where:

C_w = conductivity water at 77°F (microsiemens-centimeter)

R_{w77} = resistivity water at 77°F (ohm-meter)

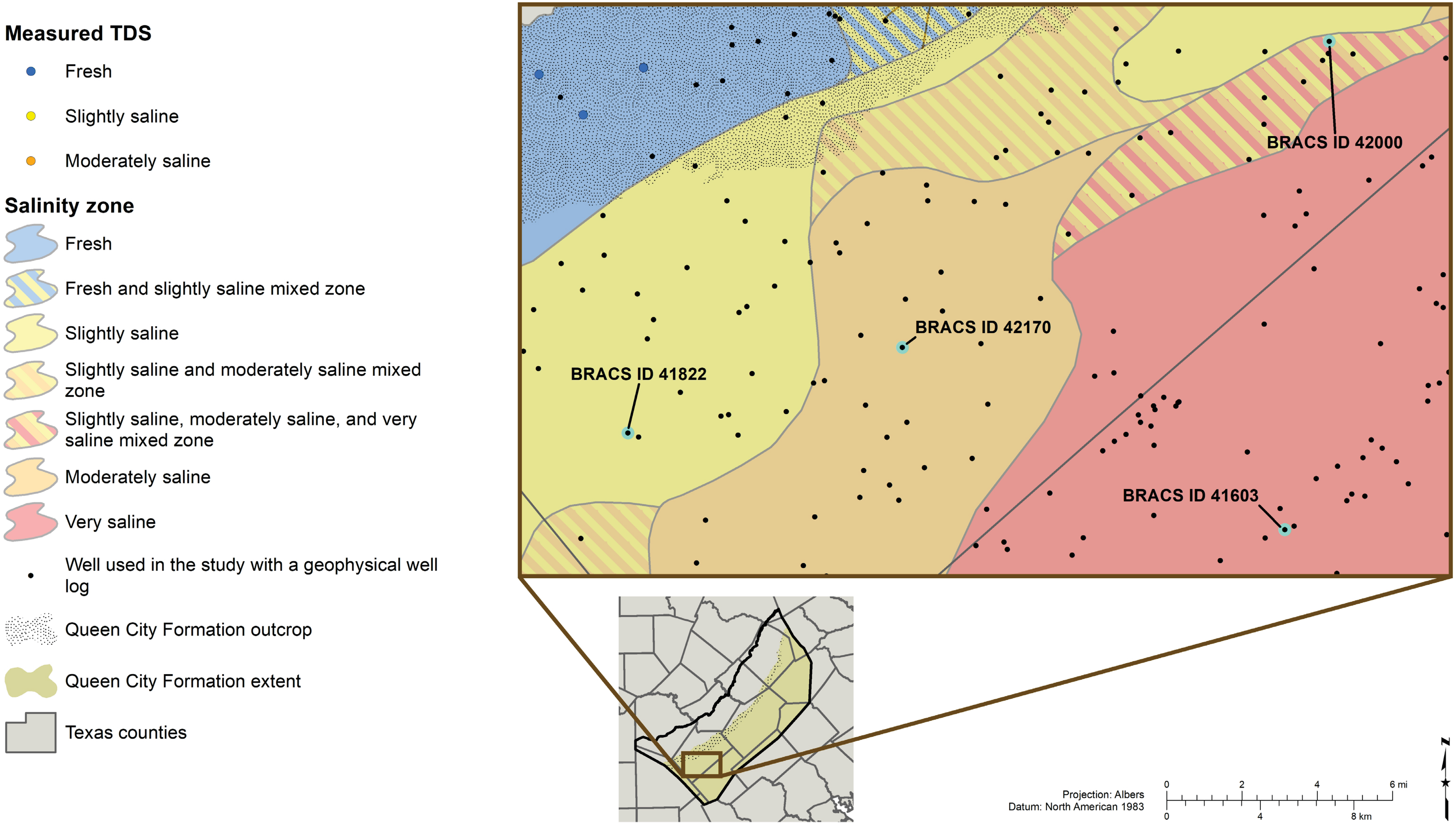
Math is Fun!

1. Determine the temperature of the formation being investigated.
2. Determine resistivity of water equivalent.
3. Correct resistivity water based on groundwater type correction factor.
4. Convert resistivity water at formation temperature to 77°F using Arp's Equation.
5. Convert resistivity water at 77°F to conductivity water at 77°F.
6. <u>**Calculate interpreted total dissolved solids.**</u>

$$TDS = ct \cdot Cw$$

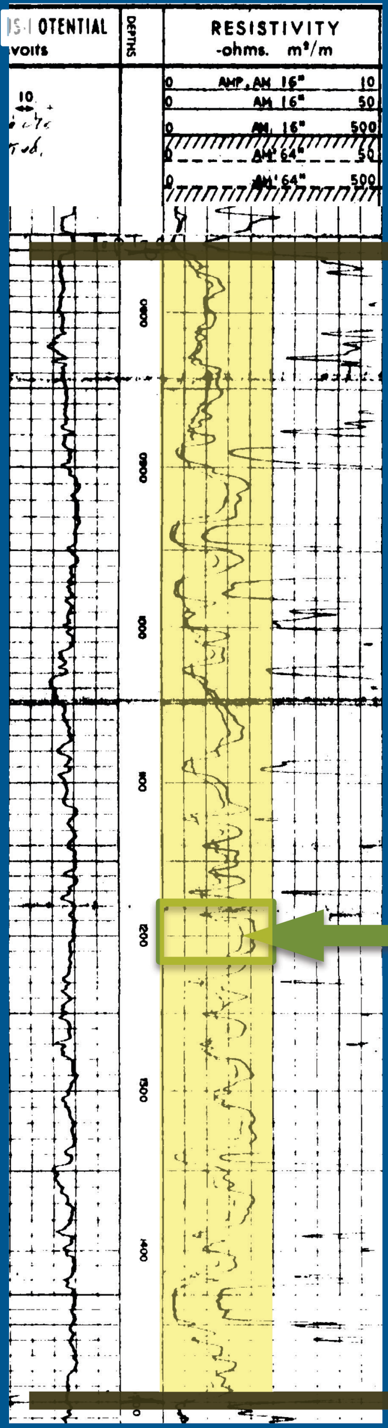
where:

TDS	= interpreted total dissolved solids (milligrams per liter)
ct	= ct conversion factor
C_w	= conductivity water at 77°F (microsiemens centimeter)



Measured TDS
Fresh
Slightly saline
Moderately saline
Salinity zone
Fresh
Fresh and slightly saline mixed zone
Slightly saline
Slightly saline and moderately saline mixed zone
Slightly saline, moderately saline, and very saline mixed zone
Moderately saline
Very saline
Well used in the study with a geophysical well log
Queen City Formation outcrop
Queen City Formation extent
Texas counties
BRACS ID 42000
BRACS ID 42170
BRACS ID 41822
BRACS ID 41603
Projection: Albers
Datum: North American 1983
0
2
4
6 mi
0
4
8 km
N

Slightly saline well 41822



Top of the Queen City Formation at 740 feet below Kelly Bushing

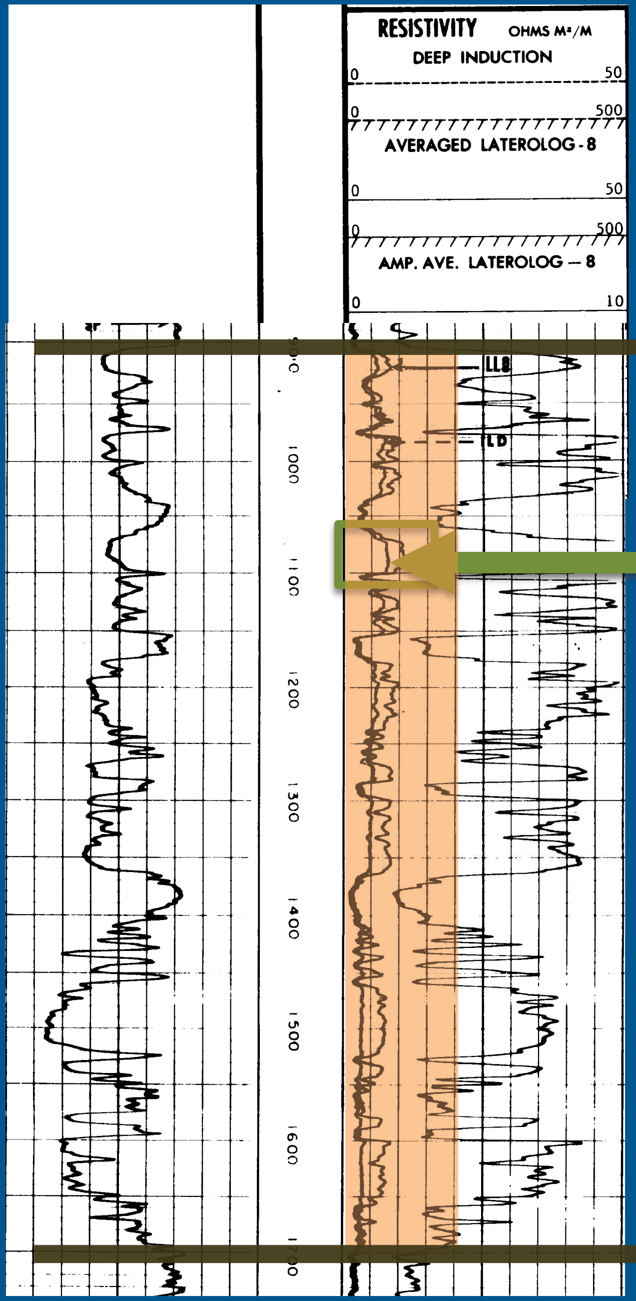
Bottom of the Queen City Formation at 1,500 feet below Kelly Bushing

$$\mathbf{1{,}824} = 0.62 * \frac{10{,}000}{\frac{0.39^{1.75} * 18}{1.25} * \frac{\left(\frac{103 - 70}{1{,}505} * 1{,}200 + 70\right) + 6.77}{77 + 6.77}}$$

$$TDS = ct * \frac{10{,}000}{\frac{\emptyset^{m} * Ro}{R_{wcRw}} * \frac{\left(\frac{Tbh - Ts}{Dt} * Df + Ts\right) + 6.77}{77 + 6.77}}$$

Value	Parameter	Units
1,505	Depth total, Dt	Feet below Kelly Bushing
1,200	Depth formation, Df	Feet below Kelly Bushing
70	Temperature surface, Ts	Degrees Fahrenheit
103	Temperature bottom hole, Tbh	Degrees Fahrenheit
18	Deep resistivity, Ro	Ohm-meter
0.39	Porosity, Ø	Percent
0.62	ct conversion factor, ct	Dimensionless
1.75	Cementation exponent, m	Dimensionless
1.25	Water quality correction factor, R_{wcRw}	Dimensionless

Moderately saline well 42170



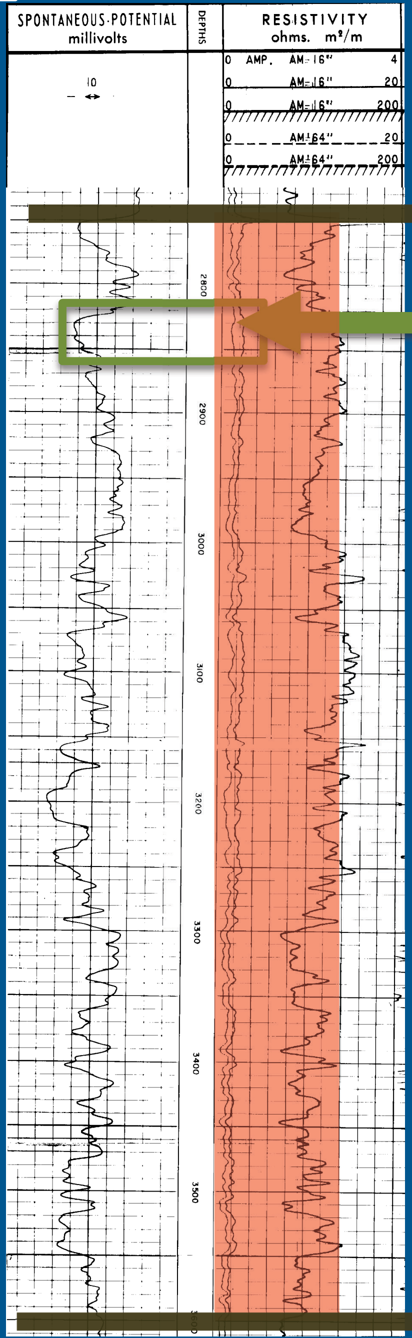
Top of the Queen City Formation at 903 feet below Kelly Bushing

Bottom of the Queen City Formation at 1,702 feet below Kelly Bushing

$$\mathbf{3{,}478} = 0.56 * \frac{10{,}000}{\frac{0.39^{1.75} * 7.5}{1} * \frac{\left(\frac{201 - 69}{7903} * 1090 + 69\right) + 6.77}{77 + 6.77}}$$

$$TDS = ct * \frac{10{,}000}{\frac{\emptyset^{m} * Ro}{R_{wcRw}} * \frac{\left(\frac{Tbh - Ts}{Dt} * Df + Ts\right) + 6.77}{77 + 6.77}}$$

Value	Parameter	Units
7903	Depth total, Dt	Feet below Kelly Bushing
1090	Depth formation, Df	Feet below Kelly Bushing
69	Temperature surface, Ts	Degrees Fahrenheit
201	Temperature bottom hole, Tbh	Degrees Fahrenheit
7.5	Deep resistivity, Ro	Ohm-meter
0.39	Porosity, Ø	Percent
0.56	ct conversion factor, ct	Dimensionless
1.75	Cementation exponent, m	Dimensionless
1	Water quality correction factor, R_{wcRw}	Dimensionless



Top of the Queen City Formation at 2,745 feet below Kelly Bushing

Very saline well 41603

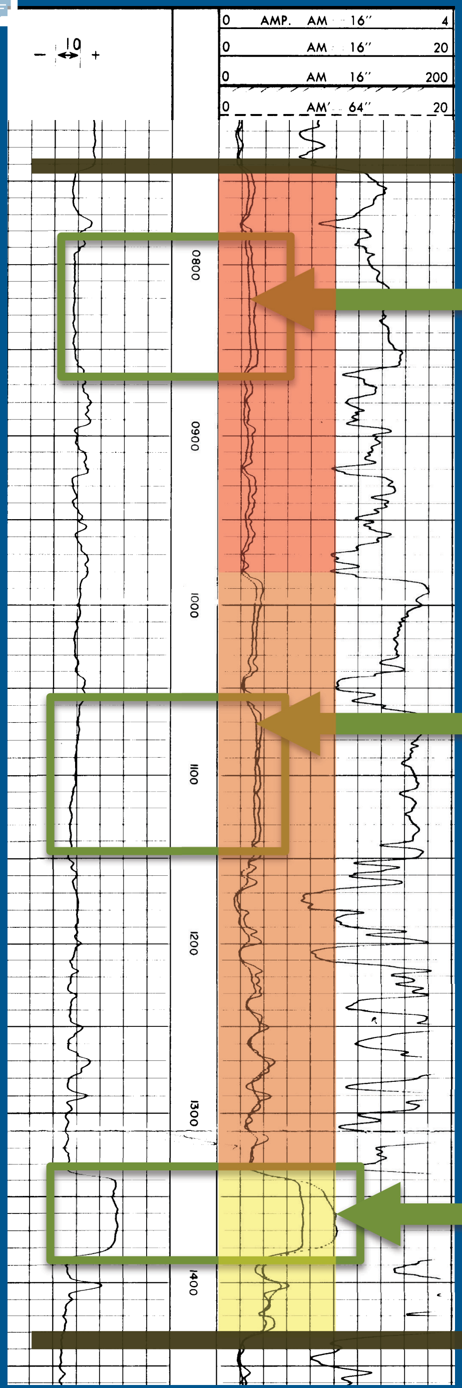
$$\mathbf{23{,}333} = 0.56 * \frac{10{,}000}{\frac{0.35^{1.75} * 1}{1} * \frac{\left(\frac{269.6 - 70}{11{,}450} * 2{,}830 + 70\right) + 6.77}{77 + 6.77}}$$

$$TDS = ct * \frac{10{,}000}{\frac{\varnothing^{m} * Ro}{R_{wcRw}} * \frac{\left(\frac{Tbh - Ts}{Dt} * Df + Ts\right) + 6.77}{77 + 6.77}}$$

Value	Parameter	Units
11,450	Depth total, Dt	Feet below Kelly Bushing
2,830	Depth formation, Df	Feet below Kelly Bushing
70	Temperature surface, Ts	Degrees Fahrenheit
269.6	Temperature bottom hole, Tbh	Degrees Fahrenheit
1	Deep resistivity, Ro	Ohm-meter
0.35	Porosity, Ø	Percent
0.56	ct conversion factor, ct	Dimensionless
1.75	Cementation exponent, m	Dimensionless
1	Water quality correction factor, R_{wcRw}	Dimensionless

Bottom of the Queen City Formation at 3,600 feet below Kelly Bushing

Mixed salinity well 42000



Top of the Queen City Formation at 740 feet below Kelly Bushing

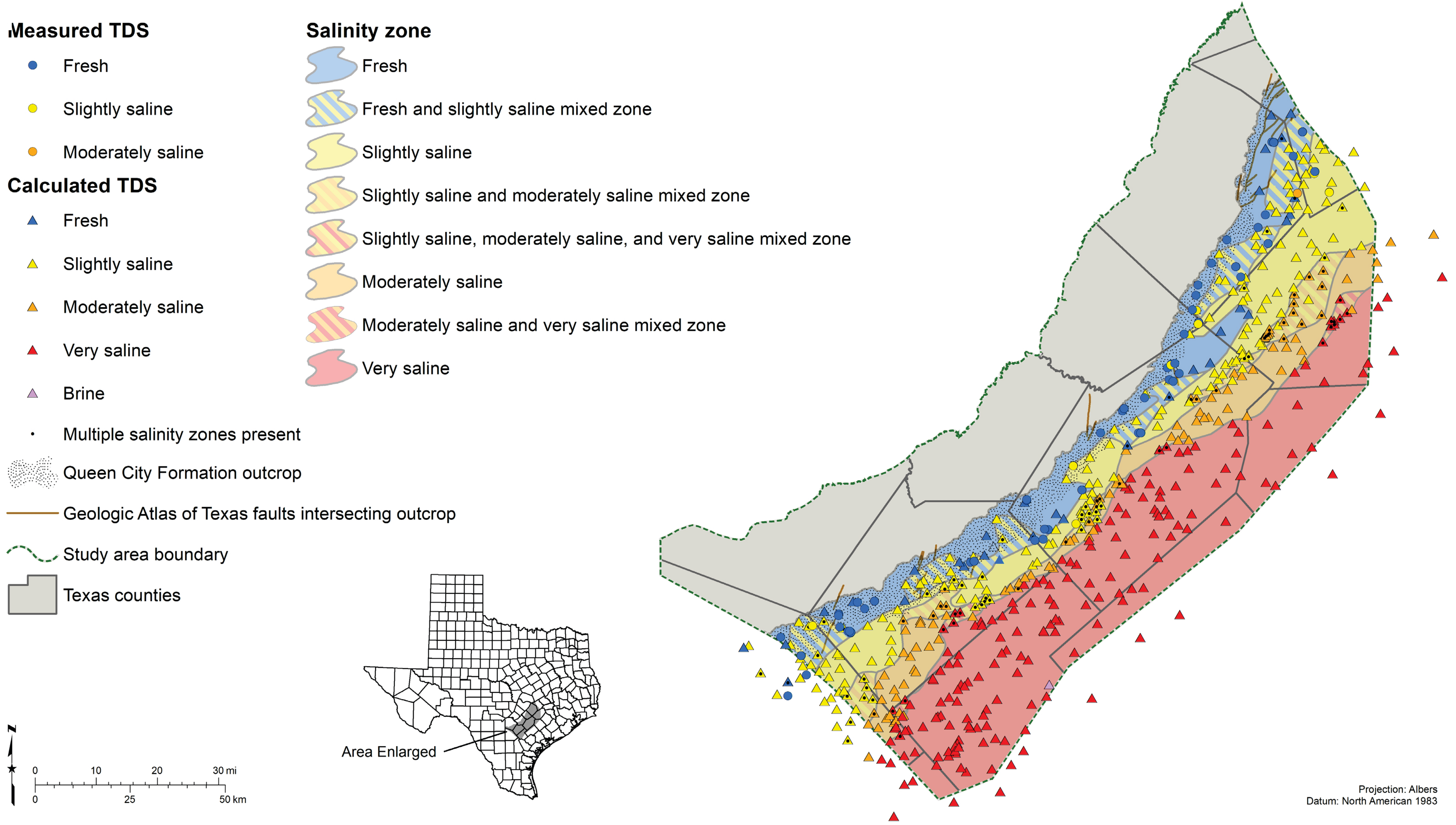
#1	#2	#3	Parameter	Units
4003	4003	4003	Depth total, Dt	Feet below Kelly Bushing
820	1070	1360	Depth formation, Df	Feet below Kelly Bushing
69	69	69	Temperature surface, Ts	Degrees Fahrenheit
127.1	127.1	127.1	Temperature bottom hole, Tbh	Degrees Fahrenheit
2.6	3.2	10	Deep resistivity, Ro	Ohm-meter
0.4	0.39	0.39	Porosity, Ø	Percent
0.56	0.56	0.57	ct conversion factor, ct	Dimensionless
1.75	1.75	1.75	Cementation exponent, m	Dimensionless
1	1	1.11	Water quality correction factor, R_{wcRw}	Dimensionless

Calculation 1, TDS = **10,370**

Calculation #2, TDS = **8,235**

Calculation #3, TDS = **2,879**

Bottom of the Queen City Formation at 1,435 feet below Kelly Bushing


Measured TDS
Fresh
Slightly saline
Moderately saline
Calculated TDS
Fresh
Slightly saline
Moderately saline
Very saline
Brine
Multiple salinity zones present
Queen City Formation outcrop
Geologic Atlas of Texas faults intersecting outcrop
Study area boundary
Texas counties
Salinity zone
Fresh
Fresh and slightly saline mixed zone
Slightly saline
Slightly saline and moderately saline mixed zone
Slightly saline, moderately saline, and very saline mixed zone
Moderately saline
Moderately saline and very saline mixed zone
Very saline
Area Enlarged
N
0 10 20 30 mi
0 25 50 km
Projection: Albers
Datum: North American 1983

Conclusions

- Resistivity logs can be used to estimate water quality
- The calculations work best when:
  - Correlations with measured water quality can be established
  - Parameters such as the porosity and cementation exponent are well defined
  - The water quality is dominated by NaCl and not SO_4^{2-} or HCO_3^-
  - Log headers are complete (bottom hole temperature, etc.)
  - Logs start shallow enough and are run before casing is placed

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http://www.twdb.texas.gov/jobs/index.asp

Work Location: Austin

Monthly Salary: $4,375.00 – 4,635.50*

Travel %: 15

Number of Positions: 2

**Salary commensurate with experience and qualifications*

Minimum Qualifications

- Graduation from an accredited four-year college or university with a Bachelor of Science in Geology, Geophysics, Hydrogeology or related field.
- Three to five years of progressive work experience in the Geology, Geophysics, and Hydrogeology field.
- Licensed as a Geoscientist-In-Training or Professional Geoscientist by the Texas Board of Professional Geoscientists.
- Previous experience with GIS applications and database applications.
- Previous experience with preparing and writing technical reports.
- Relevant education and experience can be substituted on a year-for-year basis.

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http://www.twdb.texas.gov/innovativewater/index.asp

2017 Water Plan:
http://www.twdb.texas.gov/waterplanning/swp/2017/index.asp