USING ELECTRIC LOGS TO ESTIMATE SALINITY AND RESOURCES OF FRESH AND BRACKISH GROUNDWATER

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ELECTRIC LOGS

• Borehole measurements of electrical properties versus depth

• Commonly run in both oil and gas wells and water wells

• Respond to variations in both pore-fluid composition and rock properties

• Can be used to estimate groundwater salinity where rock properties are relatively constant

• Graphically display variations in Spontaneous Potential (SP) and Resistivity with depth
LOG TYPES

**SP log** records relative difference in electrical potential
- Positive SP – groundwater salinity < borehole fluid salinity
- Neutral SP – groundwater salinity = borehole fluid salinity
- Negative SP – groundwater salinity > borehole fluid salinity
- **Qualitative indicator of groundwater salinity**

**Resistivity log** records resistance to an induced current
- High resistivity – low salinity groundwater
- Low resistivity – high salinity groundwater
- **Quantitative indicator of groundwater salinity**
Distinguishing Lithology from Groundwater salinity

- Works best in simple sand/mud sequences
- Mud and shale – neutral SP and low resistivity
- Sand and sandstone – groundwater salinity effects (next slide)
### Electric Log Response to Groundwater Salinity

<table>
<thead>
<tr>
<th>SP (mv)</th>
<th>Lith</th>
<th>Resistivity (ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50</td>
<td>Mud</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>Sand</td>
<td>1000</td>
</tr>
</tbody>
</table>

- **Freshwater sand**
  - SP positive
  - Res very high

- **Slightly saline water sand**
  - SP neutral
  - Res high

- **Moderately saline water sand**
  - SP negative
  - Res low

- **Very saline water sand**
  - SP very negative
  - Res very low
Quantifying the Resistivity / Salinity Relationship
Conductivity of Groundwater Samples

Excellent correlation!

$R^2 = 0.97$

$n = 4402$

Specific Conductance (µomhos/cm$^3$)

Total Dissolved Solids (mg/L)
\[
\text{Resistivity} = \frac{10,000}{\text{Specific Conductance}}
\]

**Specific Conductance** measured in groundwater sample at surface – no lithology effects

**Resistivity** influenced by borehole environment, lithology, etc. (correlation with TDS not as good)
Quantifying the Resistivity / Salinity Relationship
Empirical Data from Carrizo-Wilcox Aquifer

Correlation OK

$R^2 = 0.75$

$n = 79$

Resistivity (ohm-m)

Total Dissolved Solids (mg/L)
## Quantifying the Resistivity / Salinity Relationship

**Resistivity Cut-offs for Carrizo-Wilcox Aquifer**

<table>
<thead>
<tr>
<th>Salinity Classification</th>
<th>Total Dissolved Solids (mg/L)</th>
<th>Typical Resistivity Cut-offs (ohm-m)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater</td>
<td>&lt; 1,000</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Slightly saline water</td>
<td>1,000 – 3,000</td>
<td>10 – 20</td>
</tr>
<tr>
<td>Moderately saline water</td>
<td>3,000 – 10,000</td>
<td>5 – 10</td>
</tr>
<tr>
<td>Very saline water</td>
<td>&gt; 10,000</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

* Resistivity cut-offs vary with location, depth, lithology, water chemistry, etc.
CARRIZO-WILCOX AQUIFER

Eocene sand-rich fluvial-deltaic system on the Texas coastal plain

Texas

Outcrop
Confined
Study Areas

200 miles
Carrizo-Wilcox Electric Log example showing groundwater salinity increase with depth

Log trends with depth:
SP – increasing negative
Res – decreasing
South Texas Carrizo-Wilcox Cross Section

Vertical lithology/salinity profiles + stratigraphic correlation between wells

NW

Land surface

SE

Carrizo City

Wilcox

Queen City

30 miles

3000 feet

Sea Level

Freshwater sand
Slightly saline water sand
Moderately saline water sand
Very saline water sand
Shale
CARRIZO-WILCOX NET
FRESHWATER SANDSTONE
CARRIZO-WILCOX NET
SLIGHTLY SALINE WATER SANDSTONE

San Antonio

Sand Thickness (Feet)

Line of cross section
CARRIZO-WILCOX NET
VERY SALINE WATER SANDSTONE

San Antonio

Line of cross section

Gulf of Mexico

Mexico

Sand Thickness (Feet)

- 2000
- 1800
- 1600
- 1400
- 1200
- 1000
- 800
- 600
- 400
- 200
- 0

CARRIZO-WILCOX NET
VERY SALINE WATER SANDSTONE

San Antonio

Line of cross section

Gulf of Mexico

Mexico

Sand Thickness (Feet)

- 2000
- 1800
- 1600
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- 1000
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- 600
- 400
- 200
- 0
ESTIMATING BRACKISH GROUNDWATER RESOURCES

Slightly saline + moderately saline = brackish groundwater

Protecting the freshwater resource by distinguishing flow systems

• Freshwater flow system = freshwater + brackish water in laterally continuous sandstones (connected brackish groundwater)

• Brackish water flow system = brackish water vertically separated from freshwater by shales (disconnected brackish groundwater)

Separate volumetrics for connected vs disconnected brackish groundwater
Carrizo-Wilcox Stratigraphic Cross Section Showing Connected and Disconnected Brackish Groundwater

Datum: Top Carrizo-Wilcox

Thickness Feet

-0

-500

-1000

-1500

-2000

-2500

-3000

10 miles

shale

aquitard

Connected

Disconnected

Brackish water sand

Freshwater sand

Slightly saline

Moderately saline

Very saline water sand

Shale
CARRIZO-WILCOX NET CONNECTED BRACKISH WATER SANDSTONE

San Antonio

Mexico

Gulf of Mexico

Sand Thickness (Feet)

0
100
200
300
400
500
600
700

Line of cross section
CARRIZO-WILCOX NET DISCONNECTED
BRACKISH WATER SANDSTONE

Sand Thickness (Feet)

Line of cross section

San Antonio

Mexico

Gulf of Mexico
VOLUMETRIC ANALYSIS OF GROUNDWATER IN THE CARRIZO-WILCOX AQUIFER IN SOUTH TEXAS

Groundwater volume = sandstone volume * porosity

Sandstone volume = area * thickness (from net sand maps)

Porosity = 0.20 (estimated from petrographic studies)

Groundwater volume and storativity used to estimate resource
# GROUNDWATER VOLUMES
## CARRIZO-WILCOX AQUIFER IN SOUTH TEXAS

<table>
<thead>
<tr>
<th>FLOW SYSTEM</th>
<th>GROUNDWATER VOLUME $10^6$ acre-feet ($\text{km}^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater</td>
<td>458 (565)</td>
</tr>
<tr>
<td>Connected brackish water</td>
<td>94 (116)</td>
</tr>
<tr>
<td>Disconnected brackish water</td>
<td>600 (740)</td>
</tr>
</tbody>
</table>
CONCLUSIONS

• Electric logs record both lithology and groundwater salinity for continuous vertical sections through the aquifer (not just point source measurements)

• Methodology works best in simple sandstone/shale aquifer systems

• Empirical data (groundwater chemical analyses) are used to calibrate resistivity logs

• Electric logs are analyzed spatially to map aquifer thickness and to estimate volumes of fresh and brackish groundwater

• Electric-log-based stratigraphic analysis used to distinguish connected versus disconnected flow systems