

SALINE AQUIFERS IN COASTAL GEORGIA: ASSESSMENT USING BOREHOLE GEOPHYSICAL LOGS AT THE FORT PULASKI CORE SITE, CHATHAM COUNTY, GEORGIA

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Abstract. Borehole geophysical logs were collected in March 2010 from a 1,020-foot deep core hole drilled at Fort Pulaski, Chatham County, Georgia. Using these logs, a relation was developed between borehole geophysical log response and known water-quality variations in the Floridan aquifer system. Formation factors determined from this analysis ranged from 4.5 to 5.6. A value of 0.75 for the tortuosity and a value of 1.6 for the cementation factor provided a fairly good fit between log-derived salinity values and water-quality values from the well samples. Formation factors determined at the Fort Pulaski core site could be applied to similar rock types in the subsurface of coastal Georgia; and this methodology could be applied to geophysical log data to expand the current knowledge about saline aquifers in coastal Georgia and throughout the southeastern United States.

INTRODUCTION

In 2010, the U.S. Geological Survey (USGS) began a regional study of saline water resources of the southeastern United States that included parts of Georgia, South Carolina, Alabama, and all of Florida. This study is especially relevant in the coastal areas of Georgia, where saltwater intrusion has occurred and regulatory agencies have imposed limitations on groundwater withdrawals. Although saline aquifers have been identified in both carbonate and clastic formations composing the Floridan and southeastern Coastal Plain aquifer systems, the variations in salinity throughout these aquifers are not clearly defined.

Borehole resistivity and porosity logs can be used effectively to map salinity variations if the formation properties are relatively well known. To assess this methodology, borehole geophysical logs were collected from a 1,020-foot deep core hole completed in March 2010 at Fort Pulaski on Cockspur Island, Chatham County, Georgia (Fig. 1). The core hole was drilled as part of an ongoing USGS study funded by the National Cooperative Geologic Mapping Program to evaluate the geology of the Savannah River Basin. Because of the close proximity of the core hole to several deep monitoring wells, it provided an opportunity to evaluate both freshwater and brackish water zones in the carbonate Floridan aquifer system.

Several geologic and hydrogeologic units were penetrated at the test site, including the (1) surficial aquifer, composed of undifferentiated sands and clays of post-Miocene age;

(2) upper confining unit of the Floridan aquifer system, consisting of mostly clay and some sand of the Hawthorn Formation; (3) Upper Floridan aquifer, consisting of Suwannee and Ocala Limestones; (4) middle confining unit, consisting of fine-grained limestone, carbonate sands, silts, and clays in the lower part of the Ocala Limestone and upper part of the Avon Park Formation; and (5) Lower Floridan aquifer, consisting of limestone, sands, and some argillaceous carbonate units of the Avon Park Formation (Williams and Gill, 2010). The approximate boundaries of the units are shown in Figure 2.

ASSESSMENT OF SALINE AQUIFERS USING BOREHOLE GEOPHYSICAL LOGS

Salinity variations were assessed at a core hole site at Fort Pulaski, Georgia, by using borehole resistivity and porosity logs (commonly known as the resistivity-porosity method) along with water-quality sampling data from nearby deep monitoring wells. Following core retrieval from the test hole, a series of borehole geophysical logs were collected, including full-wave sonic (not shown), gamma ray, and spontaneous potential and resistivity logs (Fig. 2).

Archie (1942) showed that the resistivity of a water-saturated formation (R_o) to the resistivity of the formation water (R_w) can be related through the formation factor (F), which is expressed as:

$$F = \frac{R_o}{R_w}, \quad (1)$$

Where

- F is formation resistivity factor (dimensionless),
- R_o is resistivity of the water-saturated formation (ohmmeters), and
- R_w is resistivity of the formation water occupying pores (ohmmeters).

Given that the R_o can be estimated using a deep reading resistivity tool (in this case the 64-inch long-normal) and values of R_w can be obtained from water samples collected from three nearby wells completed at different depths in the Floridan aquifer system (38Q002, 38Q004, 38Q196, see open intervals in Fig. 2), the formation factors for the Floridan aquifer system can be readily determined. The calculated formation factors for this site range from 4.5 to 5.6 (Table 1).

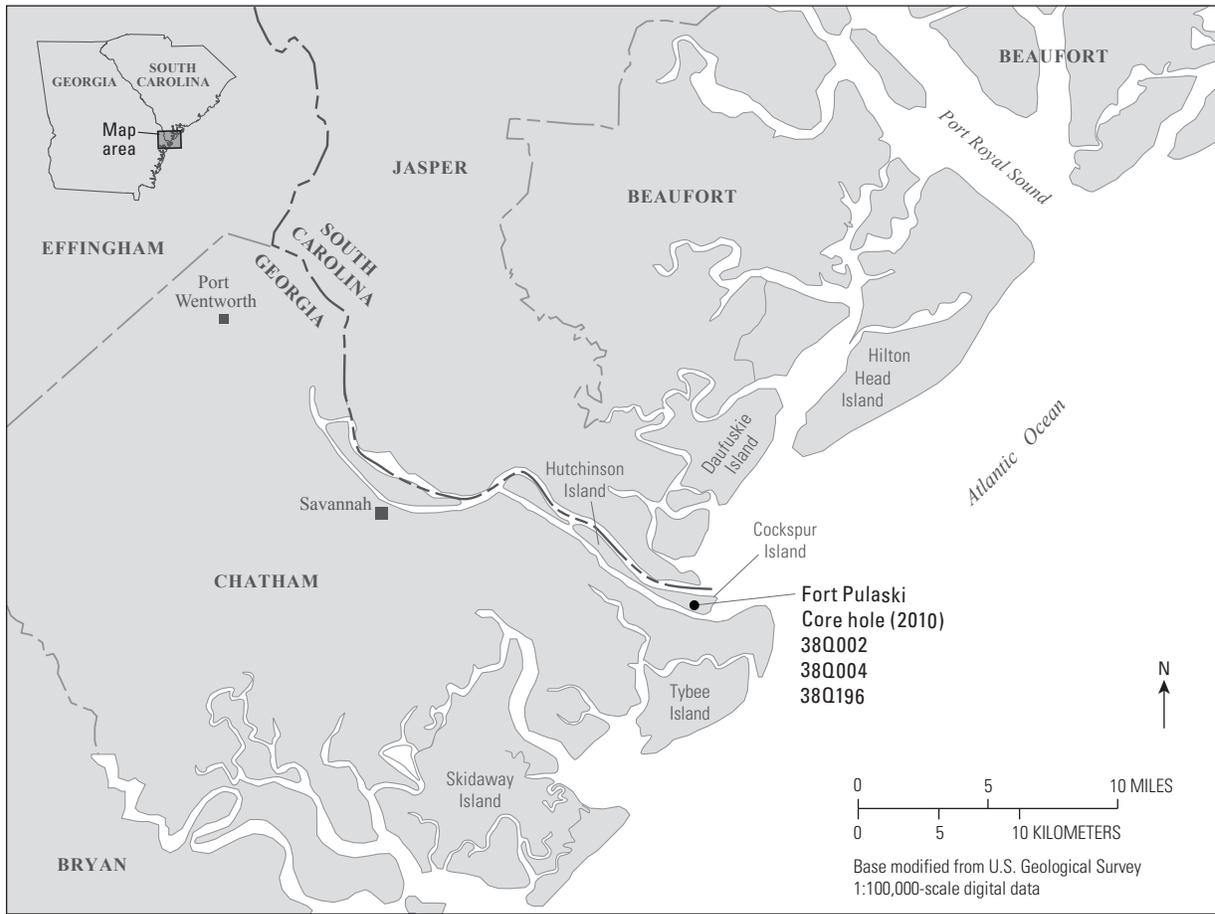


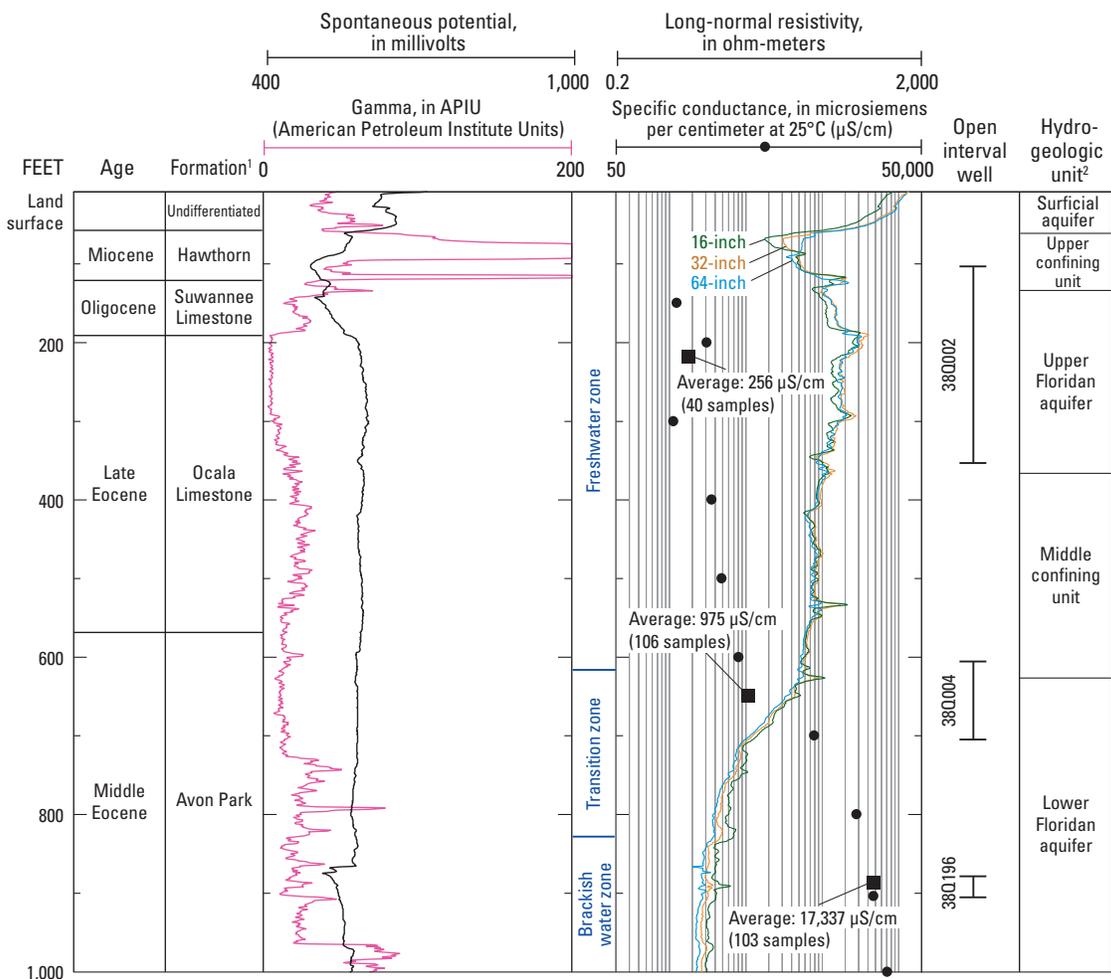
Figure 1. Location of the test wells at Fort Pulaski, Cockspur Island, Georgia.

Table 1. Calculation of formation factor from water-quality sampling data from wells at Fort Pulaski, Cockspur Island, Georgia.

[$\mu\text{S/cm}$, microsiemens per centimeter; R_w , formation water resistivity determined by dividing specific conductance by 10,000; ohm-m, ohm-meters; F , formation]

Well	Open interval (feet below land surface)		Specific conductance ¹ ($\mu\text{S/cm}$)		Calculated R_w (ohm-m)	Resistivity from logs (ohm-m)	Calculated F factor
	Top	Bottom	Minimum– Maximum	Average			
38Q002	110	348	233–354	256	39.1	180	4.6
38Q004	606	657	421–975	975	10.3	57	5.6
38Q196	870	900	14,900–38,200	17,300	0.58	2.6	4.5

¹Data obtained from USGS National Water Information System.



¹Formation tops based on Miller, 1986.

²Hydrogeologic units based on Williams and Gill, 2010

Logs collected in March 2010 by staff of the Geology of Atlantic Watersheds Project, USGS, Reston, VA and Camille Ransome, SC, Department of Environmental Health and Control

EXPLANATION

Specific conductance

- Calculation from logs
- From samples collected from wells

Figure 2. Borehole geophysical logs from the Fort Pulaski core hole (2010) showing calculated and measured specific conductance values for different depths.

Table 2. Calculation of formation factor and estimated total dissolved solids from well-log data, Fort Pulaski Core Hole, Cockspur Island, Georgia.

[LN long-normal resistivity (64-inch); ohm-m, ohm-meters; SPHI, sonic porosity; F , formation factor; R_w , formation water resistivity; T_f , formation temperature; °F, degrees Fahrenheit; Rw_{77} , formation water resistivity adjusted to 77 degees Farenheight; SC , specific conductance; $\mu S/cm$, microsiemens per centimeter; TDS , total dissolved solids; mg/L, milligram per liter]

Depth (feet below land surface)	Log data		Equation 3	Equation 4	Equation 5	Equation 6	Equation 7	Equation 8
	LN (64) (ohm-m)	SPHI (percent)	F factor	R_w (ohm-m)	T_f (°F)	Rw_{77} (ohm-m)	SC ($\mu S/cm$)	TDS (mg/L)
150	152	42	3.01	50.58	76.2	50	200	60
200	298	18	11.66	25.56	76.5	25	393	194
300	167	41	3.12	53.47	77.3	54	186	51
400	90	35	4.02	22.37	78.1	23	441	226
500	82	32	4.64	17.66	78.8	18	554	304
600	53	33	4.42	11.99	79.6	12	809	479
700	10.5	31	4.89	2.15	80.4	2.2	4,472	2,997
800	3.8	32	4.64	0.82	81.2	0.86	11,642	7,926
900	2.7	31	4.89	0.55	81.9	0.59	17,089	11,670
1,000	2.3	28	5.75	0.40	82.7	0.43	23,406	16,012

Archie (1942) also determined that the formation factor can be related to porosity by applying the following formula:

$$F = \frac{a}{\Phi^m} \quad (2)$$

Where

- m is cementation factor (dimensionless), which varies with grain size and grain-size distribution;
- a is tortuosity (dimensionless), which describes the complexity of the paths in the pores as the ratio of actual path length to straight path length; and
- Φ is porosity, which is given in percent.

Constraining the formation factor to a range from 4.5 to 5.6 (as determined from the relation of water quality to borehole resistivity) and by using the porosity determined from the well logs (Table 2), it was determined that a value of 0.75 for the tortuosity and a value of 1.6 for the cementation factor produced a fairly good fit between log-derived salinity values and water-quality values from the well samples. The values of tortuosity and cementation factor are within the range of expected values for moderately indurated limestones (Asquith and Krygowski, 2004). Substituting these values into equation 2 gives

$$F = \frac{0.75}{\Phi^{1.6}} \quad (3)$$

Using equation 3, the formation factors in the core hole can be determined by substituting porosity values into equation 3 and giving a range of values, generally from about 3 to 6

(Table 2). These log-derived formation factors correlate fairly well with the water-quality derived values, which ranged from 4.5 to 5.6. Using these values, the formation water resistivity can be determined by restating equation 1 as

$$R_w = \frac{R_o}{F} \quad (4)$$

To express R_w as specific conductance, the R_w must be first adjusted by taking into account the formation temperature (T_f). The formation temperature is linearly interpolated between the annual mean surface temperature ($AMST$) and the bottom hole temperature (BHT ; Asquith and Krygowski, 2004):

$$T_f = \left(\frac{BHT - AMST}{TD} \times FD \right) + AMST \quad (5)$$

Where

- T_f is formation temperature (degrees Fahrenheit [°F]),
- BHT is bottom hole temperature (degrees Fahrenheit),
- $AMST$ is annual mean surface temperature (degrees Fahrenheit),
- TD is total depth (feet), and
- FD is formation depth (feet).

The formation water resistivity at 77 °F (Rw_{77}) is then calculated using the Arps equation (Arps, 1953)

$$Rw_{77} = \frac{R_o(T_f + 6.77)}{77 + 6.77} \quad (6)$$

Finally, the R_w can be converted into a value of specific conductance (SC), which is measured in microsiemens per centimeter at 77 °F, using the following relation (Asquith and Krygowski, 2004)

$$SC = \frac{10,000}{R_{w77}}, \quad (7)$$

The total-dissolved solids (TDS; parts per million) of the formation water can be determined with the calculated SC values using equation 8, which describes a linear regression correlating measured TDS and SC data from Chatham County well-water samples (Fig. 3)

$$TDS = (0.6874 \times SC) - 76.901. \quad (8)$$

TDS calculations using equations 1–8 provide detailed information on salinity variations within the Floridan aquifer system. The TDS concentration at the base of the freshwater zone (605 feet) was calculated to be approximately 480 milligrams per liter (mg/L), and the concentration at the base of the transition zone (810 feet) was approximately 7,930 mg/L for this core hole (Fig. 2; Table 2).

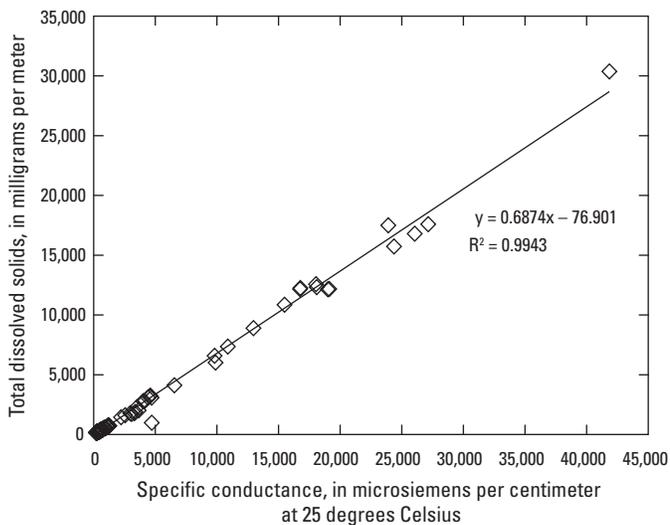


Figure 3. Correlation between total dissolved solids (TDS) and specific conductance using 139 water-quality samples from 40 wells in Chatham County, Georgia.

CONCLUSIONS

Determining salinity variations by using borehole geophysical logs can be an effective method for evaluating saline aquifers. The formation factors determined at the Fort Pulaski core hole site may be applied to similar rock types in the area. This same methodology can be applied to other geophysical log data to expand current knowledge about saline aquifers in coastal Georgia and throughout the southeastern United States.

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