Comparison of Time Domain Electromagnetic Data and Geophysical Well Logs for Hydrogeologic and Salinity Profile Interpretations

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Introduction

State-wide ground water resource management is a key responsibility of the North Carolina Division of Water Resources (DWR). Managing ground water use requires accurate information about hydrogeology. Current sources of subsurface data include borehole geologic and geophysical logs and pump tests. Because these types of data are expensive to collect, the Ground Water Branch of DWR purchased a Geonics, Ltd. Time Domain Electro-Magnetic (TDEM) survey system (model TEM58) in the Summer of 1996. This geophysical equipment allows deep sounding of subsurface resistivities. When used in collaboration with other subsurface information from boreholes, this TDEM technique is useful in delineating aquifers, confining units, and salt-water interfaces. This paper explores the Ground Water Branch's trial run of the system. Later TDEM survey results will be incorporated into aquifer framework reports written on a project basis.

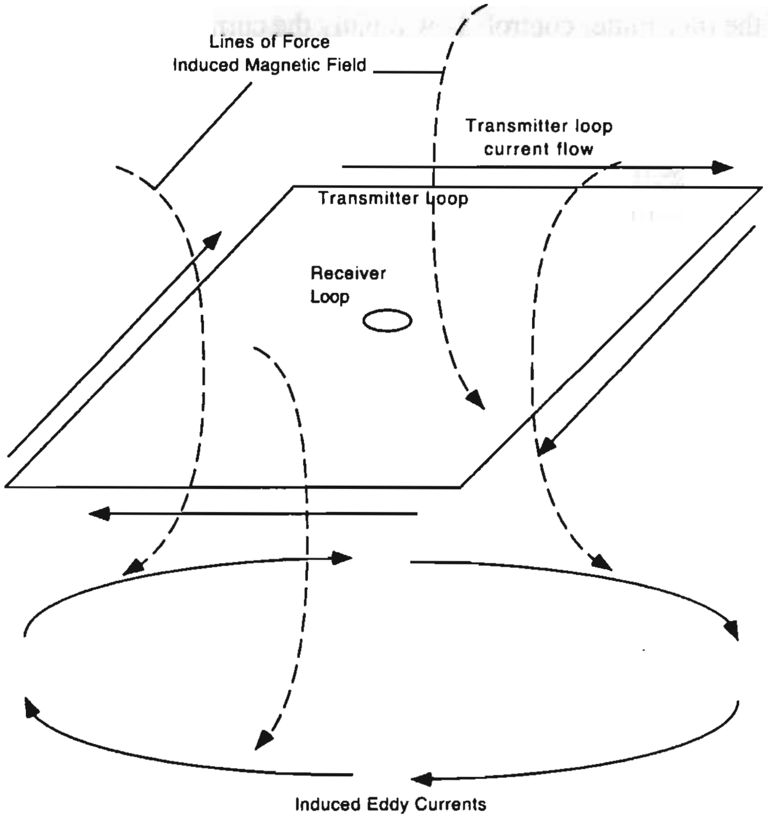
The Scuppernong Research Station in Washington County was selected for field trial of the TDEM survey system because of its location in an area of general interest in the Coastal Plain and the availability of geophysical logs, stratigraphic interpretations, and hydrogeologic data. TDEM surveys provide a resistivity-depth profile of the subsurface, based on the earth's response to an induced electromagnetic field. A geo-electric model was developed for the site, based on geophysical logs and geologic and water quality data. The geo-electric model includes the depths and resistivities of a layered sequence from the ground surface through the depth of interest. Predicted TDEM response for the geo-electric model of the site was generated using the TEMIX XL™ software package (Interpex, Ltd.), and these predicted or "forward modeling" values were compared to field data to evaluate the geo-electric model and the quality of data collected during the survey. Formation resistivities from electric logs and TDEM modeling were then used to evaluate ground water salinity at the site.

TDEM surveys will be performed in areas of interest for refinement of regional hydrogeology. TDEM surveys will provide data that can be compared with geophysical logs and water quality data to estimate the extent of aquifers and salinity trends without conventional drilling and subsurface sampling techniques. Because of the relative high cost and operational requirements for drilling, installing and maintaining wells, TDEM surveys provide a rapid, low-cost alternative for collecting data that can be used to identify potential aquifers that may be exploited, areas where geologic conditions limit the availability of ground water, and locations where salt-water intrusion and dewatering threaten existing resources.

Field Data Collection

The TDEM survey method measures the propagation of eddy currents through the subsurface. The propagation of these currents is then interpreted to provide a depth profile of resistivity. A current is passed through the TDEM transmitter loop to induce a magnetic field in the earth. Eddy currents are produced in the subsurface in response to the magnetic field. When the transmitter current is turned off, these eddy currents propagate outward and downward from the transmitter loop. During this propagation of the eddy currents, a magnetic field is generated that changes as the eddy current migrates through the subsurface, away from the transmitter coil. This field generated by the eddy currents affects the receiver coil, and is recorded by the TDEM system (Figure 1). The

Figure 1. Schematic Layout of TDEM Survey



velocity of eddy current propagation and its decay with time are both controlled by the electrical resistance of the subsurface (Spies and Frischknecht, 1988). The correlation between the eddy current behavior and the TDEM system response provides the basis for calculation of apparent resistivities from field data. Because the strength of the original signal from the TDEM system affects the output from the eddy currents, the configuration of the TDEM system must be properly input into the TEMIX XL™ software, which converts the receiver signal into an apparent resistivity values. These parameters include transmitter loop dimensions, transmitter current, receiver loop dimensions and receiver loop location with respect to the transmitter loop.

TDEM soundings were performed on state property at the DOT yard adjacent to the Scuppernong Research Station. The sounding location was selected at an open area free of features that would cause noise in the response signal, such as power lines and chain-link fences. Soundings were performed while varying the following transmitter parameters: repetition rate, integration time and delay time. All soundings were made with a 100 meter by 100 meter square transmitter coil and the receiver coil located in the center of the transmitter loop. The site location and estimated position of the 250 mg/l chloride interface in the Castle Hayne aquifer are shown on Figure 2.

The repetition rate of the transmitter controls how rapidly the current cycles are applied to the transmitter coil and the corresponding frequency of data collection by the receiver. For any given frequency setting, receiver coil current will be measured at 20 time intervals from the last cut-off of the transmitter current. These time intervals are referred to as time gates. The time gates are set to measure receiver current at optimal times for increasing depth of the eddy currents as they propagate through the subsurface. The timing of the gates is also selected to minimize ramp turn-off effects, which are artifacts in the electromagnetic field caused by the fact that the cut-off of transmitter current is not truly instantaneous, but occurs over several microseconds. The ramp turn-off time is calculated internally by the TDEM receiver based on the transmitter loop size and transmitter current. Generally, lower frequencies have time gates set with greater offset from the transmitter coil turn-off and readings are taken from eddy currents that have propagated into the deeper subsurface.

Readings were taken with the repetition rate set at frequencies of 75, 30 and 7.5 Hertz (Hz). High quality, reproducible readings were collected at each setting. However, readings from the latest seven gates at 7.5 Hz were not usable because of noise. This is because the signal strength decays as the eddy currents propagate through the subsurface. The depth of investigation can be extended

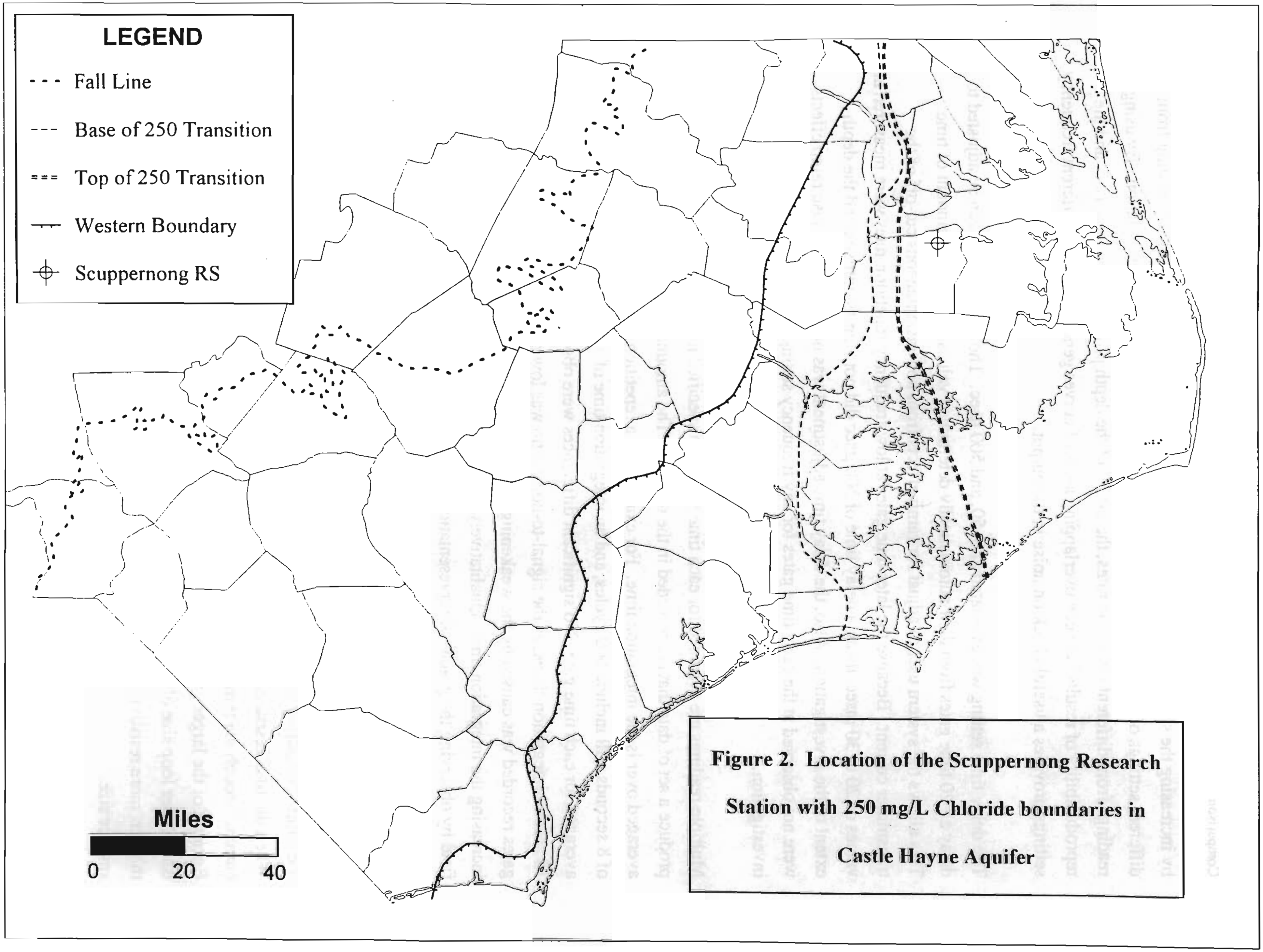


Figure 2. Location of the Scuppernong Research Station with 250 mg/L Chloride boundaries in Castle Hayne Aquifer

by increasing the size of the transmitter loop. The TEMIX XL™ software allows reading from different settings of the repetition rate to be combined in a single model interpretation. By using readings from different repetition rates, the extent of the depth profile can be increased, and the reproducibility of results between overlapping areas of curves generated by the different frequency settings provides a useful check on noise in the output.

The delay time setting was evaluated at 0, 50, and 500 µsec. The delay setting can be adjusted to delay all 20 time gates from their automatically determined values by the same amount of time. This allows the system user to adjust for ramp effects from non-instantaneous cut-off of the transmitter current. Because the later time gates at low frequency repetition rates were measured at values of 20 to 30 msec, using a delay time of 500 µsec did not significantly extend the depth extent of the investigation. Also, the delay time adjustment was not needed because ramp effects were not observed at the early time gates for any frequency setting used during the field investigation.

Multiple readings are averaged for each time gate for a specified number of transmitter cycles to produce a set of data that are recorded in the receiver. The amount of time that readings are averaged over is the integration time. For example, at a repetition rate of 75 Hz, an integration time of 8 seconds will include 600 cycles, and an integration time of 15 seconds results in 1125 values averaged for each time gate. No significant differences were observed between results over 8 and 15 second integration times, as the signal-to-noise ratio was low at the site. Noise in the latest time gates recorded was caused by the weakening of the signal strength, which is not resolved by increasing the integration time. Qualitatively, the noise level in the output can be evaluated in the field by observing the graphical representation of the output data on the liquid crystal display of the receiver unit. Using longer integration times may reduce noise in the data, but requires slightly longer time for collection of each set of observations in a data set.

An attempt was also made to collect data using a 25 meter by 25 meter transmitter loop. The transmitter would not operate because there was not sufficient resistance in the transmitter loop. When the total resistance in the transmitter loop is below a threshold value that would allow excess current through the transmitter, an automatic protection circuit keeps the transmitter from operating. Because of the larger gauge wire used in the transmitter loop in DWR's system, a minimum transmitter loop size of 50 meters by 50 meters should be used. Smaller loops can be used with a thinner, more resistive wire for the transmitter loop, or by using multiple turn transmitter loops of smaller size.

In summary, the field operation collected high-quality data without significant noise problems, except for the latest times measured. The noise at the latest time gates was caused by decreasing signal strength as the eddy currents propagated deeper into the subsurface. The favorable operating conditions did not require greater integration times or use of delay times for data collection.

Geo-electric model development

The geo-electric model of the section was developed from data of geophysical logs of wells at the Scuppernong Research Station. Because of its greater depth of investigation, the 64-inch normal (also known as long normal) log gives a more representative value of formation resistivity. This log is less affected by the effects of drilling, including mudcake development and invasion of mud filtrate into the formation. Where the total thickness of the bed is less than the electrode spacing of the logging tool, an apparent resistivity is obtained, because the tool response is affected by the resistivity of adjacent beds. For example, a fresh water bearing sand bed 3 feet thick with a true resistivity of 40 ohm-meters may have a log response somewhat less than the true resistivity, because part of the response is from adjacent beds with lower resistivity (clay beds often have resistivity values on the order of 1 to 7 ohm-meters). Also, beds with thicknesses similar to the electrode spacing of the logging tool often show "reversals" in the log response, where the reading is deflected negatively in the center of the bed, which does not correspond to the resistivity of the formation. These artifacts can sometimes be identified by comparing the normal resistivity logs with other logs, including natural gamma and self-potential logs. Individual thin beds are often not important, because they do not significantly affect the TDEM response, and are not significant components of the flow system. Evaluation of thinly interbedded sequences in development of a geo-electric model and TDEM data processing is more problematic, and will be discussed further in the discussion on comparison of predicted and actual TDEM results.

The 64-inch normal log for the Scuppernong Research Station was run on a hole that was cased to a depth of 149 feet, so this type of data was not available for the upper part of the section. A single-point resistance log was available from the land surface to a depth of 421 feet, so this data was used to define the upper layers in the geo-electric model. The single point resistance log is often used in hydrogeologic investigations because of its high resolution with respect to bed thickness; the log can accurately detect beds on the order of one foot thick.

There are several problems with using the single point resistance log to develop geo-electric models. The type of measurement is not directly comparable to other types of resistivity methods (including "normal" resistivity logs, induction logs, or surface geophysical measurements of resistivity). The single point log measures resistance between a single electrode in the tool and a reference electrode at the ground surface. Therefore the depth of investigation from the borehole wall is very shallow (usually several inches), and the response measures resistance, not resistivity (which is shown by dimensional analysis: the single point log response is measured in ohms, while normal resistivity logs provide responses measured in ohm-meters). Where low salinity mud filtrate has invaded permeable formations, the single point resistance log can be used to identify these permeable beds. However, the true resistivity, and any interpretation of formation water salinity, can not be made from the single point resistance log. Because the single point resistance log does provide information on bed thickness and a qualitative indication of hydraulic conductivity, it can be used to define layer thickness for geo-electric models, but resistivity values must be derived from other sources, including estimates from regional data on formation water salinity and lithology for the zone of interest.

At the Scuppernong Research Station, the single point resistance and 64-inch normal resistivity logs were used to develop a geo-electric model for TDEM data evaluation. The original geo-electric model is shown on Figure 3. The uppermost layer is the surficial aquifer, which was identified from the single point resistance log. The resistivity was estimated from the single point resistance value for the unit. The original estimate of resistivity was based on the greater response of the single point resistance log for this unit than for underlying fresh-water bearing units. (See the combined plot of the single point resistance and long normal resistivity logs shown on Figure 4. The initial values for the resistivity values and layer depths for the geo-electric model are listed in Table 1.)

The surficial aquifer is probably comprised of Plio-Pleistocene and Recent sandy terrace and fluvial deposits. Underlying the surficial aquifer, a layer of clay was identified from the single point resistance and self-potential logs. This unit was initially assigned a resistivity of 17 ohm-meters and a thickness of 27 feet (8.5 m). Underlying the clay bed, an interbedded sequence of sands and clays is present. Because of the interbedded nature of these deposits, they were

Figure 3. Original Geo-Electric Model for the Scuppernong Research Station

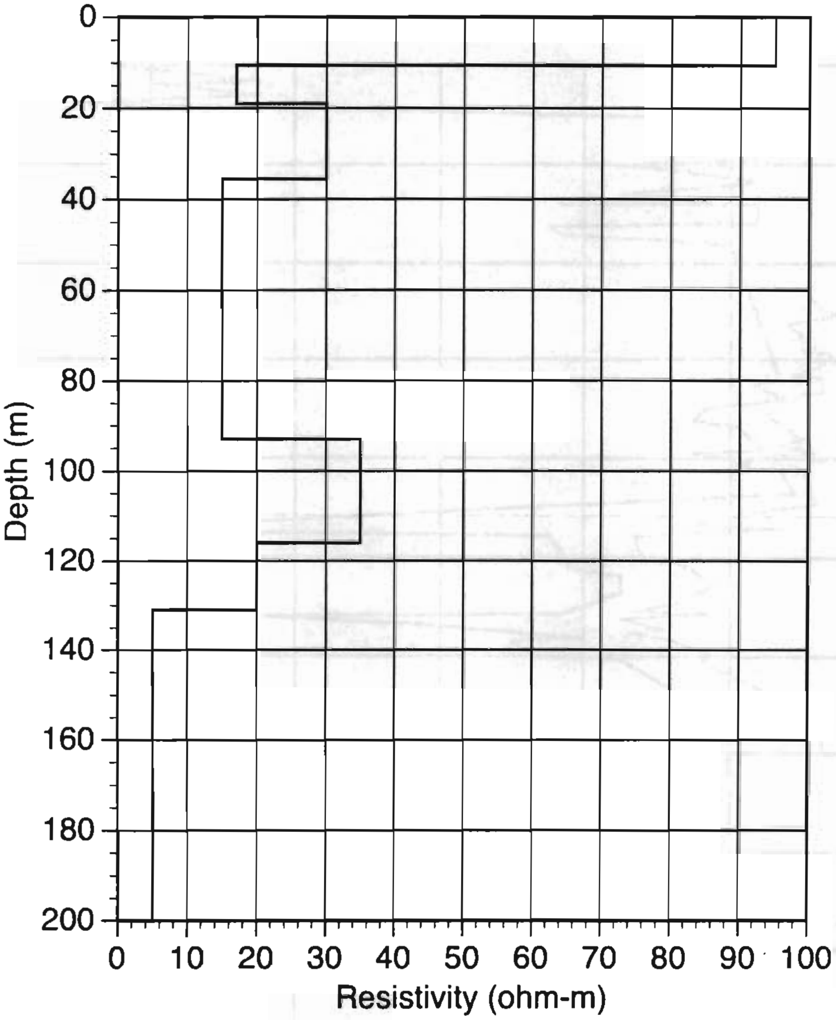


Figure 4. Combined Plot of Single Point Resistance and 64-inch Normal Geophysical Logs

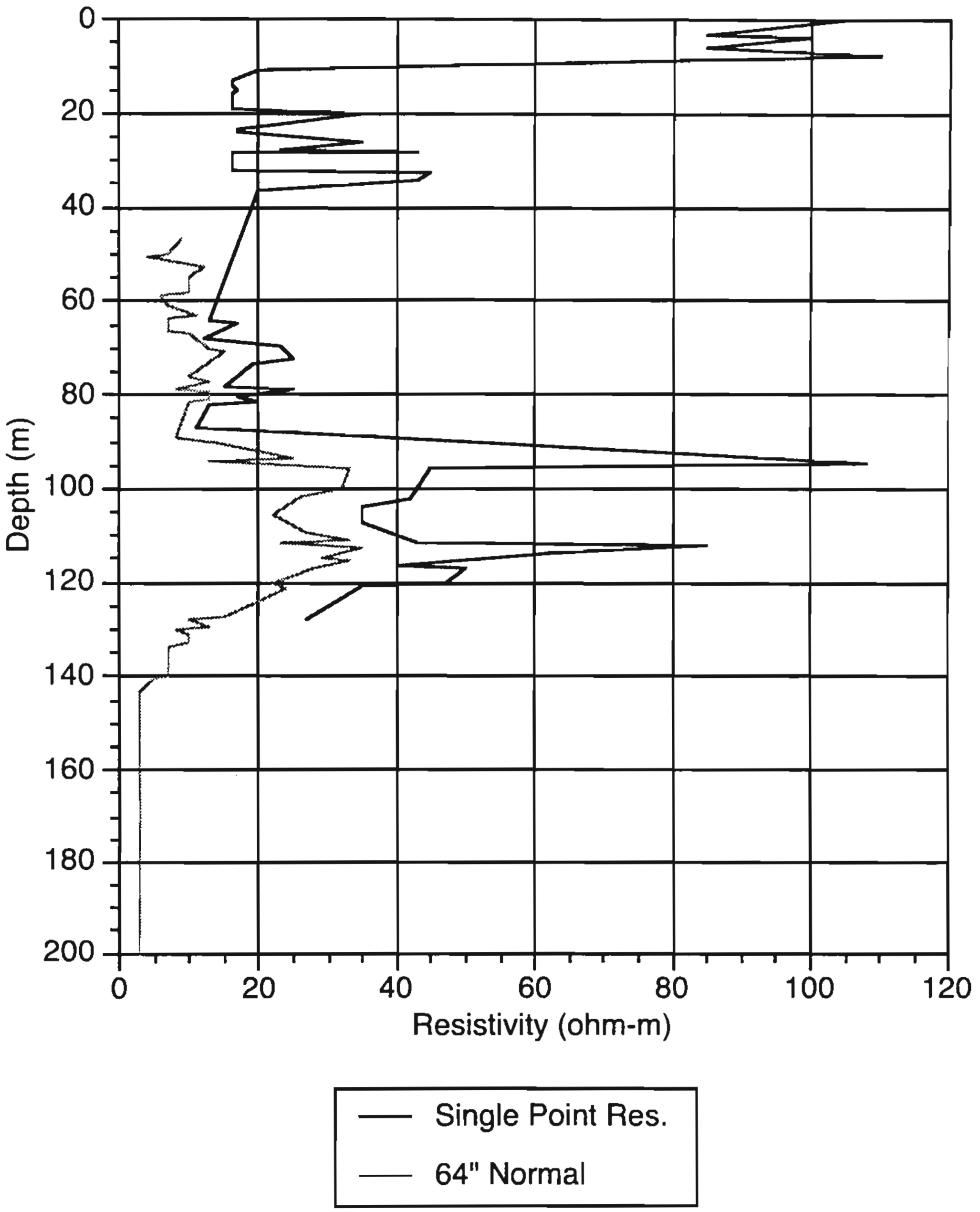


Table 1. Original Geo-electric Model Parameters

Layer Number	Resistivity (ohm-m)	Thickness (m)	Thickness (feet)	Depth Interval (m)	Depth Interval (feet)
1	95	10.5	34	0 to 10.5	0 to 34
2	17	8.5	28	10.5 to 19	34 to 62
3	30	16.5	54	19 to 35.5	62 to 116
4	15	57.5	189	35.5 to 93	116 to 305
5	35	23	75	93 to 116	305 to 380
6	20	15	50	116 to 131	380 to 430
7	5	∞	∞	>131	>430

grouped as a single layer in the initial geo-electric model, and were assigned an intermediate value of 30 ohm-meters. The resistivity for the interbedded sequence was based on a qualitative evaluation of the single point resistance log. Below this interbedded sand and clay sequence is a 189 feet thick sequence of clay deposits. Single point resistance values were used to estimate the sequence resistivity at 15 ohm-meters. This sequence probably includes Pliocene and upper Miocene deposits of the Croatan and Yorktown Formations.

Underlying the thick, low resistivity clay sequence, a relatively thick fresh-water aquifer is present, starting at a depth of 305 feet. The fresh-water bearing nature of this unit is reflected in its higher resistivity (approximately 40 ohm-meters, based on the 64-inch normal resistivity log). At a depth of approximately 380 feet, the resistivity begins to decline gradually with depth. The self-potential log does not show a corresponding decrease in porosity of the unit, however. This decline in resistivity is attributed to increasing salinity of the water in the formation with depth. Stratigraphically, this unit includes the Pungo River Formation, a phosphatic sand, and the Castle Hayne Limestone. In the geo-electric model, this sequence is represented by two layers: a layer with higher resistivity (35 ohm-meters) and a layer with intermediate resistivity (20 ohm-meters), which represents the transition to saline ground water.

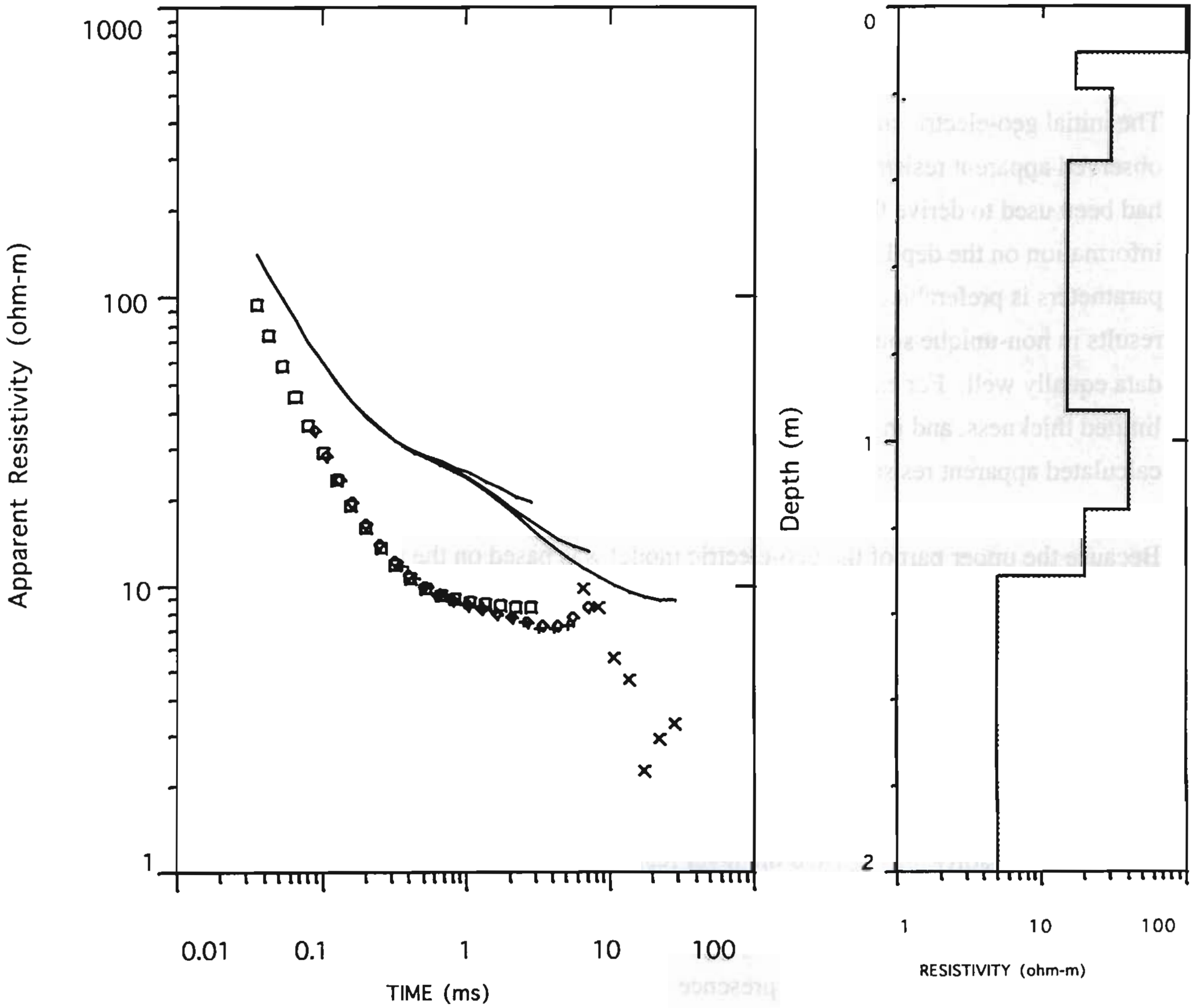
The sequence underlying the Castle Hayne is comprised of interbedded sand and clay beds. Because ground water is saline in this interval, the permeable formations have low resistivity, similar to clay beds. The geo-electric model was assigned a resistivity of 5-ohm-meters beneath the salt-water transition zone. The 64-inch normal log shows this trend, being relatively constant below a depth of 430 feet. The variations in the short normal resistivity log are due to invasion of low salinity mud filtrate into the permeable beds adjacent to the borehole wall. The TEMIX XL™ software assumes that the lowest layer of the model has infinite thickness. Therefore, the low resistivity salt-water bearing sands and clays were made the lowest layer in the model, because underlying features of different resistivity, such as bedrock, are below the depth of investigation by TDEM for the configuration used at the Scuppernong Research Station.

Comparison of Initial Geo-Electric Model Predictions and TDEM Field Data

This initial geo-electric model, derived from geophysical logs, was then used to generate predicted TDEM responses using the forward modeling feature of the TEMIX XL™ software. The predicted values based on the geo-electric model were then compared to the actual field results to evaluate the sensitivity of the survey to the features of interest (especially the depth and resistivity of fresh water bearing aquifers and the depth of transition to saline formation waters). The differences between field and predicted results were used to refine the geo-electric model and to evaluate the effects of individual parts of the stratigraphic sequence on the TDEM response.

The forward model results for TDEM profiling of the initial geo-electric model are shown on Figure 5. Notice there was a considerable discrepancy between the actual values (individual data point symbols) and the predicted model for TDEM apparent resistivity (solid line). The apparent resistivity values are the calculated interpretation of the earth's resistivity profile derived from the receiver data and from the predicted response for the geo-electric model.

Figure 5. Original Model with Output Data



While the apparent resistivity values generated by the forward model are higher than the observed values through out the time range, early and intermediate values of the predicted model are larger by up to 50 ohm-meters (note log scale of the y-axis). Because the early time values reflect the electromagnetic response from shallower depths, these results indicate that the resistivity values for the geo-electric model should be adjusted downward in the upper part of the section.

The initial geo-electric model was adjusted in an attempt to resolve the fit between the predicted and observed apparent resistivity values using the TEMIX XL™ software. Because geophysical logs had been used to derive the initial model, adjustments were made that would not conflict with log information on the depth distribution of resistivity. Having some constraints on the model parameters is preferable, because the inversion method used to calculate the apparent resistivities results in non-unique solutions. That is, different geo-electric models may fit observed TDEM data equally well. For example, one model may include a layer with very high resistivity and limited thickness, and in another model, the layer may be thicker and less resistive, resulting in a calculated apparent resistivity curve that fits the observed data equally well for both models.

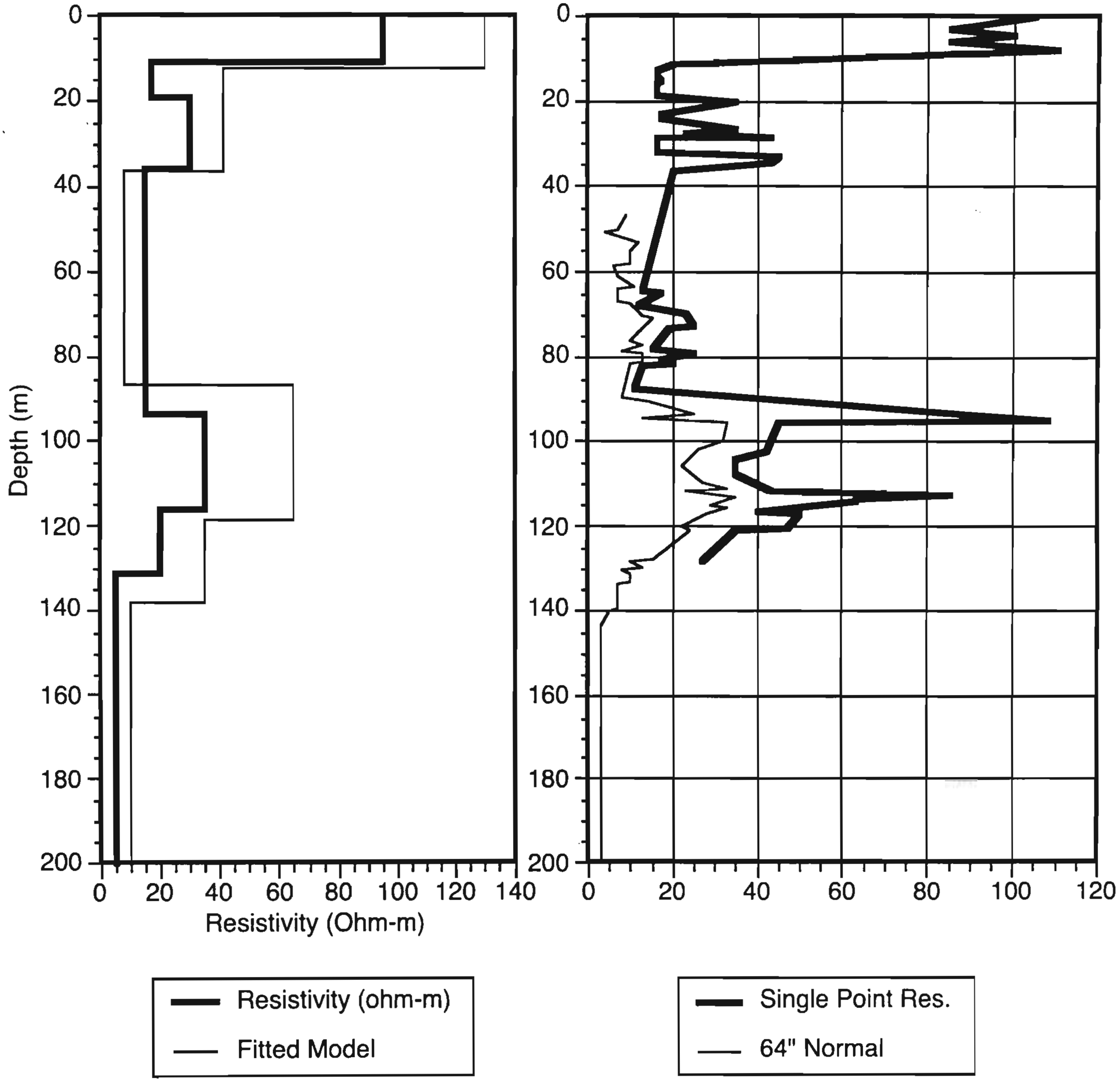
Because the upper part of the geo-electric model was based on the single point resistance log, lower confidence was placed in the resistivity values for the upper layers. Higher confidence was placed in the layer thicknesses, based on the depth resolution of the single point resistance logging tool. The adjusted model layer thicknesses and resistivities are listed in Table 2. In order to increase the fit of the geo-electric profile with the observed data, inverse modeling was performed using the TEMIX XL™ software. Because of the relative confidence in the thickness of the layers derived from the geophysical logs, these parameters were fixed in the inversion operation. Therefore, the software adjusted the layer resistivities, but not the thicknesses, to fit the predicted and observed data. The uppermost layer, representing the surficial aquifer, resistivity was increased from 95 to 130 ohm-meters. This adjustment was supported by the fact that the single point resistance log indicated the presence of some clay in the surficial aquifer, which can suppress the resistivity response on the log. The higher resistivity of the surficial aquifer reflects the low dissolved solids content of shallow ground water. However, the initial value for the surficial aquifer resistivity in the geo-electric model was nearly twice that of underlying fresh water aquifers, which were more reliably estimated from long-normal resistivity data.

Table 2. Modified Geo-electric Model Parameters

Layer Number	Resistivity (ohm-m)	Thickness (m)	Thickness (feet)	Depth Interval (m)	Depth Interval (feet)
1	130	12.25	40	0 to 12.25	0 to 40
2	41.2	24	79	12.25 to 36	40 to 119
3	8.13	50	164	36 to 86	119 to 283
4	64.5	32	105	86 to 112	283 to 388
5	32.1	20	66	112 to 131	388 to 454
6	10.8	∞	∞	>131	>454

The interbedded sand and clay sequence was originally modelled as a single layer with an intermediate resistivity of 17 ohm-meters. Closer examination of the single point resistance log revealed that the sequence includes thinly bedded (2 to 4 feet thick) sands, with interbedded clay at depths from 62 to 92 feet. Because of the limited thickness of these sand beds and their lower response on the single point resistance logs, the true resistivity of this sequence may have been underestimated on the log. The sand bed from 100 to 115 feet in depth had a larger response on the single point resistance log, reflecting its greater thickness and probably, its lower clay content. Therefore, this inversion solution of the field data yielded a resistivity of 41.2 ohm-meters for this sequence. The underlying clay sequence was represented in the inversion solution as having a resistivity of 8.13 ohm-meters, which is only slightly higher than the value derived from the 64-inch normal log response. The upper and lower Castle Hayne aquifer resistivities were derived at 64.5 and 32.1 ohm-meters, respectively. These values are higher than the geophysical log response, which may have been suppressed by the salinity of the borehole fluid during logging.

Figure 6. Geo-electric Models and Geophysical Logs



The inversion model solution resulted in a total error of 4.4 percent for the model (see Table 3 for output data and error values). This error does not include the last seven points of field data, which were "masked" or excluded from the model fit to reduce their contribution to the total error. The variance of these latest values from the model is shown by their high individual error values. The revised model with synthetic and actual values for apparent resistivity are plotted on Figure 7.

Interpretation of Water Salinity Trends

From a hydrogeologic standpoint, one of the primary goals of earth resistivity profiling is the evaluation of ground water salinity. Formation resistivity is controlled by the resistivity of pore fluids. Because dissolved solids in aqueous solutions act as electrolytes, resistivity measurements can be used to evaluate ground water salinity. The relationships between the structure of porous media, formation resistivity and fluid resistivity were determined by early workers in borehole geophysics (Archie, 1950). The correlation between fluid and formation resistivity is expressed by the Archie Equation:

$$R_t = \frac{R_w}{P^m}$$

where: R_t = formation resistivity
R_w = water resistivity
P = porosity
m = void distribution coefficient (also known as cementation factor)

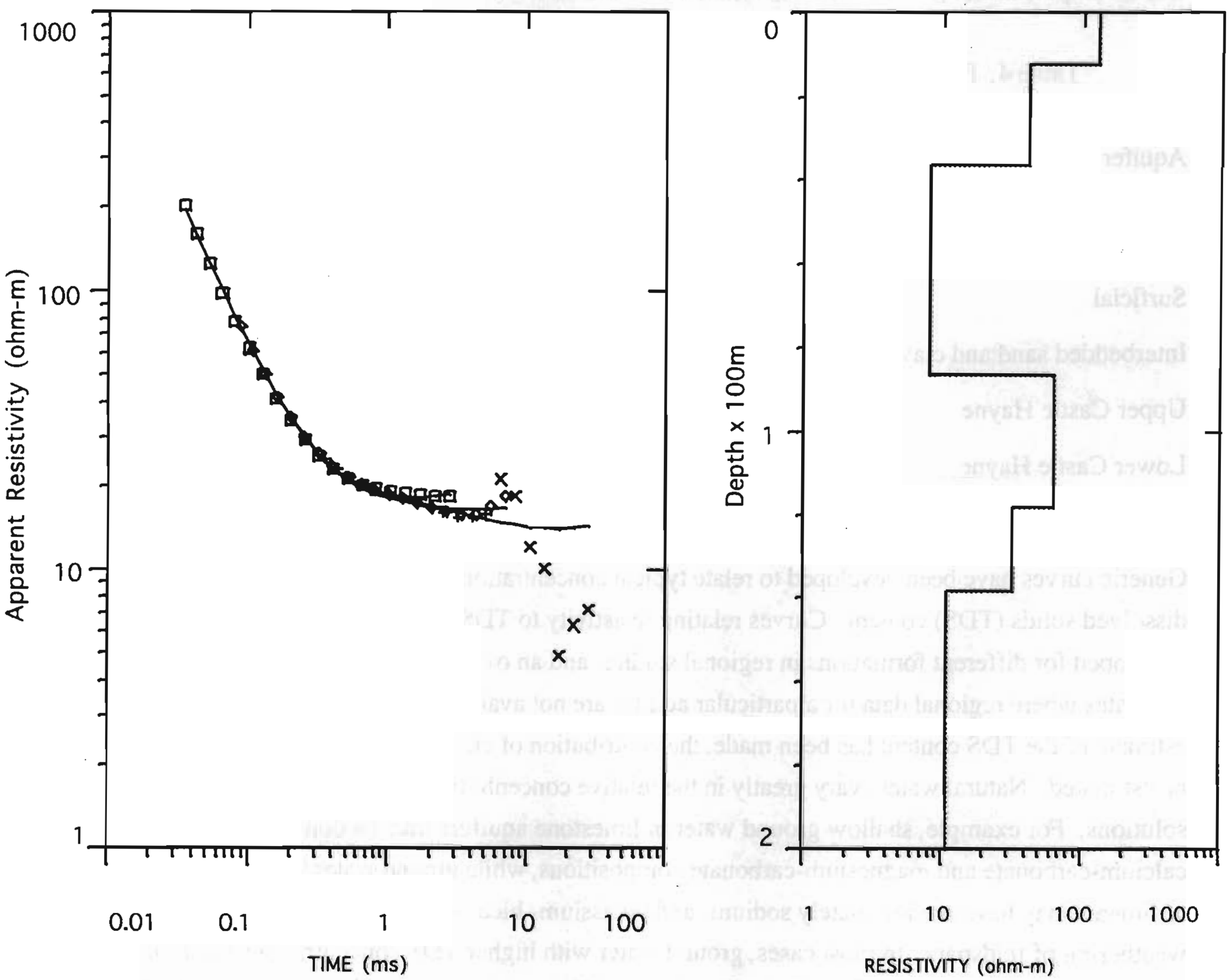
Porosity is the volume percent of void space in the formation, and the void distribution coefficient is an exponential factor that represents the effectiveness of the connections of pore spaces. For granular porous media based on ideal geometric relationships (e.g., cubic packing of spheres) this factor can be calculated, but for geologic materials, it is derived for different formations by analyzing samples for all other variables in the equation. In practice, laboratory data are used to develop regional averages of P and m values for different aquifers (Nelson, 1994).

Using the Archie equation, the water resistivity of subsurface units can be estimated from formation resistivity. Based on lithology of the units and regional data for similar units from the

Table 3. Example Field Data and Revised Model Output

Data Point	Time (msec)	Observed (nV/m^2)	Calculated (nV/m^2)	Difference (percent)	Frequency (Hz)
1	0.0352	82485	87554	-6.14	75
2	0.0427	73320	74600	-1.74	75
3	0.0525	63291	62509	1.23	75
4	0.0647	53637	51723	3.56	75
5	0.0802	44318	42135	4.92	75
6	0.100	35595	33595	5.61	75
7	0.125	27792	26258	5.52	75
8	0.158	21094	20038	5.00	75
9	0.199	15470	14840	4.06	75
10	0.252	10959	10624	3.06	75
11	0.319	7444	7302	1.90	75
12	0.405	4840	4814	0.547	75
13	0.514	3012	3041	-0.966	75
14	0.654	1797	1848	-2.82	75
15	0.832	1037	1083	-4.44	75
16	1.05	585	617	-5.49	75
17	1.34	327	343	-4.86	75
18	1.71	181	187	-3.61	75
19	2.19	100	101	-0.43	75
20	2.79	55.3	53.6	3.21	75
21	0.0881	37523	38424	-2.4	30
22	0.106	31335	31442	-0.985	30
23	0.131	24945	25053	-0.432	30
24	0.161	19499	19530	-0.159	30
25	0.200	14767	14800	-0.244	30
26	0.25	10730	10783	-0.496	30
27	0.314	7479	7549	-0.928	30
28	0.395	4994	5071	-1.54	30
29	0.499	3188	3263	-2.35	30
30	0.631	1961	2025	-3.25	30
31	0.799	1166	1214	-4.15	30
32	1.01	680	708	-4.15	30
33	1.28	393	406	-3.31	30
34	1.63	226	229	-1.28	30
35	2.08	131	128	2.00	30
36	2.64	75.9	72.0	5.17	30
37	3.37	43.2	40.0	7.36	30
38	4.29	23.4	21.9	5.9	30
39	5.47	11.5	11.9	-4.09	30
40	6.97	5.56	6.41	-15.2	30

Figure 7. Revised Model and Output



Gulf Coastal Plain, estimates were made for the porosity and cementation factors to calculate water resistivities for aquifers at the Scuppernong Research Station (Jones and Buford, 1951). The parameter estimates and calculated water resistivities and inferred water composition are listed in Table 4.

The concentrations and types of ions determine the electrical conductivity of a solution. Different ionic species have different contributions to solution electrical conductivity (Drever, 1982). For example, water containing 500 mg/l sodium chloride has a resistivity of 10 ohm-meters, while a solution of 500 mg/l sodium bicarbonate has a resistivity of 22 ohm-meters. Therefore, the relative concentrations of different dissolved solids must be considered in any attempt to infer water composition (e.g. chloride content) from water resistivity.

Table 4. Formation Parameters, Water Resistivity and Compositional Estimates

Aquifer	Formation Resistivity (ohm-m)	Porosity	Cementation Factor	Water Resistivity (ohm-m)	Total Dissolved Solids (mg/l)	Chloride (mg/l)
Surficial	130	0.30	1.2	30.7	193	41
Interbedded sand and clay	41.2	0.30	1.4	7.6	801	251
Upper Castle Hayne	64.5	0.32	1.9	7.4	827	265
Lower Castle Hayne	32.1	0.30	1.9	3.3	1,917	972

Generic curves have been developed to relate typical concentrations of natural waters to their total dissolved solids (TDS) content. Curves relating resistivity to TDS content and have been developed for different formations in regional studies, and an overall average curve can be used for estimates where regional data for a particular aquifer are not available (see Figure 8). Once an estimate of the TDS content has been made, the contribution of chloride to the TDS value can also be estimated. Natural waters vary greatly in the relative concentration of different ions in dilute solutions. For example, shallow ground water in limestone aquifers may be dominated by calcium-carbonate and magnesium-carbonate compositions, while ground water in clastic sediments may have predominately sodium- and potassium- bicarbonate ions produced by weathering of feldspars. In most cases, ground water with higher TDS concentrations is similar to sea water, and the relative contribution of sodium and chloride ions to TDS can be estimated with more confidence. The general curve relating chloride to TDS concentrations is shown in Figure 9. These general concentration relationships were used to derive the chloride estimates for the aquifers listed in Table 4.

Figure 8. Water Resistivity vs. TDS Concentration for Typical Ground Waters

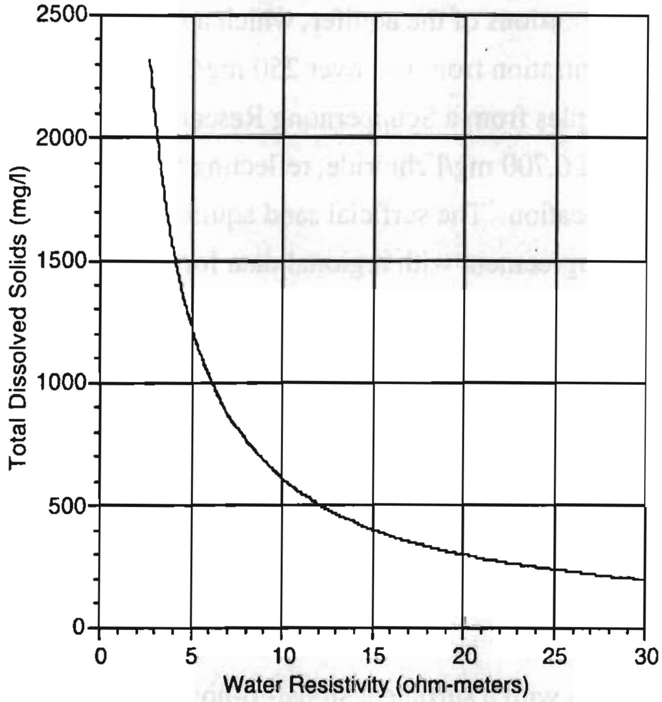
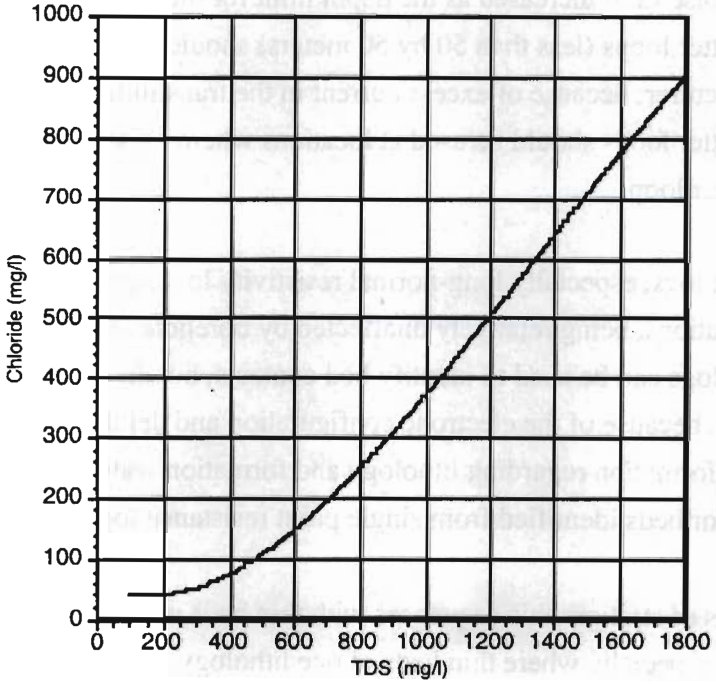


Figure 9. Chloride vs. TDS Concentrations for Typical Ground Waters



The estimated chloride concentrations agree fairly well with regional water quality information. Regional trends show the Scuppernong Research Station is located east of the 250 mg/l chloride interface for the upper and lower portions of the aquifer, which agrees with the calculated values, with an increasing chloride concentration from just over 250 mg/l to nearly 1,000 mg/l in the Castle Hayne aquifer. Water samples from a Scuppernong Research Station well screened at a depth of 547 to 577 feet contained 6,700 mg/l chloride, reflecting the increasing chloride concentration with depth at this location. The surficial sand aquifer has calculated chloride values below 250 mg/l, which is also in agreement with regional data for shallow aquifers in the area.

Conclusions

Based on the results obtained at the Scuppernong Research Station and comparison with geophysical logs, the following conclusions can be made about TDEM investigation of the site and the use of the method to evaluate salt-water intrusion and aquifer delineation in the North Carolina Coastal Plain:

1. TDEM surveys provide data with a sufficient signal-to-noise ratio for interpreting geo-electric sections to depths of hundreds of meters in the Coastal Plain, especially where sources of artificial electromagnetic noise are not present, and where a sufficient transmitter loop size is used. Varying the integration time and delay times for TDEM setup did not significantly affect the survey results. The signal-to-noise ratio increased as the depth limit for the survey configuration was reached. Small transmitter loops (less than 50 by 50 meters) should not be used with the wire provided by the manufacturer, because of excess current in the transmitter. A more resistive wire or multiple turn transmitter loops should be used at locations where only a small area is accessible for placing the transmitter loop.

2. Geophysical well logs, especially long-normal resistivity logs, give accurate values for the resistivity of thick formations, being relatively unaffected by borehole and drilling fluid effects. Single-point resistance logs can be used to identify bed contacts, but do not provide good values for formation resistivity, because of the electrode configuration and depth of investigation from the borehole wall. Other information regarding lithology and formation water salinity must be used to infer resistivity values for beds identified from single point resistance logs.

3. TDEM soundings of stratigraphic sequences with thin beds may not reflect the presence of the thin bed lithologies, especially where thin beds of one lithology are present in a relatively thick

sequence dominated by another lithology. For example, the sequence of clayey sediments underlying the surficial aquifer contained thin sandy beds that did not significantly affect TDEM response in that interval.

4. TDEM surveys provide sufficient resolution and sensitivity for identification of fresh water and salt water bearing permeable units, especially where the dissolved solids content can be related to the resistivity of the formation water for a given aquifer or stratigraphic sequence. As regional water quality data are compiled for each aquifer, more precise correlations between water resistivity and chemical composition can be made in the future.

5. TDEM surveys can be conducted to provide additional data on the extent of aquifers and salt-water intrusion in the Coastal Plain. Existing data from wells and geophysical logs can be supplemented by TDEM surveys at locations between existing data locations. TDEM surveys will be performed in the North Albemarle and Capacity Use Area #1 studies being conducted by DWR in order to increase the confidence in aquifer correlations, to identify interfaces between salt and fresh water and to refine parameters for numerical modeling of flow systems. Where aquifer correlations are problematic, and where significant changes occur in the subsurface salinity profile, TDEM soundings will be performed to help delineate these changes in subsurface conditions. TDEM surveys will also provide additional data in ares where existing monitoring locations are widely spaced. Because data can be collected relatively rapidly (up to 6 locations per day) TDEM can be used to interpret hydrogeologic conditions at a significant number of locations in a relatively short time, and at less expense than conventional geologic sampling techniques. Additional testing of setup parameters and survey configurations will also be carried out to assure that the soundings are optimized for collection of high quality data for the hydrogeologic settings being evaluated.

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Equipment

Geonics Limited, TEM58 time domain electromagnetic survey system includes the PROTEM digital receiver and low-frequency receiver coil, transmitter and 300*300 meter transmitter loop, and 20 Amp generator

Interpex Limited, TEMIX XL™ ver. 4, Transient Electromagnetic Data Interpretation Software

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