ground water

Geophysical Monitoring and Evaluation of Coastal Plain Aquifers

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Abstract

We use time domain electromagnetic (TDEM) soundings to monitor ground water conditions beneath the coastal plain in eastern North Carolina. The TDEM method measures the earth's response to an induced electromagnetic field. The resulting signal is converted, through a complex inversion process, to apparent resistivity values, which can be directly correlated to borehole resistivity logs. TDEM soundings are used to map the interface between fresh and salt water within coastal aquifers, and estimate depth to basement when siting new monitoring wells. Focused TDEM surveys have identified areas of salt water encroachment caused by high volumes of discharge from local supply wells. Electromagnetic sounding, when used in tandem with the state's network of monitoring wells, is an accurate and inexpensive tool for evaluating fresh water/salt water relationships on both local and regional scales within coastal plain aquifers.

Introduction

Background

Ground water is the principal source of fresh water for communities in the central coastal plain of North Carolina, and a steadily increasing demand for this finite resource has resulted in declining water levels, salt water encroachment, dewatering, and land subsidence in some areas of the coastal plain. To prevent future water supply shortages and damage to aquifers, 15 counties have been designated by the state as the Central Coastal Plain Capacity Use Area (CCPCUA) (Figure 1). Within the CCPCUA, the North Carolina Division of Water Resources (NC-DWR) will regulate ground water withdrawals in excess of 100,000 gpd, and the more heavily used Cretaceous aquifers will be subject to phased reductions of withdrawals over a 16-year period (Division of Water Resources 1998).

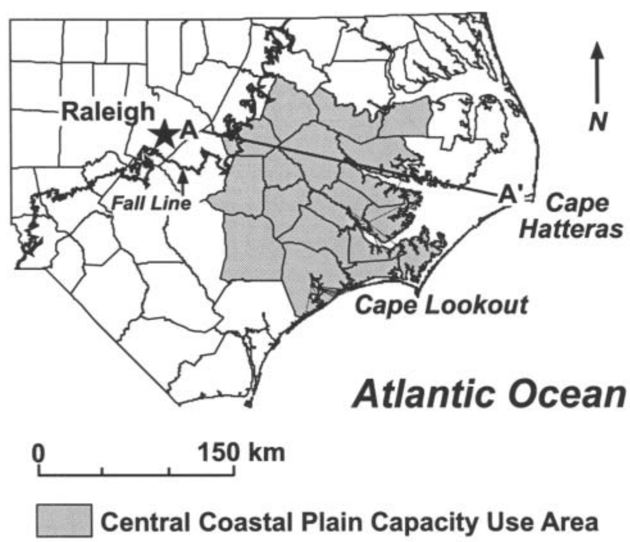

Figure 1. Regional map of eastern North Carolina, showing Central Coastal Plain Capacity Use Area (gray shading). Section A-A′ corresponds to cross section in Figure 4.

To manage more efficiently North Carolina's water resources, NC-DWR maintains a network of ground water research stations, 65 of which are located in the eastern counties of the state within the CCPCUA. Each research

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Received July 2002, accepted March 2003.

station consists of one to several monitoring wells, which are screened in one or more of the eight principal coastal plain aquifers (Figure 2). Baseline data on water levels are collected on a quarterly basis at each research station, and chloride content is periodically measured to determine the extent of salt water encroachment within individual aquifers. Chloride data from the monitoring well network are also used to map fresh water/salt water interfaces for the major aquifers of the region (Figure 3). For mapping purposes, the landward edge of a fresh water/salt water interface is defined where the 250 ppm chloride boundary intersects the base of an aquifer; the seaward edge occurs where the 250 ppm boundary intersects the top of the aquifer. Because of the limited number and irregular distribution of observation wells, however, the position of the fresh water/salt water interface in the various hydrostratigraphic units is not well constrained. Since 1996, NC-DWR personnel have conducted a systematic program of surface geophysical surveys of coastal plain aquifers using the time domain electromagnetic (TDEM) method (Strum 1997; Land and Lautier 2001). TDEM soundings are used in conjunction with borehole geophysical records to more precisely define the position of the transition zones within individual coastal plain aquifers. By October 2002, 155 TDEM soundings had been conducted within the CCPCUA. For comparison, NC-DWR collects data from a total of 253 monitoring wells at the 65 research stations within the central coastal plain.

Hydrologic Setting

The coastal plain of North Carolina makes up ~45% of the state, extending from the eastern edge of the Piedmont to the Atlantic Ocean (Figure 1). Elevations range from sea level to ~35 m at the Fall Line, where coastal plain sediments pinch out against igneous and metamorphic rocks of the Piedmont province. The inner coastal plain has a gently rolling land surface, in contrast to the low-relief Tidewater region, which consists of swamp forests, pocosins, and broad, shallow sounds and estuaries (Reynolds 1992; Reynolds and Spruill 1995; Winner and Coble 1996). Outcrop is scarce in this subdued terrain, making subsurface information essential for characterizing the regional geology.

An eastward-thickening wedge of Cretaceous through Cenozoic sediments overlying pre-Cretaceous crystalline

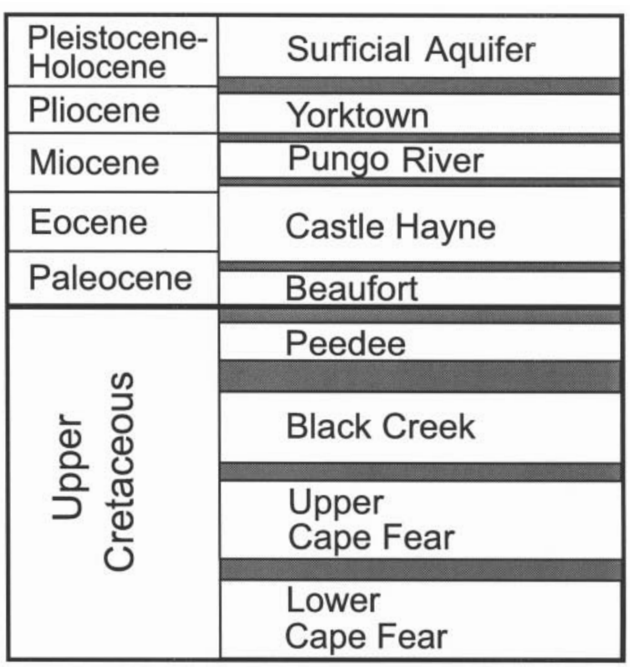

Figure 2. Hydrostratigraphic column for eastern North Carolina. In this and subsequent figures, coastal plain aquifers are represented by a white background; gray shading indicates regional confining beds. The Castle Hayne Aquifer is a vuggy to cavernous limestone. The other aquifers indicated are predominantly siliciclastic units, although carbonate content in the Peedee and younger formations may vary significantly across the study area.

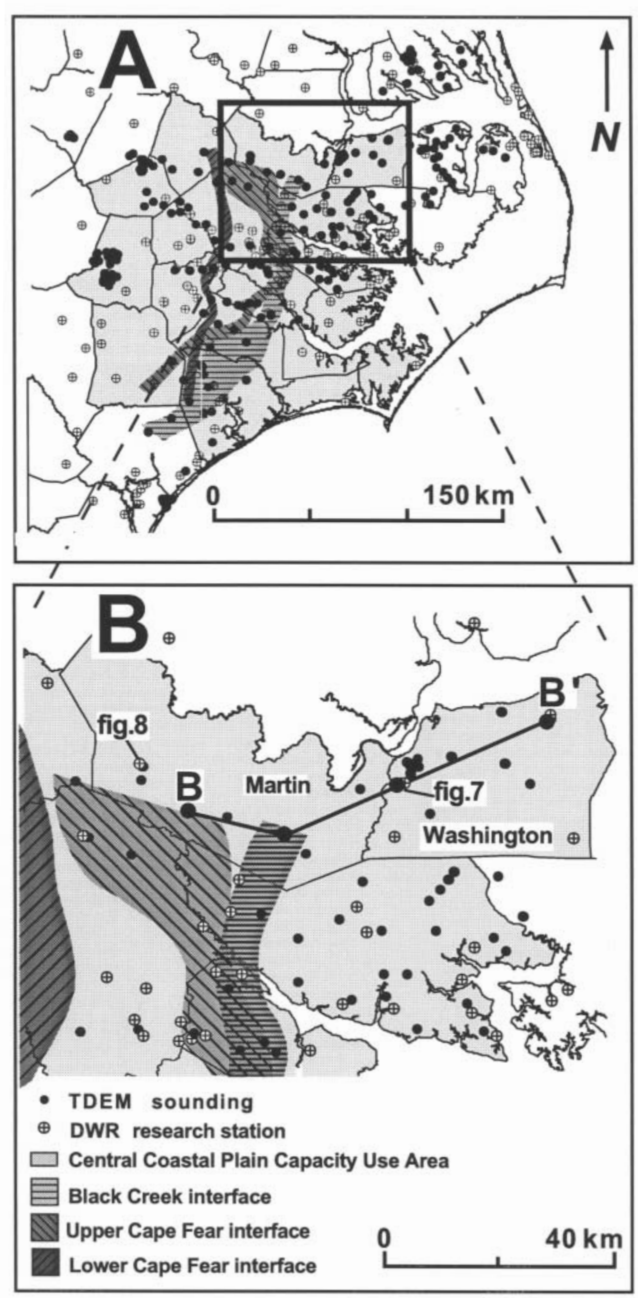

Figure 3. (a) Map of central coastal plain of North Carolina showing fresh water/salt water interfaces for the three principal Cretaceous aquifers, and locations of NC-DWR research stations (crosshair circles) and TDEM soundings (filled circles). (b) Detail of Figure 4a showing locations of research stations at Plymouth (Figure 7) and Gold Point (Figure 8).

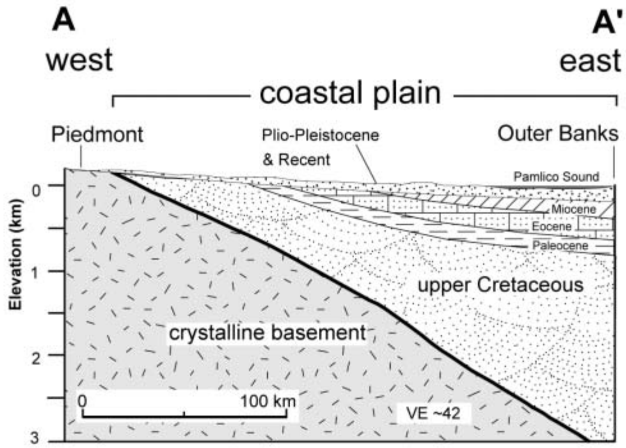

Figure 4. Diagrammatic cross section A-A′ showing eastward-dipping wedge of coastal plain sediments overlying pre-Cretaceous igneous and metamorphic basement rock. Location of A-A′ is shown in Figure 1 (after Reynolds and Spruill 1995).

basement (Figure 4) underlies eastern North Carolina. The sedimentary section ranges in thickness from a feather edge at the Fall Line to ~3000 m beneath Cape Hatteras, within which are contained some of the most productive and regionally extensive aquifers in the state (Figure 2). The older and deeper part of the section consists of predominantly nonmarine and transitional siliciclastic sediments, whereas younger strata are more marine in character, with a greater proportion of carbonates. Although locally heterogeneous, the coastal plain aquifers behave on a regional scale as continuous hydrologic units extending for hundreds of square kilometers. Individual aquifers have distinct water quality parameters, and hydraulic heads that change significantly across regional confining beds (Winner and Coble 1996; Lautier 1998).

The coastal plain wedge of sediments was deposited during repeated cycles of transgression and regression associated with opening of the Atlantic Ocean. During sea level highstands, the strata would have been charged to varying degrees with salt water, with chloride concentrations of ~19,000 ppm, equivalent to sea water salinities. As sea level declined, aquifers beneath the coastal plain were flushed with fresh water (in this report, fresh water is defined by the Environmental Protection Agency secondary standard as having chloride concentrations less than 250 ppm). The rate of flushing would depend on the amount of fresh water flowing through the system. A surficial aquifer subject to regular recharge by rainfall would require only a year or two for complete flushing to occur, whereas the same process might require several thousand years for a deep, confined aquifer (Winner and Coble 1996).

Because flushing is such a slow process in confined aquifers, it is likely that the boundary between fresh and salt water is not in equilibrium (Meisler et al. 1984). Multiple transgressive-regressive cycles have resulted in a complex transition zone beneath the coastal plain that may be quite broad, both vertically (tens to hundreds of meters) and laterally (several kilometers). The seaward extent of fresh water is unique to each aquifer and depends on several factors, including (1) thickness and hydraulic properties of individual aquifers and their overlying confining beds, (2) hydraulic gradients, and (3) the rate and location of ground water recharge (Winner and Coble 1996; Lautier 2002). In addition, internal heterogeneities will cause significant variations in the width and position of the fresh water/salt water interface for a given hydrologic unit (Figure 3a). For example, in those areas where an aquifer contains a high percentage of permeable material, fresh water can more efficiently displace salt water as it flows downgradient, resulting in a broad interface that projects farther toward the coast than in areas where aquifer transmissivity is lower.

Methods

Electrical Survey Methods

Transient, or TDEM, sounding belongs to a class of surface geophysical procedures that use induced electric currents and electromagnetic fields to characterize subsurface conditions. Electrical conductivity is an intrinsic property of the chemistry of ground water, so electrical surveying methods are well suited for studying fresh water/salt water relationships in coastal aquifers. When analyzing the results of an electrical or electromagnetic survey, it is common practice to assume an empirical relationship between the resistivity of pore waters and total dissolved solids, allowing distinctions to be made between fresh, brackish, and saline zones within an aquifer (Mills et al. 1988; Ebraheem et al. 1997).

Surface geophysical techniques for measuring electrochemical properties of subsurface fluids fall into the two broad categories of electrical and electromagnetic methods. The principal difference between the two procedures lies in the manner of driving current flow (Fetter 1994). Electrical resistivity surveys directly introduce an electrical current into the ground by means of implanted metal electrodes (Williams and Belaval 2001). Electromagnetic methods, on the other hand, introduce electrical currents into the subsurface with an induced electromagnetic field (Stewart and Gay 1986; Mills et al. 1988). The TDEM method, as employed in this investigation, measures subsurface conductivity variations in the Z-direction, and the final product of a TDEM sounding (after processing) is a vertical profile of bulk resistivity vs. depth.

TDEM Sounding

During a TDEM survey, a primary electromagnetic field is generated by a loop of transmitter cable laid on the ground, through which alternating current is passed with equal periods of time-on and time-off, at frequencies usually ranging from 3 to 75 Hz. The transmitted waveform that results is a bipolar square wave with a 50% duty cycle (a positive square current pulse, followed by a time-off period of equal duration, followed by a negative current pulse of the same duration). A receiver located near the center of the transmitter loop only makes measurements during the time-off period. Termination of the current is not instantaneous, but occurs over a very brief period of time (a few microseconds) known as the ramp time, during which the electromagnetic field is time-variant. In accordance with Faraday's law (Halliday and Resnick 1974), this abrupt change in the primary field will create an electromagnetic induction, or voltage pulse, in the earth beneath the loop, which in turn generates eddy current flow in the subsurface. Because of finite ground resistivity, the eddy current immediately begins to decay, in the process creating an additional voltage pulse, and associated eddy current flow, at greater depth. As the process continues, the result is a series of eddy currents that propagate downward and outward into the subsurface beneath the transmitter loop (Figure 5) (McNeill 1994). The intensity of the eddy currents at specific times and depths is determined by the bulk conductivity of subsurface rock units and their contained fluids. Depth of investigation depends on the time interval after shutoff of the primary current, because later the receiver is sensing eddy currents at progressively greater depths (Mills et al. 1988; Goldman et al. 1991; McNeill 1994).

A typical onshore TDEM survey consists of a Geonics Ltd. Protem 57-D™ transmitter powered by a portable gasoline generator, connected to a square loop of single-turn, ungrounded, insulated cable 50 to 300 m on a side (Figure 5). Signal strength of the transmitter is proportional to the product of transmitter loop area and loop current, so exploration depth can be increased by increasing the size of the transmitter loop (Stewart and Gay 1986). A multi-turn air coil 1 m in diameter located inside the loop serves as a receiver antenna, and is connected by a short length of cable to a Protem digital receiver. The receiver and transmitter communicate with each other through a longer reference cable that links the two devices. This widely used configuration is known as a central loop array (McNeill 1994).

The receiver measures the amplitude of current flow with time by measuring the decaying magnetic field generated by the eddy currents. Field measurements consist of readings of voltage output (in nanovolts/m^2) recorded at 20 discrete time intervals, or time gates, ranging from a few μs

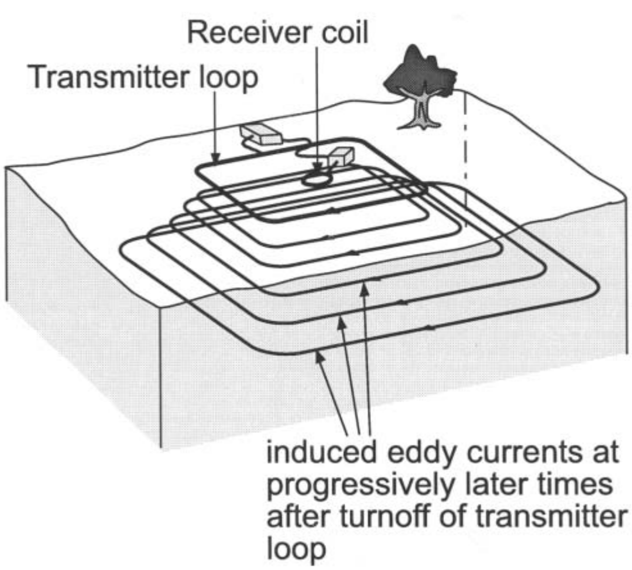

Figure 5. Cartoon showing TDEM central loop array. Size of the transmitter loop ranges from 50 to 300 m on a side, depending on desired depth of investigation.

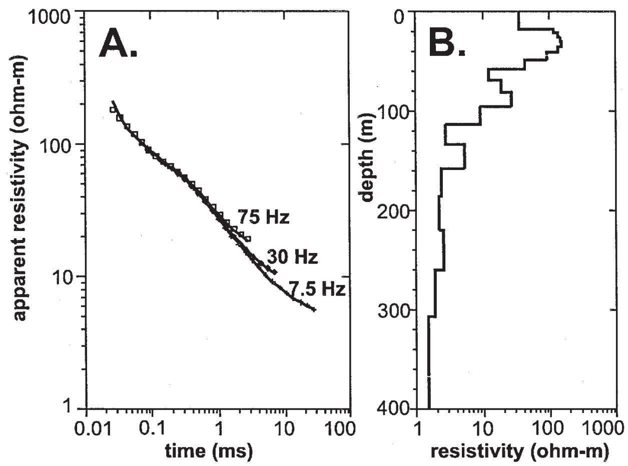

Figure 6. (a) Example of apparent resistivity vs. time, measured at 20 time gates after transmitter shutoff. Lines are synthetic curve fits to resistivity values at three different frequencies (75, 30, and 7.5 Hz). (b) Model of resistivity vs. depth generated by TEMIX XL smooth modeling procedure.

to a few hundreds of ms after transmitter current is turned off, depending on the desired depth of investigation. Several hundred transient decay measurements are commonly made during a single sounding, and measurements are stacked to improve signal to noise ratio (Strum 1997). A geoelectric section is derived during processing whereby the raw data are converted, through a complex inversion process, from voltage as a function of time to apparent resistivity (ohm-m) vs. depth, using TEMIX XL™ software (Interpex Ltd. 1996) (Figure 6). A one-dimensional model is used during processing, based on the assumption that within the survey area any lateral variations in resistivity are small relative to vertical changes in geoelectrical properties (Stewart and Gay 1986; Mills et al. 1988). The software allows the user to specify minimum and maximum depths, and a maximum of 19 layers for a specific model.

It should be noted that the resulting resistivity profile is not unique, but will vary depending on the choice of depth range and number of layers, as well as the frequencies selected for the inversion process. Informed choices for these parameters, and an accurate profile, require a thorough understanding of the regional geology and hydrostratigraphy. A geoelectric section based on inversion of TDEM data without such geologic context will be of little value.

The TEMIX XL software can combine up to three different frequency soundings into a single inversion (Figure 6) (Strum 1997). A TDEM sounding at a specific site may consist of as many as five separate runs, at frequencies of 75, 30, 7.5, 3, and 0.75 Hz. Inversions based on lower-frequency runs have greater depth of investigation—sometimes as deep as 500 m, depending on the level of electromagnetic noise in the survey area. The resulting TDEM profile tends to be somewhat generalized, with rather subdued resistivity variations, but is often useful in estimating depth to high resistivity crystalline basement rock. Inversion results based on the three highest frequencies provide better resolution at shallow depths, and are most useful for defining the position of the fresh water/salt water interface within an aquifer. At high frequencies, the minimum bed thickness that can be resolved is ~15 m, depending in part on the maximum depth and number of layers selected during data processing.

Transient electromagnetic sounding has several advantages over frequency domain methods and DC resistivity surveys, including better vertical resolution and lower sensitivity to noise, to variations in surface topography, and to dipping strata effects. A sounding consisting of five frequency runs can be completed in two hours or less, depending on field conditions and size of the transmitter loop, with data quality comparable to that of most borehole resistivity logs. TDEM is the only electrical/electromagnetic survey method that allows for transmitter-receiver spacing substantially less than the depth of investigation; thus soundings can be spaced closer together, effectively increasing lateral resolution of a survey (Mills et al. 1988). Because measurements of the decaying magnetic field are made only during the transmitter's time-off period—that is, in the absence of a primary field—the TDEM method is not very sensitive to location of the receiver coil, or to variations in transmitter-receiver geometry (Goldman et al. 1991; McNeill 1994). Accuracy of the TDEM method appears to be limited at shallower depths (<50 m) due to interference from the transmitter shutoff ramp at early times. At greater depths, accuracy is limited only by transmitter power and background noise (Stewart and Gay 1986).

It is important to understand that a TDEM sounding is responding to the bulk resistivity of an entire rock unit, and thus provides information about both formation lithology, e.g., clay content and porosity, and contained fluids (fresh vs. salt water) (Mills et al. 1988). Nonunique solutions are inevitable, and interpretation of data collected in areas of complex stratigraphy can be somewhat challenging. The predictive value of TDEM soundings is thus greatly enhanced when they are calibrated with nearby borehole records.

Results and Discussion

Although TDEM soundings have been made throughout the coastal plain and eastern Piedmont region of North Carolina, specific examples that follow are from the northern portion of the CCPCUA, in Washington and Martin counties (Figure 3). Rural communities in this part of the state rely almost exclusively on ground water for their water supply; however, prior to 2001, hydrologic investigations in these two counties were hindered by a lack of subsurface information. NC-DWR had no monitoring wells at all in Martin County, and operated only four widely spaced research stations in Washington County. Regional hydrologic maps (Lautier 2002) indicate that the fresh water/salt water interfaces for three major aquifers extend into this area (Figure 3b), but their location and geometry are unclear.

Comparison of Borehole and TDEM Resistivity

Formation resistivity values interpreted from a TDEM sounding are often site-specific—that is, absolute values of resistivity for a given aquifer may vary between two sites in different parts of the coastal plain, although chloride concentrations may be the same at both sites. Such discrepancies undoubtedly reflect differences in the pore water composition of total dissolved solids other than chlorides, and can be resolved by calibrating the TDEM data with borehole records. TDEM soundings are conducted within 1 km of existing research stations wherever possible, allowing correlation of apparent resistivity profiles with borehole geophysical logs and chloride measurements. TDEM surveys can then be extrapolated to other parts of the coastal plain between research stations.

For obvious reasons, the emphasis of this phase of the fieldwork has been on collecting data near those research stations where resistivity logs were run (surprisingly, resistivity logs are available for only a small fraction of monitoring wells in the well network). One such sounding was made in western Washington County ~1 km west of the NC-DWR Plymouth Research Station. The pilot hole for the Plymouth Station penetrated all of the principal coastal plain aquifers, and was logged with 64-inch normal resistivity tools from 38 m to a total depth of 458 m. Chloride measurements are available for most of the aquifers, either from stem tests conducted during drilling of the initial pilot hole, or from samples taken from screened intervals in monitoring wells subsequently installed at the site.

The TDEM resistivity sounding shows good correlation with the borehole resistivity log at the Plymouth Station (Figure 7). Absolute values of resistivity display significant variations, a phenomenon also reported by previous workers (Mills et al. 1988). The sequence and thickness of layers, however, and the relative values of high and low resistivity, are consistent between the two records. For example, the near-surface high resistivity zone (>100 ohm-m) on the TDEM profile, indicative of fresh water in the shallower aquifers, coincides with a thick high resistivity zone on the borehole record. Both profiles also display uniformly low resistivity at greater depths, primarily due to saline ground water conditions.

Chloride data also correlate well with TDEM measurements. Two observation wells at the Plymouth Station are screened at different intervals in the Castle Hayne Limestone, the principal source of fresh water in western Washington County. A chloride value of 28 ppm was measured from the shallower screen, set near the top of the Castle Hayne Aquifer, and coincides with TDEM resistivities >100 ohm-m (Figure 7). Chloride values of 250 ppm were measured from a deeper screened interval near the base of the aquifer. The TDEM record from the deeper zone shows resistivities of 25 ohm-m (borehole resistivities from the same interval are 22 to 26 ohm-m). The deeper screen appears to be set in a vertical transition zone from fresh to salt water. Additional TDEM surveys in the Plymouth area indicate that upconing of salt water may be occurring due to excessive withdrawals from local supply wells, most of which are screened near the base of the Castle Hayne Aquifer.

In the underlying Beaufort Sand, a stem test sample yielded chloride values of 1710 ppm. TDEM resistivity from this interval is 7 ohm-m, corresponding to borehole resistivity measurements of ~6 to 11 ohm-m. Below 126 m, both TDEM and borehole logs show resistivity values <5 ohm-m, consistent with measured chloride concentrations in excess of 5000 ppm in the deeper Cretaceous aquifers.

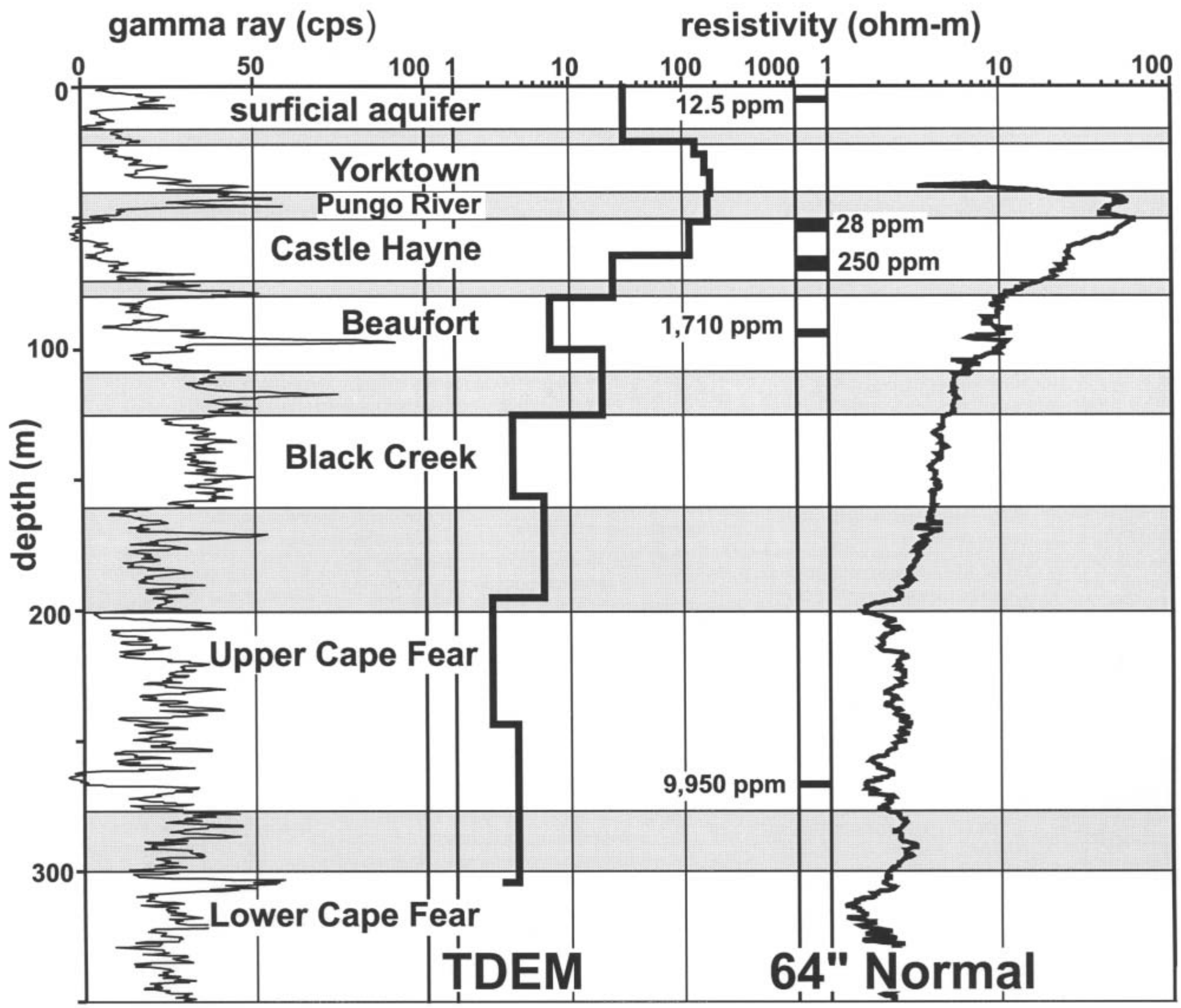

Figure 7. Gamma ray log (left) and 64-inch normal borehole resistivity log (right) measured in pilot hole at the Plymouth Research Station, Washington County, North Carolina (location in Figure 4b). The TDEM sounding (center) was taken ~1 km west of the research station. In this and subsequent figures, black bars adjacent to resistivity profiles show screened intervals from which water samples were collected in research station monitoring wells. Numbers next to bars are measured chloride values, in ppm. Gray shading indicates confining units.

The presence of dispersed or interbedded clay will suppress the bulk resistivity of an aquifer, as indicated by the Black Creek section from ~120 to 160 m depth (Figure 7). The relatively high gamma ray count in this interval reflects the clay-rich character of the Black Creek Aquifer in western Washington County. Low resistivity measurements on both the TDEM sounding and borehole resistivity log represent the combined effects of clay content and high salinity conditions within the Black Creek Aquifer at this station.

TDEM as a Predictive Tool

In early 2002, NC-DWR installed its first research station in Martin County, near the town of Gold Point. The pilot hole penetrated the entire sedimentary section, and was drilled and logged to crystalline basement. The Gold Point Station is ~15 km from the nearest deep borehole, and depth to basement for this portion of the coastal plain is known only in a general sense. Projected total depth for the pilot hole was therefore based on a TDEM sounding conducted adjacent to the proposed well site prior to drilling (Figure 8). Depth to basement was estimated to be ~194 m, based on an increase in resistivity at the bottom of the TDEM profile. The pilot hole was subsequently drilled to 196 m total depth, where bit refusal occurred in crystalline bedrock at the base of the Lower Cape Fear Aquifer. TDEM soundings have since been used to accurately predict depth to basement within 2 m at two additional research stations drilled in the central coastal plain.

Prior to drilling the Gold Point wells, TDEM surveys in Martin County and regional hydrologic maps (Lautier 2002) indicated the research station should lie within the fresh water/salt water interface for the Upper Cape Fear Aquifer (Figure 3b). The borehole resistivity log from Gold Point, which dips below 10 ohm-m over a relatively short interval (130 to 140 m) near the base of the Upper Cape Fear, and maintains low resistivity values to total depth (Figure 8), confirms the mapped position of the interface. TDEM resistivity measurements at Gold Point also decline to <10 ohm-m below 138 m. Based on previous investigations (Lautier 1998, 2002), we have determined that 10

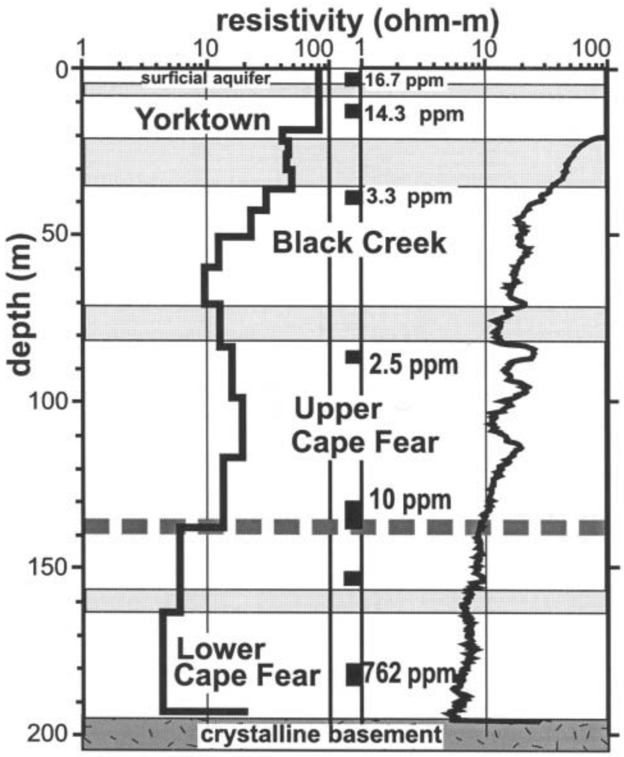

Figure 8. A 64-inch normal borehole resistivity log (right) from Gold Point Research Station pilot hole, Martin County, North Carolina, and TDEM resistivity sounding (left) measured ~100 m south of the research station (location in figure 4B). Heavy dashed line is the fresh water/salt water interface for the Upper Cape Fear Aquifer. Black bars indicate screened intervals, while gray shading indicates confining units.

ohm-m resistivity on a TDEM record is empirically significant in estimating the position of the 250 ppm chlorides boundary within the Cretaceous aquifers. The borehole log demonstrates that the Gold Point pilot hole intersected the fresh water/salt water interface ~20 m above the base of the Upper Cape Fear Aquifer, as predicted by TDEM sounding. Chloride measurements support both sets of resistivity data, showing fresh water (<10 ppm) in the upper portion of the Upper Cape Fear Aquifer and chloride values of 762 ppm in the Lower Cape Fear (Figure 8).

Regional Hydrology

A west-east, dip-parallel TDEM transect (Figure 9) illustrates regional hydrologic and hydrostratigraphic variations within the Cretaceous-Tertiary section beneath the coastal plain. Most prominent are a high resistivity near-surface interval, indicative of fresh water; and a generally low resistivity section at greater depths due to high salinity conditions (note that the TDEM records above ~50 m are less precise due to transmitter interference during data collection). Salinity of ground water is usually the predominant influence on TDEM resistivity measurements (Goldman et al. 1991), thus TDEM records do not always lend themselves well to lithostratigraphic correlation. In the shallower part of a TDEM profile, however, distinctions can often be made between high resistivity, fresh water aquifers and low-resistivity clays in the intervening confining beds. For example, a thick, well-developed confining unit between the Yorktown and Castle Hayne aquifers is readily apparent on the east end of the geoelectric section (Figure 9) because of resistivity contrasts between the fresh water aquifers and clays. Similar variations in resistivity accentuate the Black Creek confining unit on the west end of the transect. By contrast, any hydrostratigraphic detail is almost completely masked in the deeper portion of the section, where low-resistivity, highly saline aquifers are difficult to distinguish from intervening clays.

Fresh water/salt water transition zones are shown on the cross section by vertical and lateral variations in resistivity within individual aquifers (Figure 9). High resistivity values (>100 ohm-m) in the shallow portion of a TDEM sounding reflect near-surface fresh water conditions. TDEM resistivity measurements of ~1 to 5 ohm-m indicate the presence of more saline water (>250 ppm chloride concentration). Interpretation of intermediate resistivity measurements (10 to 100 ohm-m) is more equivocal and site-specific. In Washington County, such intermediate resistivities are inferred to represent a transition zone from fresh to salt water conditions. A fresh water/salt water transition in the Castle Hayne Aquifer is clearly indicated on the geoelectric section (easternmost two soundings on B-B′), an interpretation supported by chloride data from monitoring wells. A similar transition zone is indicated farther west in both the Black Creek and Upper Cape Fear aquifers. Generalizations based on absolute values of resistivity from TDEM soundings, however, must be applied with caution. For example, the Black Creek monitoring well at Gold Point Research Station tested fresh water (3.3 ppm chlorides) from an interval with only 32 ohm-m TDEM resistivity (Figure 8), demonstrating that TDEM sounding is most effective when the data can be calibrated with water samples from monitoring wells in the region being surveyed.

Summary

TDEM surveys provide an efficient, inexpensive, and semi-quantitative method of evaluating ground water resources in coastal aquifers, at fairly high vertical resolution, to depths of several hundred meters, on both local and regional scales. Apart from routine maintenance, labor is the only real cost involved in conducting a TDEM sounding, after the initial investment in equipment and software. In addition, TDEM sites can be easily revisited to determine if significant changes in the local hydrologic system have occurred over time. This aspect of the TDEM method has yet to be evaluated in a systematic manner, and should be included in the next phase of investigations of the hydrology of North Carolina's coastal plain.

The relationship between TDEM resistivity and chloride content is summarized in the next section and in Table 1, with the following disclaimer: interpretation of TDEM records would be relatively straightforward if the coastal plain aquifer system consisted of alternating beds of pure quartz sand separated by confining units composed of 100% clay. In reality, the coastal plain stratigraphic section consists of a complex blend of several lithologies; that is, heterogeneous sand and limestone aquifers containing highly variable amounts of both dispersed and interbedded clays, separated

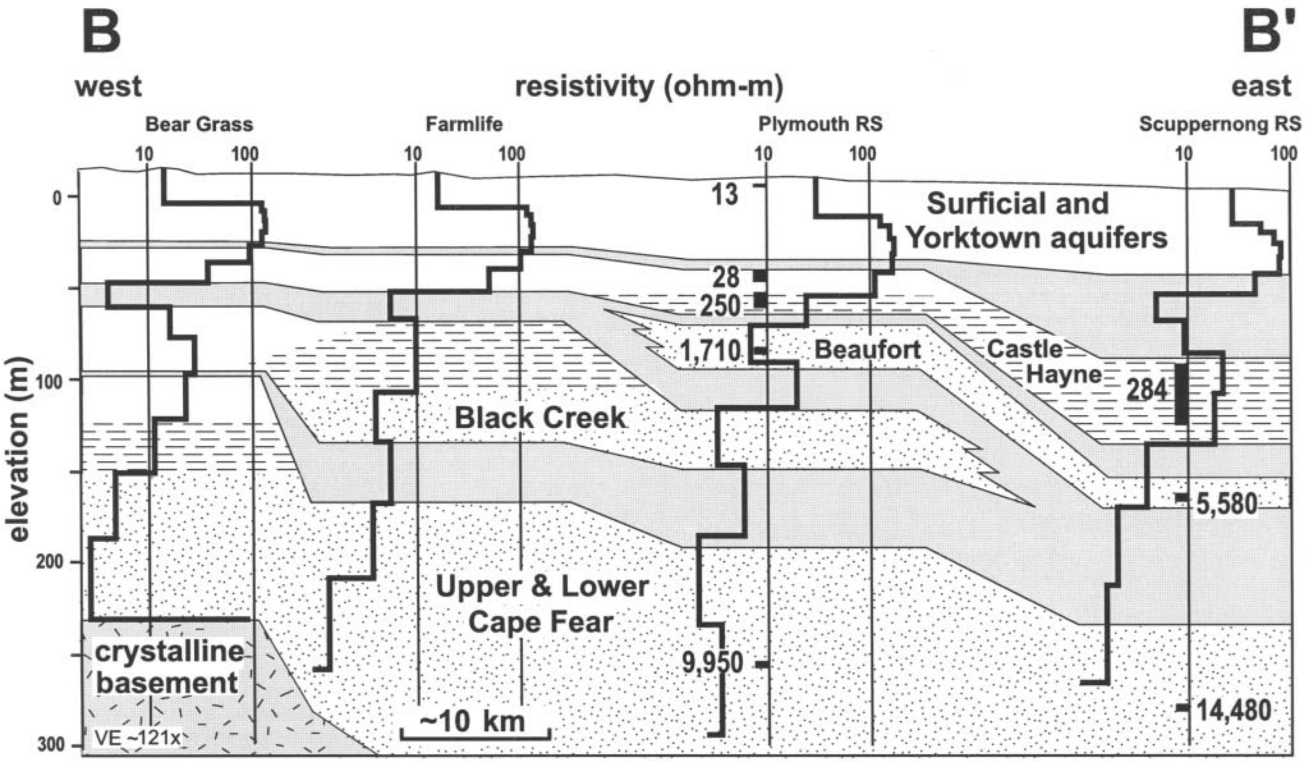

Figure 9. West-east TDEM transect across Martin and Washington counties, showing variations in apparent resistivity vs. elevation (sea level datum). Location of B-B′ is shown in Figure 4b. Horizontal scale (ohm-m) for individual profiles is logarithmic. The two easternmost TDEM soundings were taken within 1 km of NC-DWR research station monitoring wells. Black bars indicate screened intervals, while gray shading indicates confining units. Numbers next to bars are measured chloride values (ppm). Coastal plain aquifers are shown in white, gray shading shows regional confining beds. Stipple pattern represents saline ground water conditions (>1000 ppm chlorides). Horizontal dashed pattern shows inferred fresh water/salt water transition zones.

by sandy clay confining beds. Both clay and saline pore fluids will suppress the bulk resistivity of an aquifer, and unknitting the two signals is one of the more challenging aspects of interpreting data from a TDEM sounding. This problem is best resolved by calibrating TDEM data with logs and water samples from nearby boreholes, combined with a thorough understanding of the local and regional hydrostratigraphic setting.

Summary of TDEM Survey Method

(1) High resistivity values at relatively shallow depths consistently indicate the presence of fresh water in surficial and near-surface aquifers. (2) Resistivities significantly <10 ohm-m generally indicate the presence of saline formation fluids (chloride values >250 ppm). (3) An increase in resistivity at the bottom of a TDEM profile may signify crystalline basement rock. In areas where the deeper aquifers are saline, the contrast between low resistivity, salt water-saturated sands overlying high resistivity crystalline bedrock is very obvious. Tight (low porosity) sands or the presence of hydrocarbons could also cause high resistivity values at depth, but we have not found unequivocal evidence of these phenomena in our investigations. (4) The presence of clay complicates the interpretation of intermediate resistivity values on a TDEM sounding, because clay suppresses the bulk resistivity of an aquifer in ways that are difficult to quantify; thus, a fresh water zone containing a high percentage of dispersed or interbedded clays will have a lower apparent resistivity than a clean sand or limestone aquifer. (5) The presence of dissolved solids other than chlorides will influence TDEM resistivity measurements, particularly in limestone aquifers such as Castle Hayne. (6) The vertical transition from fresh to salty conditions may not be abrupt, but can occur over a fairly broad depth range of several meters to tens of meters. TDEM resistivity within a transition zone may range from ~10 to 100 ohm-m, depending on chloride concentration, clay content, porosity, and the presence of other dissolved solids. (7) Absolute values of TDEM resistivity are often site-specific. Generalizations about relationships between resistivity, chloride content, and total dissolved solids must thus be carefully applied, particularly when comparing TDEM

Table 1
Relationship Between TDEM Resistivity Measurements and Chloride Concentrations in Siliclastic Aquifers and Tertiary Carbonate Aquifers (Caste Hayne Limestone)

	Siliciclastic (ohm-m)	Carbonate (ohm-m)
Fresh water (<250 ppm chlorides)	>10	>100
Brackish water (250–500 ppm)	7–10	10–100
Saline water (>500 ppm)	1–7	<10
Clay	7–10	7–10

Resistivities will vary depending on the volume of dispersed or interbedded clays that occur within the aquifer.

soundings that are more than a few km apart. (8) A TDEM sounding used alone will not provide the same degree of vertical resolution as a borehole record; however, a much higher effective level of precision can be attained when TDEM measurements are integrated with existing borehole data, thereby significantly increasing the density of subsurface information in a given area. (9) As with any geophysical method, TDEM records must be analyzed in context. In areas of complex stratigraphy and hydrology characteristic of coastal plain aquifers, a thorough understanding of the regional hydrogeologic framework is essential to interpret effectively TDEM data.

Acknowledgments

The North Carolina Division of Water Resources, Department of Environment and Natural Resources provided funding for this work. Jeffrey Walker, Blake Rouse, Chris Kimbro, Danny Jones, and Greg Rudolph provided assistance in the field and logistical support for data collection. The authors wish to thank Dr. Walter Borowski, Eastern Kentucky University, for his critical review of the paper. The paper also benefited from comments by Robert Sterrett and two anonymous reviewers.

Editor's Note: The use of brand names in peer-reviewed papers is for identification purposes only and does not constitute endorsement by the authors, their employees, or the National Ground Water Association.

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