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Saltwater intrusion into the freshwater aquifer in the eastern shore of Virginia: a reconnaissance electrical resistivity survey

Ali A. Nowroozi *, Stephen B. Horrocks, Peter Henderson

Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, VA 23529-0496, USA

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Abstract

Contrasts between apparent high resistivity of the saturated freshwater zones and apparent low resistivity of the saturated saltwater zone are recorded on 111 Schlumberger sounding field curves. The field measurements are inverted to subsurface layers. Generally, resistivity decreases with depth from the high value of the unsaturated zone near the surface to the low values of the saltwater saturated zone at depth of 30 to 130 m. Contour maps are constructed for variations of resistivity at depths of 3, 5, 10, 20, 30, 40, 50, 60, 70, 100 and 130 m. Resistivity contours of less than 30 Ω m, are indicated at depths of 5–20 m near the narrow bands of Chesapeake Bay and the Atlantic Ocean in the coastal regions of Accomack County. Within the area covered by the cities of Onancock, Accomac, and Wachapreaque, low-resistivity contours of less than 30 Ω m are observed from 30 to 60 m depth. In 70 to 130 m depth range, a major part of Accomack County is covered by low-resistivity contours of 10 to 30 Ω m which connect the Chesapeake Bay to the Atlantic Ocean. Vertical profiles of the contour maps indicate the shape of the saltwater plumes. The interface appears to be as shallow as 30 m where intrusion has occurred, and extends downward to a depth of 130 m where the saltwater of the Atlantic ocean and Chesapeake Bay are connected.

Keywords: Intrusion of saltwater; Freshwater aquifers; Resistivity survey; Eastern shore; Delmarva Peninsula

1. Introduction

There are no running streams in the Eastern Shore of Virginia; therefore, water needed for the economic development of this area is drawn from the groundwater aquifers. More than 15 million gal per day of water are exploited from these sources, (Horsley Witten Hegemann, 1992). In the coastal areas, withdrawal of a large volume of groundwater may allow saltwater intrusion into the freshwater aquifers. This potential saltwater contamination poses a threat to the sustainable development and economic well being of the Eastern Shore. Measurements from water quality research stations indicate that in several areas the salt/freshwater interface is relatively shallow and water withdrawals are from depths close to the salt/freshwater

* Corresponding author. Department of Geological Sciences, Old Dominion University, Norfolk, VA 23529-0496, USA. Fax: +1-804-683-5194; E-mail: anowrooz@odu.edu

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interface. An excessive level of water withdrawal from these regions may cause intrusion of saltwater into freshwater aquifers (Fennema and Newton, 1982). Furthermore, ground water modeling by Richardson (1992) indicates that, based on certain simulation parameters, some saltwater contamination in a few areas of the Eastern Shore are possible. In addition, the Ground Water Supply Protection and Management Plan for the Eastern Shore of Virginia (Horsley Witten Hegemann, 1992) recommended further study to quantify the limits of salinity (e.g., greater than 250 mg chloride per liter) for this area. This information is essential for water allocations and establishment of the limitations that may be required to be set on water withdrawals from some regions.

The large differences between the resistivity of saltwater saturated zones and the freshwater saturated zones have been used by a number of investigators for determination of saltwater intrusion in many coastal areas(Van Dam and Meulenkamp, 1967; De Breuk and De Moor, 1969; Zohdy, 1969; Sabet, 1975; Respond, 1990; Ginsberg and Levanton, 1976; Urish and Frohlich, 1990; and Frohlich et al., 1994) In addition, Goodell (1986) and Flanzenbaum (1986) used electromagnetic methods to determine saltwater intrusion into a freshwater aquifer in the Eastern Shore and Southeastern Virginia.

Van Dam and Meulenkamp (1967) determined salinity of ground water in the western part of the Netherlands using the resistivity method. Their interpreted resistivities were closely related to the salinity of groundwater. In some areas the estimated depth of the interface was checked by subsequent drilling; errors up to 15% or more were encountered in areas of insufficient data on resistivity, geology or hydrogeology. They consider 40, 12, and 3 Ω m as fresh, brackish, and saline water, respectively. Zohdy (1969) used the resistivity method to show that the static water table was at a depth of about 300 ft in El Paso, TX, while the salt/freshwater interface varied from this depth to about 1700 ft. In the New England coastal zone, Frohlich et al. (1994) reported that a layer with resistivity of 230 Ω m or less is indicative of saltwater pollution in the freshwater lenses.

Sabet (1975) estimated a range of 20 Ω m to several hundred ohm meters for the resistivity of clean sand and gravel (not containing silt or shale) which is saturated with freshwater in southeastern region of Virginia and the northern part of North Carolina. He also reported that the resistivity of the same sand containing silt, clay or brackish water is much lower and concluded that freshwater is unlikely to be produced from horizons of resistivity less than 10 Ω m. Furthermore, he reported that the resistivity of freshwater-bearing horizons (water containing less than 1000 mg/l of dissolved solids) varies between 19 and 25 Ω m, but that the resistivity determined by electrical soundings is not necessarily the same as that obtained from sampling wells.

2. Regional geology

The Eastern Shore of Virginia consists of Northampton and Accomack Counties. In the east, a series of salt marshes and barrier islands separate the region from the Atlantic Ocean, and in the west are pocket beaches and shallow tidal creeks of the Chesapeake Bay. This area is approximately 70 miles long and 6 to 10 miles wide trending approximately N–S; it is nearly flat with the maximum elevation of about 50 ft in Accomack and about 40 ft in Northampton County. The soil consists of 8 to 10 in. of sandy loam topsoil and 30 in. of sandy clay soil. The regional geology has been discussed extensively by Cushing et al. (1973), Robbins et al. (1975), Shideler et al. (1984), Mixon (1985), Coleman and Mixon (1988), Coleman et al. (1990), Foyle and Oertel (1992), and Foyle (1994). The Eastern Shore geology consists of sediments dipping northeast with a thickness of 3000 ft in the west of the Peninsula. The thickness of layers increases to about 7500 ft in the east of the Peninsula (Meng and Harsh, 1988). The sedimentary layers overlie a hard-rock basement that also dips northeast. The sediments have a complicated depositional history (Foyle, 1994) and vary in age from Early Cretaceous to recent. Robbins et al. (1975) estimated that about 70% of the sediments is from Early to Late Cretaceous age deposited in a fluvial environment. In addition, about 30% of the sediments are of Tertiary age deposited in a marine environment (Cushing et al., 1985). Mixon (1985) concluded that the Tertiary sediments are overlain by a veneer of Quaternary sediments deposited in several different environments. Some of the surficial sediments are very thick where sediments fill the large valley cuts across the peninsula (Foster, 1990).

Fig. 1 presents the geology of eastern Virginia based on Mixon (1985). The surface geological units are sedimentary deposits of coastal barrier–lagoon complexes and estuarine marshes, Qs, Qm, and Qsm, (Holocene); fluvial and estuarine deposits of Onancock lowland, Qp and Qk (Holocene and Pleistocene); marginal-marine deposits bordering the eastern part of central upland, Qw and Qj (Pleistocene); and marginal-marine, estuarine and fluvial deposits

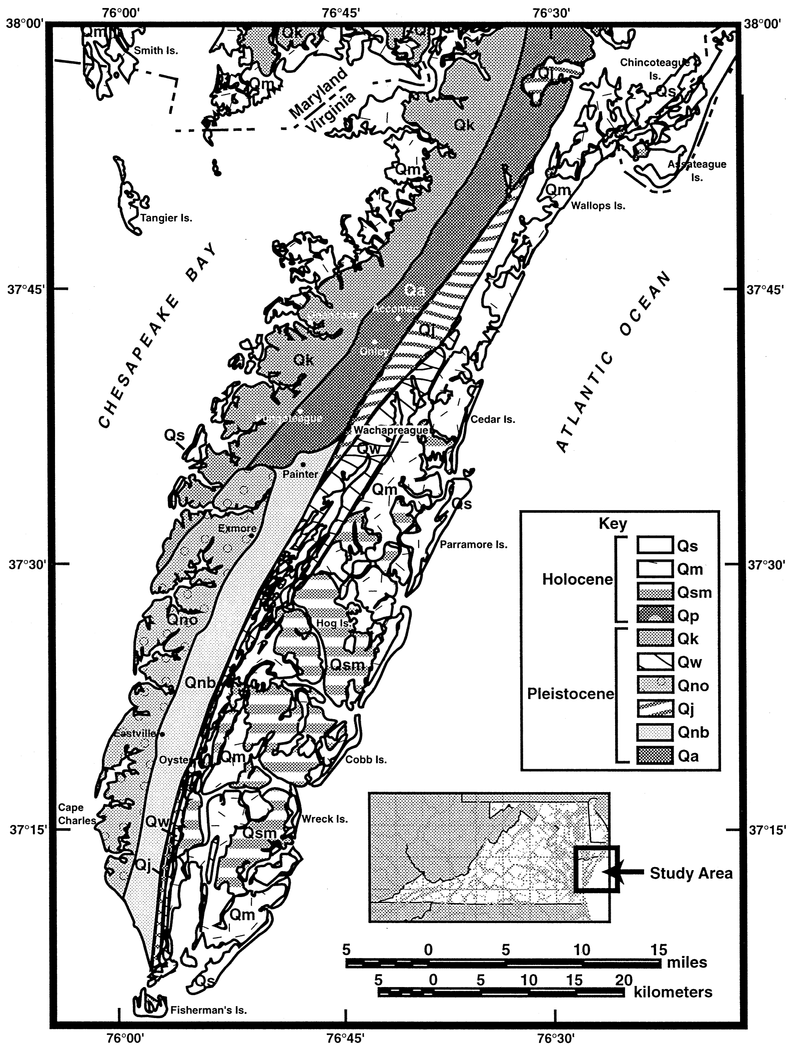

Fig. 1. The surficial geology of Eastern Shore of Virginia. This map is modified from (Mixon, 1985).

of central upland and Franktown plain, Qno, Qnb, and Qa (Pleistocene). The composition of strata varies considerably, but mostly consists of sand, shell fragments, mud, peat, gravel, silts, and silty clays. These strata collectively form the shallower Columbia aquifer. Below the Columbia aquifer lies the Yorktown formation of middle Pliocene age. The Yorktown formation is composed of glauconitic sand, some sandy gravel, and silty clay with shell fragments which also constitute an important freshwater aquifer of this area (Mixon, 1985).

3. Hydrogeology

The average precipitation for the land area is roughly 43 in. annually with heaviest rainfall occurring from June through September (Ball, 1977). Freshwater derived from the rainfall seeps through the shallower porous strata and forces the brackish and salty water away from the land. The sources of freshwater include the shallower unconfined Columbia aquifer of Pleistocene to Holocene age, as well as a series of confined aquifers associated with the Yorktown formation of Miocene to Pliocene age (Meng and Harsh, 1988).

The composition of the Quaternary Columbia sediments ranges from very fine silty sand to very coarse and gravelly clean sand inter-bedded with clay and silt. The Yorktown sediments consist mainly of a shelly formation of Pliocene age (Mixon, 1985) which is exposed on the southwestern bank of the James River and extends toward the Chesapeake and into the Atlantic margin. The deeper regional salty arte-

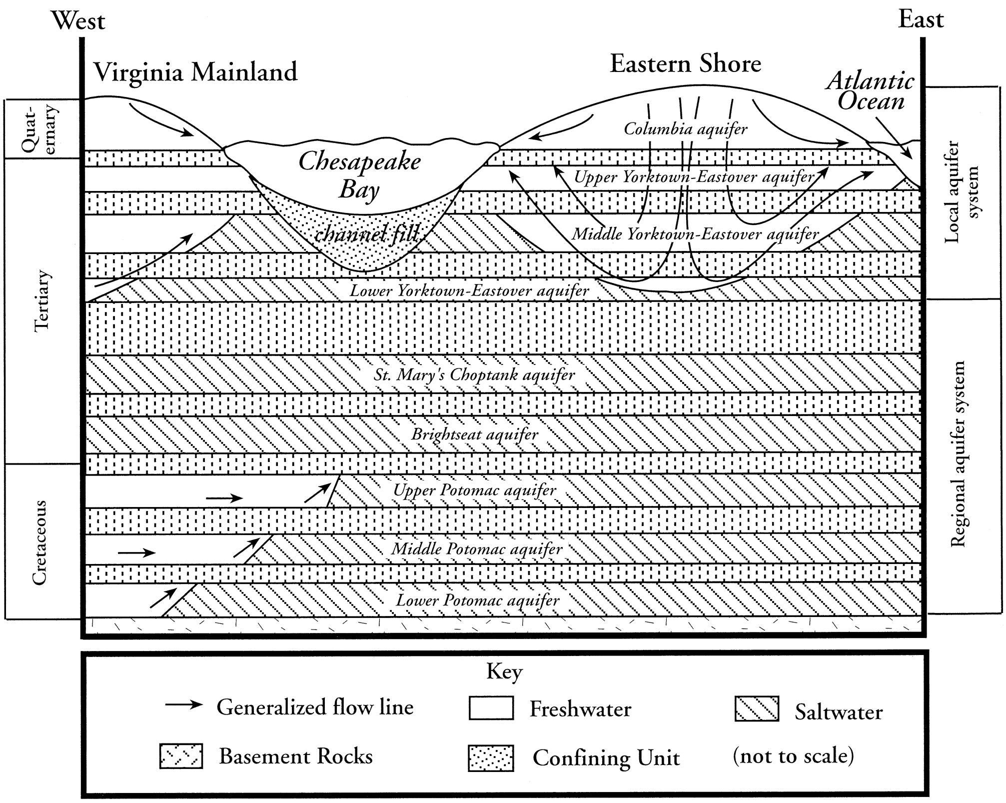

Fig. 2. A schematic diagram of confined and unconfined aquifers and generalized flow lines, modified from (Richardson, 1992).

sian aquifers (Brightseat, and Potomac formations) which extend into the Atlantic margin also consist of sand and gravel of Cretaceous age. The freshwater aquifers are recharged by infiltration of the surface water and yearly precipitation. A schematic diagram of the aquifers and the generalized flow lines is given in Fig. 2 (Richardson, 1992).

The total withdrawal of water from the subsurface was about 15.6 million gal per day in 1991 (Horsley Witten Hegemann, 1992). The high yielding wells are drilled within depths of 80 to 300 ft; at greater depths the salinity of water increases to the extent that the water is unfit for most uses (Ball, 1977). We are in agreement with him; we have estimated by our resistivity method that the average depth to the 7 Ω m iso-resistivity surface which we have proposed as the brackish water is about 305 ft.

The major pumping centers in the Eastern Shore are Perdue at 1.57 million gal per day and Holly Farm Poultry Products at 0.745 million gal per day, followed by several townships (Fennema and Newton, 1982). The positions of the major centers in the Northampton county are given in Fig. 3. The water withdrawals for the Bayshore Concrete, the town of Cape Charles, the C & D Sea Food are 53 000, 16 3000, and 59 000 gal per day, respectively (Fennema and Newton, 1982).

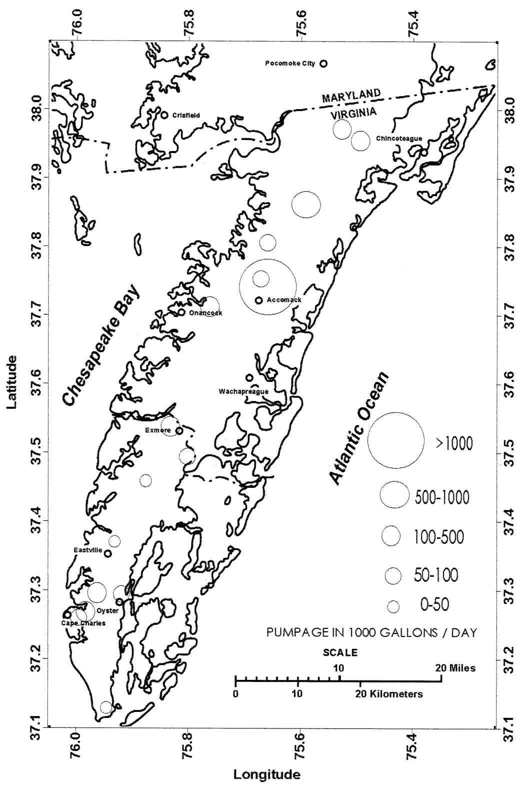

Fig. 3. Positions and identities of the major pumping centers in Northampton County. Water withdrawal for Bayshore Concrete, the town of Cape Charles, and C & D Sea Food are 53 000, 16 3000, and 59 000 gal per day, respectively (Fennema and Newton, 1982).

4. Equipment and field methods

We have used the Schlumberger array and the Syscal R2 Model electric resistivity meter to conduct this survey. When deployed, the Syscal R2 measures and displays the apparent resistivity. We have used an external AC generator which produces a maximum of 2200 W of power as a source for the current power supply. The current and electrode spacings were measured in meters and varied from 1 to 400 m for the current electrodes and from 0.2 m to 30 m for the potential electrodes. The selected current electrode spacings are: 1.0, 1.5, 2, 3, 5, 7, 10, 12, 16, 20, 24, 30, 40, 50, 60, 80, 100, 120, 150, 200, 250, 300, 400 m. The central locations of the 111 soundings are illustrated in Fig. 5. All data were plotted in the field to check the quality of data and to avoid mistakes. The increase of potential electrode spacing often is marked by a discontinuity in the field curve. At the discontinuities, we repeated the measurements. The field curves are smoothed before digitization.

5. Data processing, inversion and modeling

We experimented with several programs for interpretation of resistivity data. In some programs (Zhdanov and Keller, 1994; RESIX-IP, 1988), theoretical curves are calculated from a set of subsurface models, and the results are compared with the observed field curves. A model is chosen that produces a good match between the observed and the theoretical curve. In other programs, an initial model is introduced which is then iterated until a good match between the observed and the theoretical curve is found.

We checked the subsurface structures obtained by these programs for the resistivity soundings near three existing boreholes. We found that the programs of Zohdy and Bisdorf (1989) gave a more consistent result and was easier to apply. Therefore, a series of programs by Zohdy (1989), Zohdy and Bisdorf (1989), and Bisdorf and Zohdy (1990) are used for inversion of the field measurements. The current electrode spacing, a, and apparent resistivity, ρ_a, are the inputs to the program and the subsurface structures, $h(I)$, $\rho(I)$, $I=1, n$, are the program outputs. The parameters $h(I)$ and, $\rho(I)$ are thickness and resistivity of the layer I and n is the total number of the layers in the model. The value of n is initially assumed to be equal to the number of points in the field curve. The model parameters are printed in the form of a table for several horizontal layers with varying resistivities and thicknesses. Also, the program plots the digitized field curve, the calculated apparent resistivities based on the calculated model, and the model itself.

We have also used another program by Zohdy and Bisdorf (1989) to find the depths at several constant resistivity values for contouring purposes. When possible, the depth at constant resistivity values of 1500, 1000, 700, 450, 300, 200, 150, 100, 70, 45, 30, 20, 15, 10, 7, 4.5, and 3 Ω m were estimated by this program and saved in a separate file for interpretation. Furthermore, additional files for variation of resistivity at constant depth of 3, 5, 10, 20, 30, 40, 50, 60, 70, 100, and 130 m were created from the results of the inversion processes. These procedures were applied to all 111 soundings. The SURFER program (Golden Software, 1994) was used to obtain the resistivity contour maps at various depths, and depth to various iso-resistivity surfaces. From the resistivity contour maps, three cross-sections indicating the variations of resistivity with depth were also constructed. The resistivity maps give the horizontal extent and the cross-sections indicate the vertical extent of the saltwater intrusion.

6. Interpretation of resistivity models

Layer resistivities obtained by the inversion process are controlled by the resistivity of the pore water and the resistivity of the host rock (Telford et al., 1990; Burger, 1992). Resistivity of water may vary from 0.2 to over 1000 Ω m depending on its ionic concentration and the amount of dissolved solids. Average seawater

Table 1
Resistivity of water and sediments

Resistivity, Ω m	Sediments	Interpretation
0.5–2.0	Very porous sand, or saturated clay	Seawater; very saline water; TDS: about 20 000 mg/l
2.0–4.5	Porous sand, or saturated clay	Saline water; TDS: about 10 000 mg/l
4.5–10.0	Sandy saturated, or sandy clay	Salty Brackish water; TDS: 10 000–1500 mg/l
10.0–15.0	Sandy clay, sandy gravel	Brackish water; TDS: 5000–1500 mg/l
15.0–30.0	Sand, gravel, some clay	Poor quality fresh water TDS: 1500–700 mg/l
30.0–70.0	Sand, gravel, minor clay	Intermediate quality Fresh water; TDS ~ 100 mg/l
70.0–100.0	Sand, gravel, no clay	Good quality fresh water; TDS small
More than 100.0	Coarse sand, gravel, no clay	Very good quality fresh water; TDS very small

Modified from (Zohdy et al., 1993).

has a resistivity of 0.2 Ω m. For rocks containing water and clay, the conductivity is

$$1/\rho_{\mathrm{r}} = (S_{\mathrm{w}} V_{\mathrm{cl}})/\rho_{\mathrm{cl}} + \left(S_{\mathrm{w}}^2 \phi^m\right)/a\rho_{\mathrm{w}},$$

where ρ_{r} = resistivity of rock; ρ_{w} = resistivity of pore water; a, and m are the coefficients in the Archie equation in which the numerical value of a is between 0.6 to 1.0 and the numerical value of m is between 1.4 to 2.2; ϕ = fractional porosity; S_{w} = fractional water saturation; V_{cl} = volume of clay fraction, and ρ_{cl} = resistivity of the clay fraction (Simandoux, 1963; Ward, 1990).

The parameters which control the resistivity in the this equation may vary with depth and are not easily measurable. Thus, a wide range of resistivity is often reported for a particular water saturated material. Resistivity of natural water

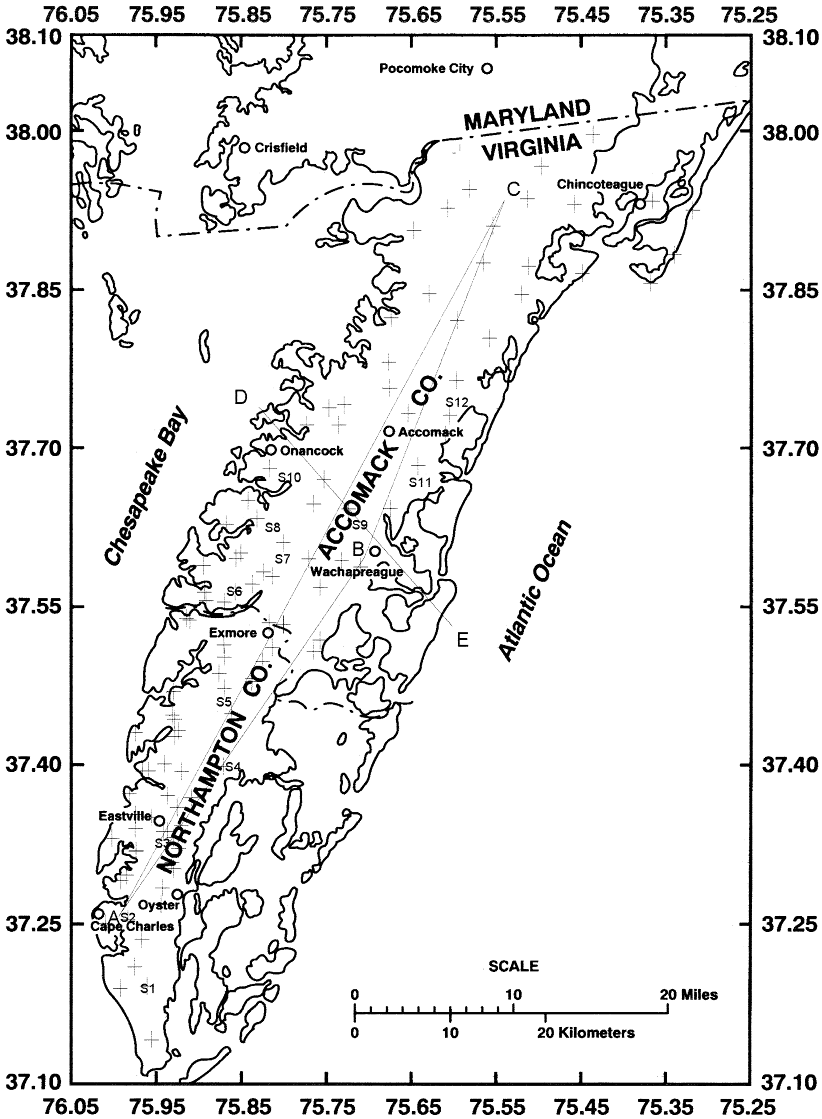

Fig. 4. Central positions of the 111 Schlumberger soundings are marked by +. The results and conclusions of this paper are based on all 111 soundings. Only the details of 12 soundings, marked s1 to s12, are presented in Fig. 5.

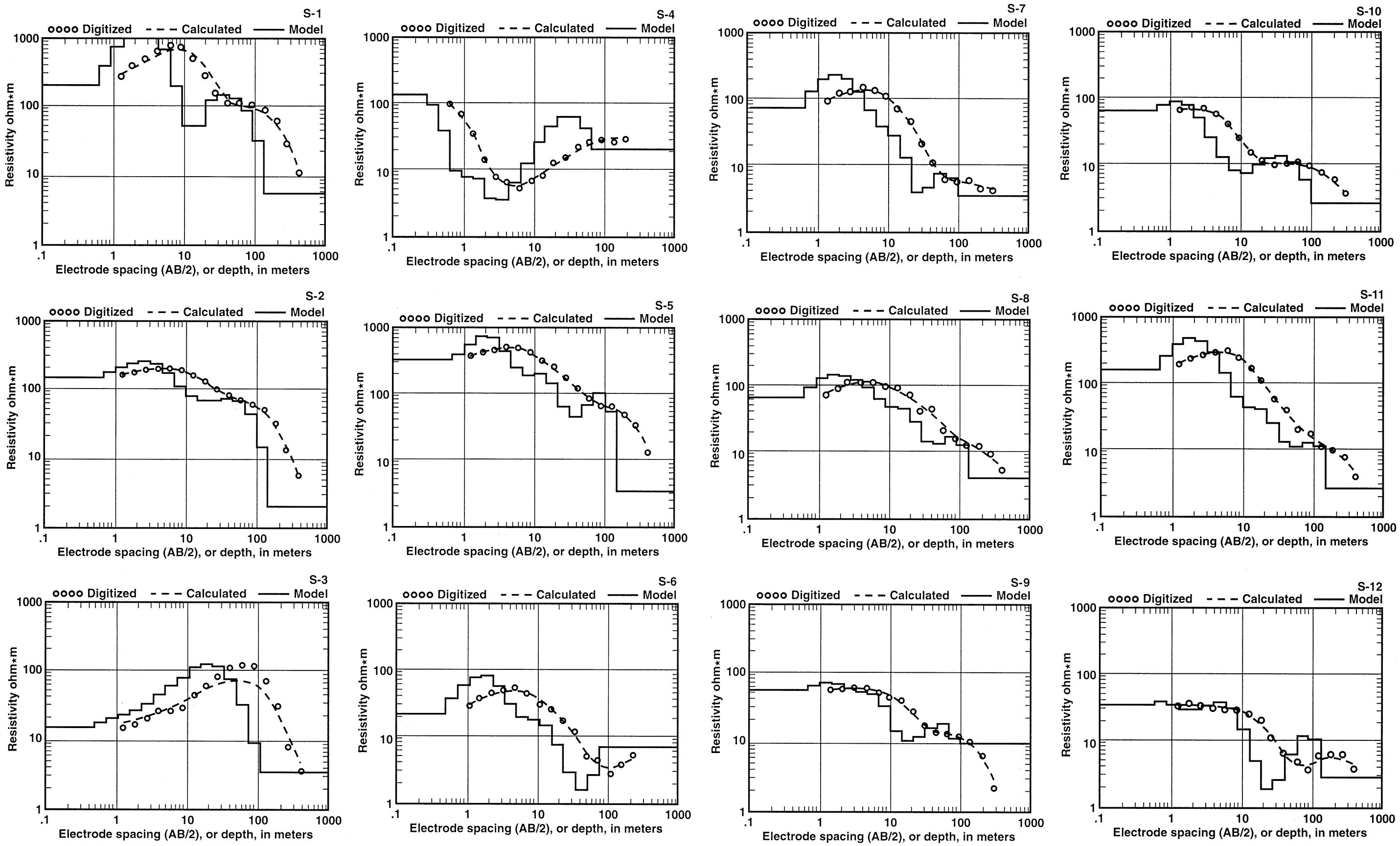

Fig. 5. Presentation of 12 sample soundings. Digitized field curves, circles. Subsurface models, solid lines. Theoretical curves based on models, dashed lines.

and sediments without clay may vary from 1 to 100 Ω m while the resistivity of wet clays alone may vary from 1 to 120 Ω m (Parasnis, 1986). The resistivity of a layer saturated by saline water and some dissolved solids is in the range of 8 to 50 Ω m (De Breuk and De Moor, 1969; Sabet, 1975; Goodell, 1986; Flanzenbaum, 1986; Zohdy et al., 1993).

In this work, we were interested in finding resistivity corresponding to 240 to 250 mg/l of dissolved solid. This level of dissolved solid was recommended to the Eastern Shore of Virginia Ground Water Committee by Horsley Witten Hegemann (1992) as representing good quality water. Based on laboratory measurements, the total filterable residue in a water sample may be obtained by multiplying its conductivity in microohms per centimeters by an empirical factor which may have a range of 0.55 to 0.9 depending on its soluble components (Greenberg et al., 1980). Noting that conductivity is the inverse of the resistivity and, assuming an average factor of 0.725, we calculated that 242 mg/l of dissolved solid corresponds to a resistivity of 30 Ω m. However, since the range of dissolved solids may vary from 300 mg/l to 183 mg/l if a factor 0.9 or 0.55 is used, we have assumed that, the 30 Ω m value corresponds to the outer boundary of the saltwater intrusion areas. This value may vary between the 10 Ω m and 50 Ω m as suggested by Sabet (1975) and Flanzenbaum (1986). Zohdy et al. (1993) presented a useful account of resistivity variation as a function of salinity and water quality for the Oxnard Plain, CA. A modified form of their presentation is shown in Table 1 and is used as a guide for the interpretation of resistivity data in terms of probable lithology and water quality in our work.

7. Important features of field curves and their interpretation

To be brief, we have selected a sample of 12 field curves for detail presentation. Their positions are marked s1 to s12 in Fig. 4 with the remaining positions marked but not numbered. The important features of the remaining soundings are similar to the features of the 12 selected soundings.

A majority of the Schlumberger soundings (75%) have an apparent resistivity in the range of 20 to 200 Ω m at 1-m current electrode spacing, then the resistivity remains nearly constant or increases to a few 100 Ω m at about 10

Table 2
An interpretation of 12 selected sample soundings

Sounding	Latitude	Longitude	R at 20 m	R at 30 m	D 70 Ω m
s1	37.19219	75.95986	113	134	−9.7
s2	37.25236	76.00877	66	66	−15.3
s3	37.34016	75.93583	1253	1159	−97.4
s4	37.40236	75.86986	64.33	63.09	−0.5
s5	37.47733	75.86897	155.02	68.7	−25.9
s6	37.56916	75.85638	78	30	−20.8
s7	37.61586	75.79963	13	4	−5.3
s8	37.63861	75.83055	30	14	−6.2
s9	37.64855	75.67416	11	14	−1
s10	37.68611	75.81555	10	12	−0.7
s11	37.68891	75.64136	44	26	−8
s12	37.77008	75.59619	20	28	−14.3

Resistivity in Ω m at 20 m and 30 m are given as R at 20 m and R at 30 m, respectively.
Depth to the 70 Ω m iso-resistivity surface is given by D 70 Ω m.

m spacing. The resistivity decreases to a few Ω m at the maximum spacing of about 400 m. Often, for spacings of 10 to 100 m, a plateau of several tens of Ω m, or a change in the decreasing slope of the apparent resistivity curves was observed. For example, nine of the 12 selected soundings have these features. Theoretical models indicate that for these cases the true resistivity ρ_n for layer n increases for $n = 1$ to 4 or 5, then decreases for the next few layers.

A minority of the soundings (for example, s4, s6 and s12) exhibit a minimum resistivity at a spacing of about 100 m, then increase slightly to a resistivity value of 5 to 20 Ω m. Theoretical models indicate that for this condition the true resistivity ρ_n for the first few layers is nearly constant, the resistivities of the next several layers decreases, the resistivities of the next few layers increases, and the resistivities of all deeper layers decreases. Fig. 5 presents the

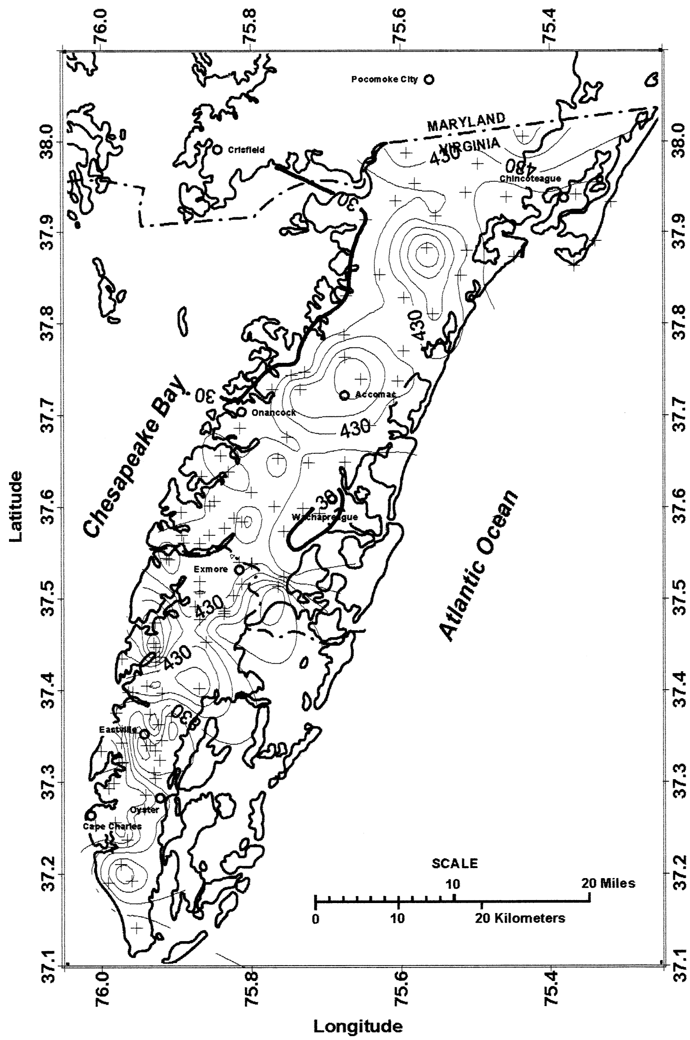

Fig. 6. Resistivity map at the 3 m depth. Contour interval is 200 Ω m. The 30 Ω m contour line is darker and bold. Low resistivity tracts are noted in the coastal zone of the Chesapeake Bay and north of Onancock. In this figure and other figures, pluses (+) indicate the central positions of the electrical soundings.

results of soundings s1–s12. For each sounding, the digitized field curve, the model, and the calculated theoretical curve based on the adopted model are presented.

8. Interpretation of resistivity contour maps

Table 2 presents a sample of the interpreted resistivities at depths of 20 and 30 m, and the depth to the iso-resistivity surface of 70 Ω m for the 12 selected soundings. We made tables similar to Table 2 containing location (latitude, longitude), and resistivity at 11 constant depths of 3, 5, 10, 20, 30, 40, 50, 60, 70, 100 and, 130 m; as well as tables containing location (latitude, longitude) and depths to the six iso-resistivity surfaces at constant 150, 100, 70, 30, 15 and, 7 Ω m for the entire 111 soundings. Table 2 is a sample which gives a combined version for the selected soundings. The tables for the 111 soundings were used as input to the

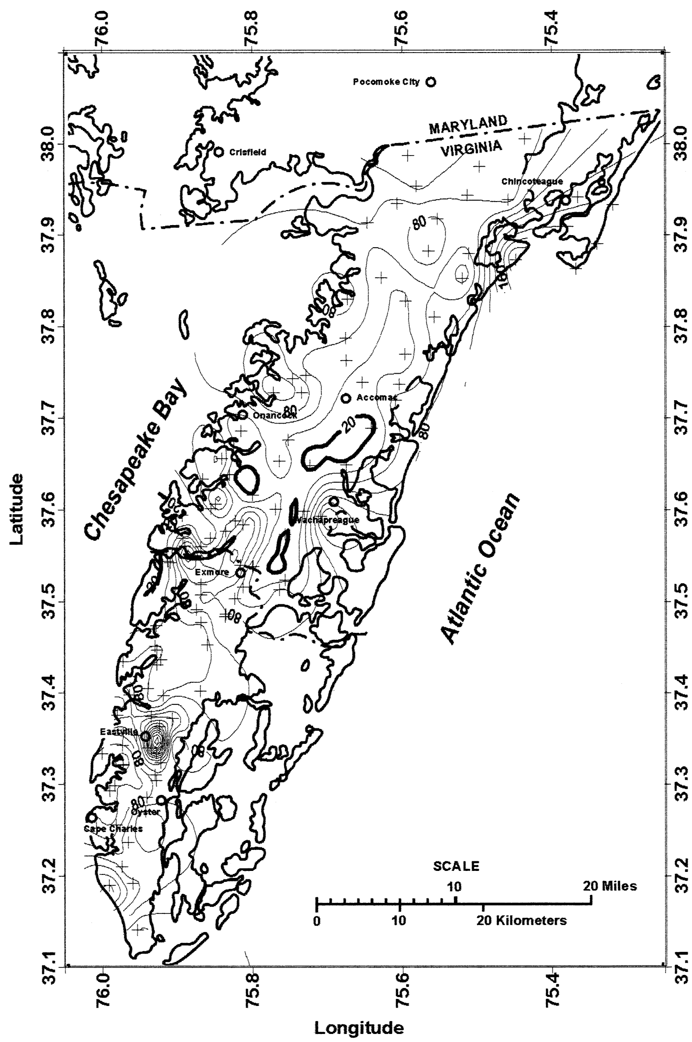

Fig. 7. Resistivity map at the 40 m depth. Contour interval is 20 Ω m. At this depth, regions with resistivities lower than 30 Ω m are expanded. The possibility of saltwater intrusion is shown by the 30 Ω m contour between Exmore, Onancock, Accomac, and Wachapreaque.

SURFER program for production of the contour maps. The number of soundings used for preparation of the resistivity contour maps decreases with depth; it is 111 for resistivity maps at depth of 3 to 10 m and it reduces to 40 for a depth of 130 m. The reason for this reduced number at greater depth is that greater penetration depths require larger electrode spacings than were used in our surveys.

From 11 contour maps of resistivity variation at constant depths, we only present the maps at depth of 3, 40, 70 and 100 m. These maps show the horizontal extent of the saltwater intrusion at those depths. The details of resistivity variation with depth are presented later in the three resistivity cross-sections AB, ABC and DE. The cross-sections show the vertical extent of the saltwater intrusion and are based on the results of the 11 contour maps. In all of the resistivity contour maps and cross-sections the 30 Ω m contour lines are marked by darker lines.

Fig. 6 presents the resistivity at 3 m depth; the contour intervals are 200 Ω m. Actual resistivity data show a variation of 2 to about

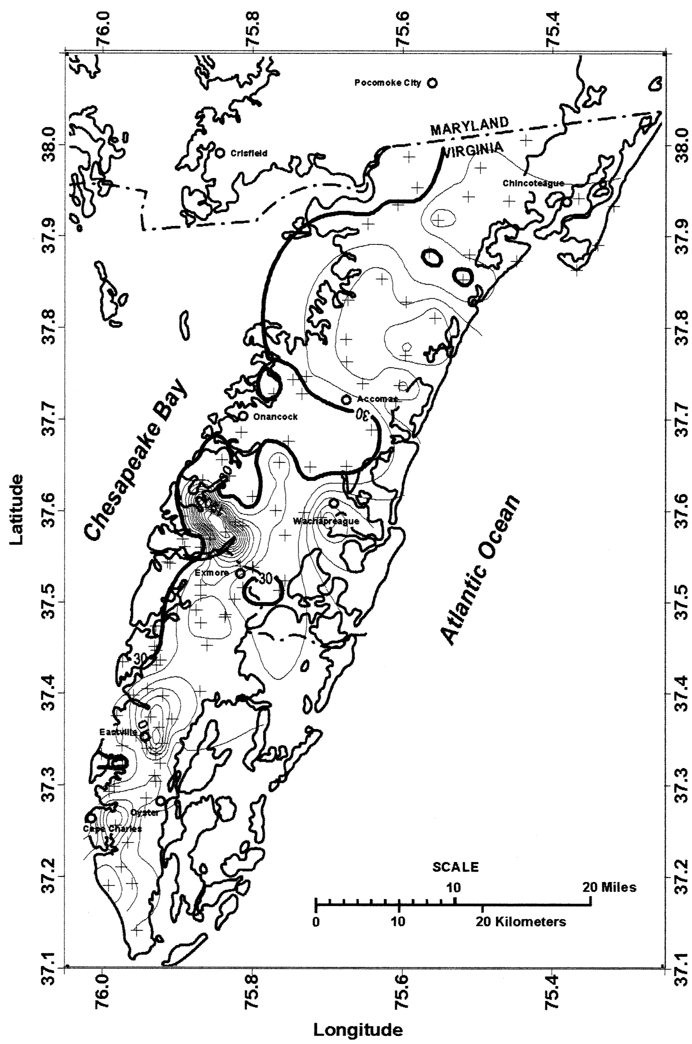

Fig. 8. Resistivity map at the 70 m depth. At this depth, a major portion of the Bay coastal region indicates low resistivity; the intrusion appears to cover the area east of the Onancock and extends toward the Atlantic coastal region.

2500 Ω m at 3 to 5 m depth. A major part of the map shows the resistivity of the unsaturated surface layers near the top of the shallow Colombia aquifers; exceptions are the western coastal area north of Onancock and a small area near the Wachapreaque. In these areas some saturated zones are indicated by the presence of the 30 Ω m contours which suggest contamination of saltwater by tidal creeks and inlets. Furthermore, the relatively higher resistivity zones are noted north of Accomac, and southeast of Exmore.

Fig. 7 shows the resistivity contour map at 40 m depth; the contour interval is 20 Ω m. Based on distribution of the 30 Ω m contour, this map shows that at the 40 m depth in the area between Exmore, Onancock, Accomack and Wachapreaque there are some possible zones of slatwater intrusion. We have interpreted these low resistivity zones as areas where saltwater has intruded into the freshwater zone from below.

Fig. 8 shows the resistivity contour map at depth of 70 m. This map indicates the intrusion

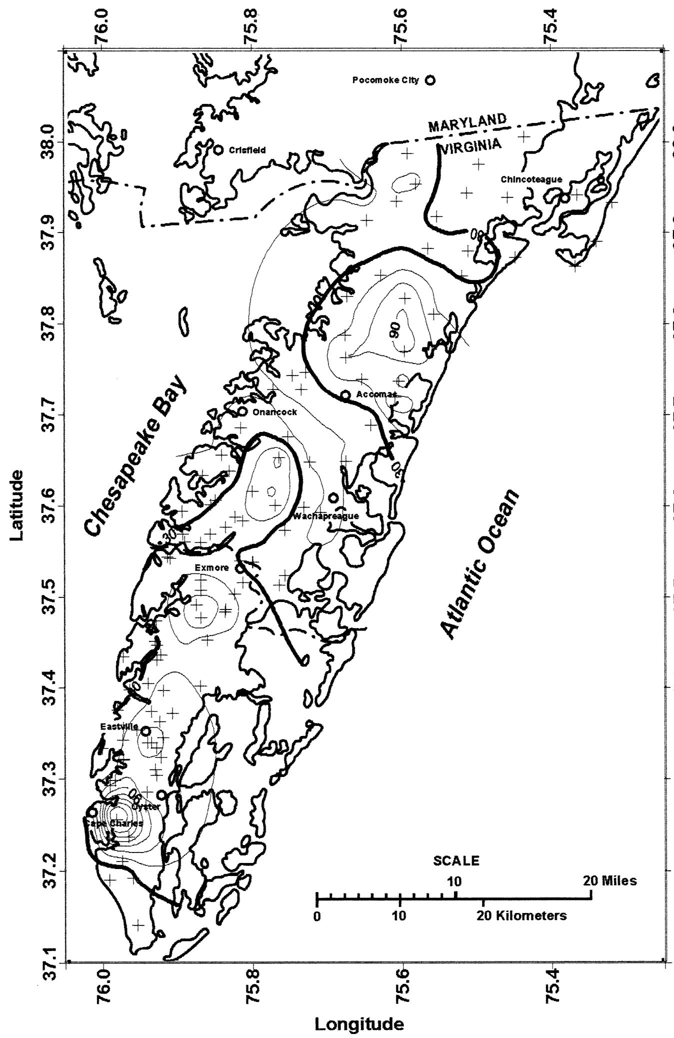

Fig. 9. Resistivity map at depth of 100 m. At this depth, saltwater intrusion appears to cover the entire middle part of the Eastern Shore, from Onancock toward Accomac and Wachapreaque and the Atlantic coastal regions and to the most southern part of the Eastern Shore. Parts of this area may have resistivities lower than 20 Ω m.

of saltwater from the coastal region of the Chesapeake Bay toward the shores of the Atlantic Ocean. The coastal region of the Bay from the Maryland/Virginia border in the north to near Eastville in the south is covered by tracts of low resistivity (less than 30 Ω m). The front of the intrusion appears to be in the vicinity of Onancock where the 30 Ω m contour extends inland southeast of Onancock and to the coastal region of the Atlantic Ocean in the east in the vicinity of Accomack. At 100 m depth, in Fig. 9, the 30 Ω m and 20 Ω m contours cover the coastal region of the Bay as well as the area between Onancock, Accomac, and Wachapreaque from the shore of the Bay toward the Ocean.

9. Interpretation of resistivity cross-sections

Three cross-sections were derived from the 11 resistivity maps. The positions of the cross-sections are shown in Fig. 5, marked as AC, ABC and DE, respectively. The sections show the shape and the vertical extend of the low-resistivity saltwater intrusion plumes. In all cross-sections, the high-value contours associated with the unsaturated zone at shallow depths are omitted to increase clarity.

Section AC starts at A (37.25 N, 76.0 W) and ends at C (37.95 N, 75.52 E); it has a total length of about 84.2 km and a strike of N29E. This section passes by the Eastville, Exmore, and Accomac townships. Fig. 10 shows the intrusion of saltwater along line AC from a depth of 130 to about 60 m. The saltwater plume is located between 50 to 60 km from point A in the southwestern part of Accomac. At the 65 km mark from point A to the end of the section at point B, the saltwater is indicated at a depth greater than 110 m.

Section ABC shown in Fig. 11 has the same end points as section AC; the mid-point B (37.95 N, 75.52 W) is near Wachapreaque. This section has a length of 89.4 km with features similar to the features of section AC. The saltwater plume is slightly broader and the top of the plume is slightly deeper under point B. The saltwater is intruded from 50 km to the end of

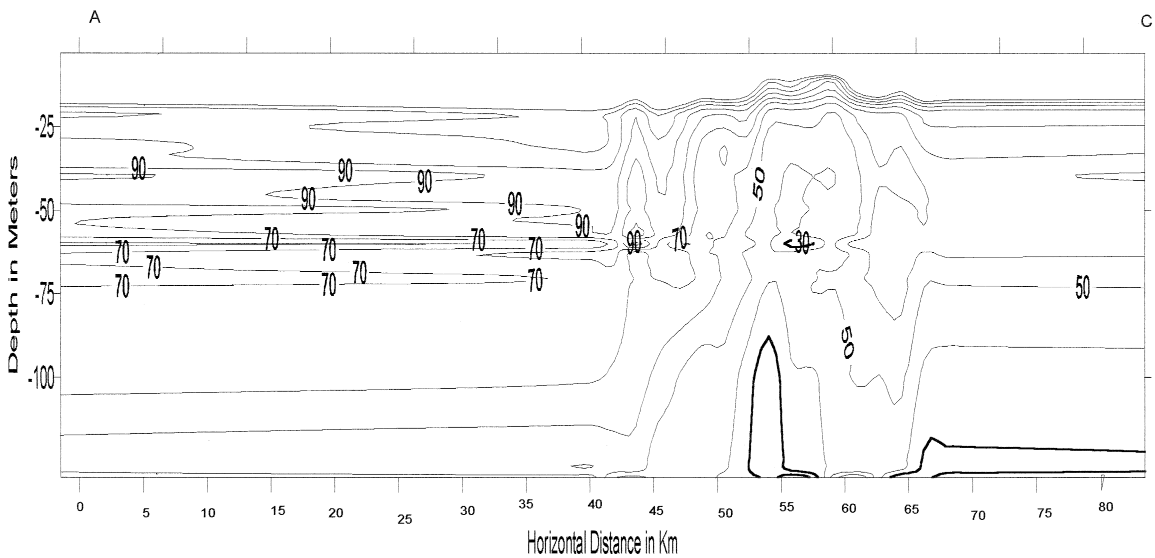

Fig. 10. Resistivity cross-section along line AC. Contour interval is 10 Ω m. Between the 50 and 55 km marks, the saltwater plume is indicated by resistivities of 30 Ω m and lower, and it rises to a depth of less than 80 m. In addition, resistivities less than 30 Ω m are indicated from the 65 km mark toward the end of this section.

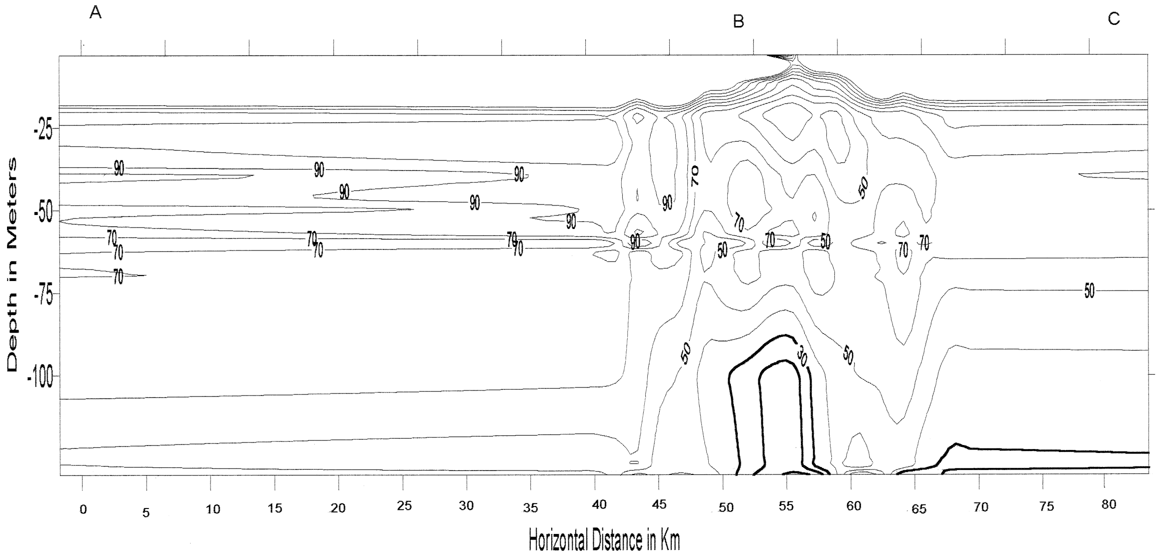

Fig. 11. Resistivity cross-section along ABC line. This section is similar to section AC. The saltwater plume includes resistivities lower than 15 Ω m; it rises to a depth of about 80 m. Resistivities less than 25 Ω m are indicated from the 65 km mark toward the end of the section.

section at point C. Both sections show the resistivity vs. depth north of the saltwater plume to be different from that south of the plume. In the northern area the lower resistivities are at shallower depths. For example, the 50 Ω m contours are near 50 m depth in the north near point C, but the 50 Ω m contours are near 130 m depth in the south near point A.

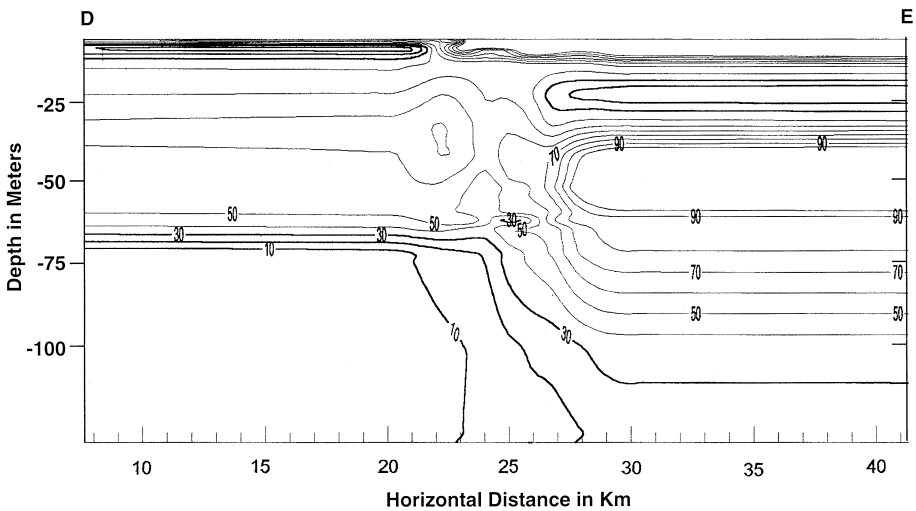

Fig. 12. Resistivity cross-section along DE line. This section shows three regions of resistivities lower than 30 Ω m: (1) at shallow depth of about 5 m between beginning of the section and 22 km mark; (2) at the depth of 10 to 15 m from 27 km mark toward the end of the section; and (3) the intrusion covering the entire section from point D starting approximately at a depth of 65 m and ending at point E at a depth of about 110 m.

Section DE starts at point D (37.82 N, 75.90 W) in the Chesapeake Bay and ends at E (37.55 N, 75.50 W) in the Atlantic Ocean. The segment crossing the land has a length of about 33 km as shown in Fig. 12. This section shows that the variations of resistivity with depth are sharply different between the bay side and the ocean side. At the bay side, there is a thin layer of higher resistivity on top of a low-resistivity zone, probably associated with saltwater intrusion from the bay. This zone extends from a shallower depth near the surface to a depth of about 5 m. The resistivity increases to the range of 60–70 Ω m at a depth of about 30 m and then decreases to less than 10 Ω m at deeper depths. At the ocean side, the higher resistivity shallow zone extends to a depth of about 15 m, then a low-resistivity zone starts and extends to a depth of about 30 m, this low-resistivity zone is probably associated with saltwater intrusion from the ocean. Under this zone, the resistivity increases to about 90 Ω m at a depth of about 60 m. This resistivity increase may indicate the possibility of better quality water under the

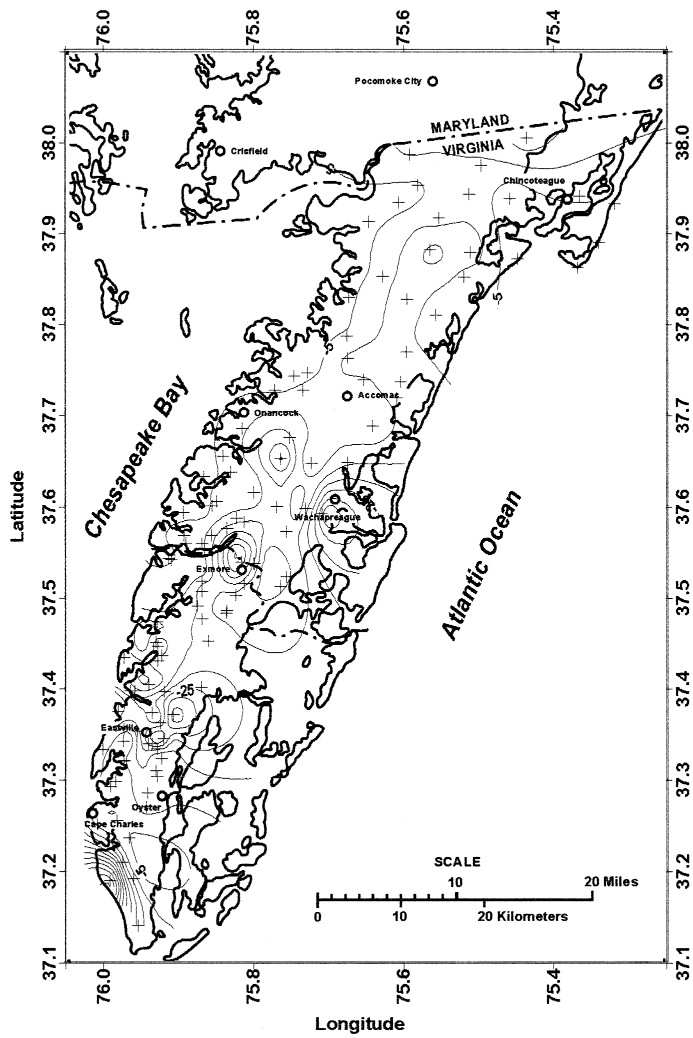

Fig. 13. Depths to the 150 Ω m iso-resistivity surface. The average depth is 12.95 m, probably indicating the top of the water table.

saltwater zone, although drilling and water samples are needed for verification. At a depth of 60 m, the resistivity decreases to less than 10 Ω m, indicating a major intrusion from the ocean side.

10. Depths to the iso-resistivity surfaces

The maps of iso-resistivity surfaces may have some limited applications for estimating the depth to a particular water quality at a location. We propose that good quality freshwater may be found between the water table and the 70 Ω m iso-resistivity surface, whereas between the 70 and 30 Ω m iso-resistivity surfaces there is an intermediate quality freshwater. Between the 30 and 15 Ω m iso-resistivity surfaces there is brackish water and between the 15 and 7 Ω m iso-resistivity surfaces there is salty brackish water with high concentrations of total dissolved solids. Finally, saline water lies below the 7 Ω m iso-resistivity surface.

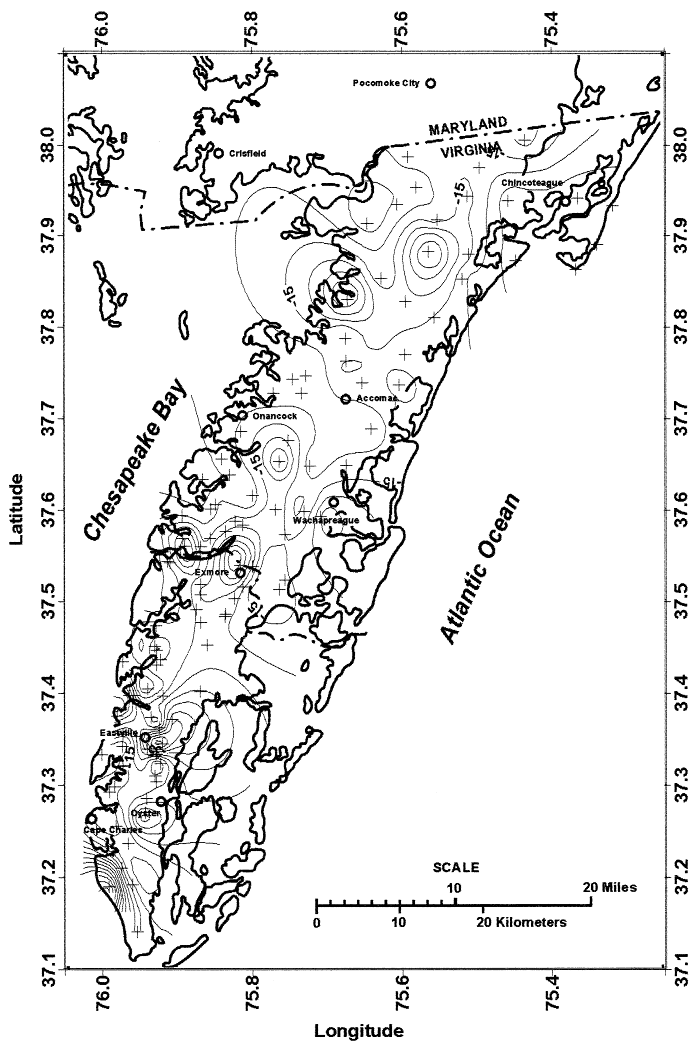

Fig. 14. Depths to the 100 Ω m iso-resistivity surface. The average depth is 18.02 m. This surface is within the Columbia aquifer.

Figs. 13 and 14 present the shape of the 150 and 100 Ω m iso-resistivity surfaces at the average depths of −12.95 and −18.02 m, respectively. The wells in the Columbia aquifer which produce freshwater have a depth range of 25 to 74 ft (7.62 to 22.56 m) (Richardson, 1992). Thus, both of the iso-resistivity surfaces are within the Columbia aquifer. There are some areas shown in Fig. 14 having closed contour depths of 18, 22 and, 30 m north of Accomac, in the vicinity of Exmore, and east of Eastville, respectively.

Fig. 15 presents the depth to the 70 Ω m surface. The average depth to this surface is 82.6 ft (24.88 m). The wells which produce freshwater from the upper Yorktown–Eastover aquifer have a depth range of 95 to 190 ft (28.96 to 57.93 m) (Richardson, 1992). Thus, the 70 Ω m iso-resistivity surface is located near the base of the Columbia aquifer and the

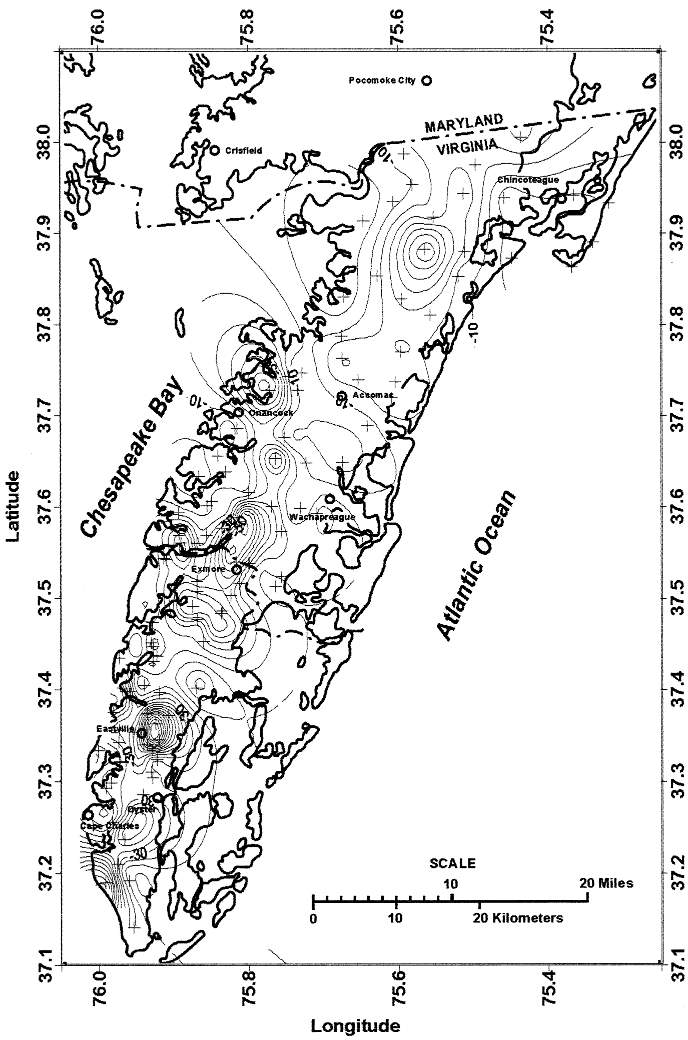

Fig. 15. Depths to the 70 Ω m iso-resistivity surface. The average depth is 24.88 m. This surface is probably the base of the Columbia aquifer.

top of the upper Yorktown–Eastover aquifer. No saltwater is reported in this part of the aquifer. Freshwater zones in the depth range of 24 to 36 m are indicated inland, between Chincoteaque and Accomac, and south of Exmore, respectively. These zones, as expected, are in the middle of the Eastern Shore, relatively far away from the shores.

Fig. 16 shows the depth to the 15 Ω m surface at an average depth of 254 ft (77.46 m). The wells which produce fresh to salty water from the middle Yorktown–Eastover aquifer have a depth range of 115 to 280 ft (35.06 to 85.36 m) (Richardson, 1992). Thus, this surface is in the middle Yorktown–Eastover aquifer. Fig. 17 represents the 7 Ω m surface at an average depth of 305 ft (92.97 m), corresponding to the lower Yorktown–Eastover aquifer. Nearly 50% of the wells in this unit are producing water with more than 250 mg of chloride

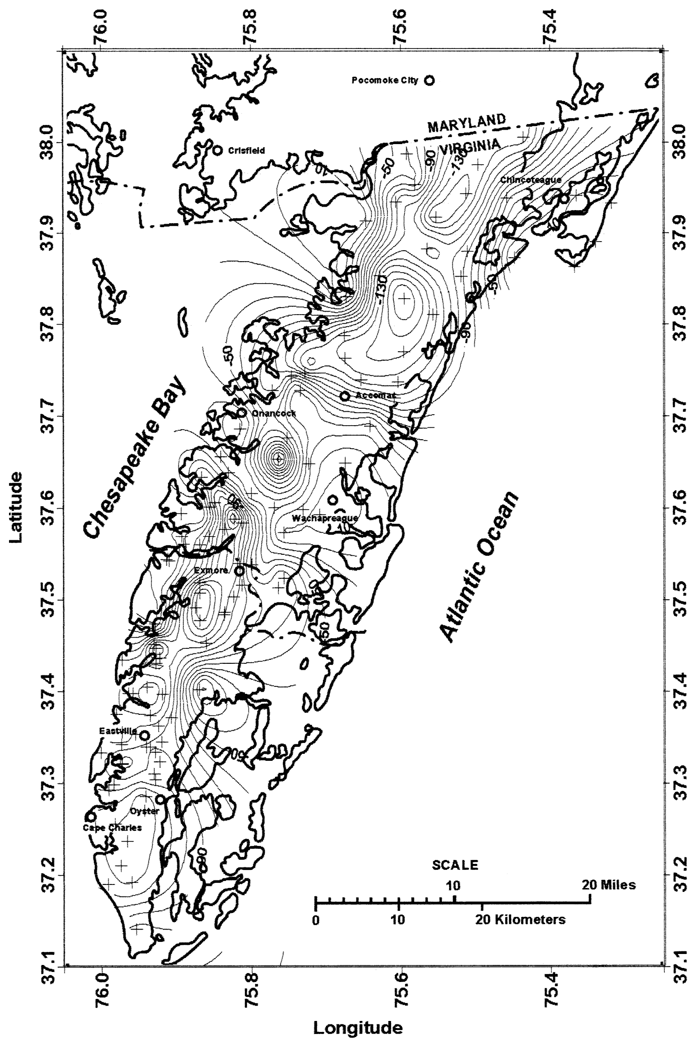

Fig. 16. Depths to the 15 Ω m iso-resistivity surface. The average depth is 77.46 m. This surface is probably within the middle Yorketown–Eastover aquifer.

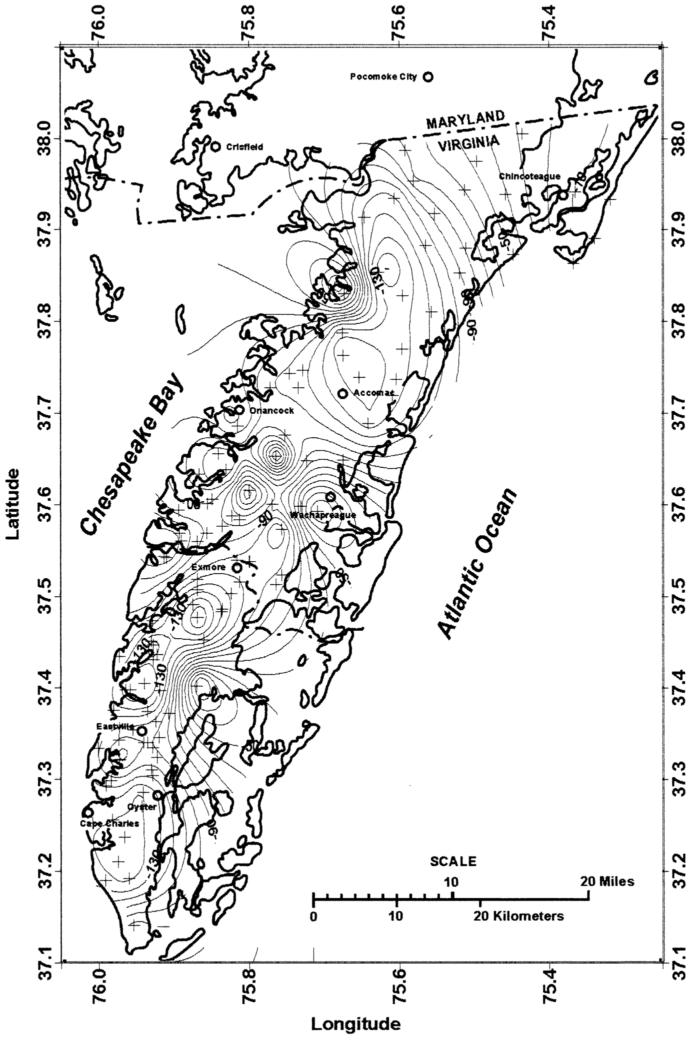

Fig. 17. Depths to the 7 Ω m iso-resistivity surface. The average depth is 92.97 m. This surface is approximately within the lower Yorketown–Eastover aquifer.

per liter. Thus, below this surface the groundwater appears to be mostly salty.

11. Conclusions

In this reconnaissance survey, we found that the Schlumberger sounding resistivity method is a powerful tool for investigating the saltwater/freshwater interface in the geological setting of the Eastern Shore of Virginia. In the shallow-depth range down to 5 m, the interpreted field resistivity data yielded a wide range of resistivity layers which vary from 50 Ω m to over 1000 Ω m. The lower ranges are very close to the shores indicating intrusion effects of saltwater, while higher values inland indicate the resistivity of unsaturated top layers. Between 10 to 30 m depth, low-resistivity layers are indicated around Wachapreaque, which expand with depth and cover most of the Atlantic coast. This is either due to sea water saturated sediments or to high clay content in the sediments near the Atlantic coast. From 30 to 130 m depth, an expanding low-resistivity plume is observed between Onancock, Accomac, and Wachapreaque, which indicates saltwater intrusion. The interpreted resistivity maps also signify that the saltwater moves from the direction of Chesapeake Bay toward the Atlantic Ocean and, at 130 m depth a major portion of the Eastern Shore is covered by very low resistivity layers. The interpreted resistivity cross-sections show that the saltwater plumes mark the difference between the resistivity character of the layers across the Eastern Shore. In the northern and northwestern regions of the plume, the lower resistivity zones are at a shallower depth. In some areas, there may be higher quality water under the near-surface saltwater zone.

Acknowledgements

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