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2D ELECTRICAL RESISTIVITY IMAGING OF THE EFFECT OF TIDE ON GROUNDWATER QUALITY IN OGULAGHA ESTUARY, WESTERN NIGER DELTA, NIGERIA

O. Ohwoghere- Asuma

Department of Geology, Delta state university, Abraka, Nigeria
Ohwonero@gmail.com, ooasuma@delsu.edu.ng

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ABSTRACT
The flow of saltwater from the ocean at high tide to the shoreline has substantial effect on groundwater quality of aquifer adjoining the sea. During high tide, saltwater from the sea inundates the ground surface close to the sea and infiltrates into the subsurface. The flow often terminates at the high tide mark or upper shoreface with resultant effect of degrading aquifers adjacent to the ocean. The objective of this study is to investigate the effect that saltwater precipitated by tide has on groundwater quality. Two profiles parallel to the ocean and one further inland were carried out with the aid of a 64 multi-electrodes SAS 4000 ABEM Terrameter. A spacing of 5m and 2.5m were used for the acquisition of 2D electrical resistivity data respectively. The profiles parallel to the ocean and placed at the high tide mark revealed resistivity values that ranged from 0.375 Ωm to 4.2Ωm with saltwater/freshwater depth greater than 51m deep. Resistivity increases gradationally with depth, which significantly suggests increasing freshness of the groundwater depth. Further inland resistivity ranged from 7.4 Ωm to 494Ωm, which indicates presence of clay and freshwater respectively. The study concludes that quality of groundwater beneath the high tide mark is evidently affected by saltwater enhanced by tide. The thickness of the saltwater is more than 50.8m as revealed by the resistivity low of 4.2 Ωm for the aquifer close to the sea. The effect of tide is most pronounced on the upper most geologic layers situated at the high-tide-mark but with no significant impact on aquifer situated further inland from the high-tide-mark. Further study on the exact position of saltwater/freshwater boundary is recommended for possible placement and subsequent monitoring of intrusion.

Key words: Saltwater, high tide mark, 2D ERI, groundwater quality, Ogulagha

INTRODUCTION
The Western Niger Delta consists of multichannel estuaries and streams that discharge freshwater and brackish into the Atlantic Ocean. The physio-chemical property of an estuary to a large extent is mainly influenced by the volume of freshwater flowing from continent and subsequently discharging into the sea. The hydrological and hydraulic regimes of Ogulagha estuaries are driven by quantity of freshwater that discharges into the sea, amount of rainfall, the degree of usage of freshwater at the upstream of the rivers, tidal forcing and the slope of the beach.

Depending on the volume of freshwater discharging into the ocean, saline water from the ocean may intrude inland aquifers situated several kilometers away due to overstressing of groundwater aquifers (Jakovovic et al., 2011; Werner and Simmons, 2009; Oude Essink et al., 2010; Zhou et al., 2005; Custodio, 2002). The process is responsible for degradation of groundwater quality in coastal areas. Very close to the ocean are sand beaches and beneath them are groundwater aquifers. Groundwater aquifer hydraulically connected to sea is influenced by amplitude of tidal oscillation of the sea and the slope of the beach (Liu, et al., 2012; Singaraja et al., 2016). Groundwater levels in aquifers adjacent to the coast often fluctuate in accordance with the amplitude of tide (Zhou et al., 2006). At high tide, saltwater from the ocean inundates the beach up to the high tide mark. The effect of tide on groundwater level decreases with distance from the coast (Turner et al., 1996; Sun 1997; Li and Jiao 2003;).

The freshwater in coastal aquifers and saline water that inundates beaches mix by dispersion initiated by convention process (Cooper, 1959). The mixing is often promoted by tide and wave (Kooi, et al., 2000). The effect of tidal forcing on mixing zone thickness is influenced by the amplitude of the tide and characteristic of the aquifer. The effect tide of relatively small amplitude has on mixing zone thickness is insignificant (Ataie-Ashtiani et al., 2001), while tides with large amplitude of 3.8m and above are known to have significant impact on the mixing zones, but with an insignificant effect on its thickness (Morrow et al., 2010). The effect can be likened to sea level rise, where saltwater from the sea inundates the beach. The difference is that tide is not at equilibrium unlike sea level rise but fluctuates between high and low. The infiltration of saline water into aquifers render them more conductive, and such can be discriminated from non-conductive freshwater on the passage of current.

Several geophysical methods including electrical resistivity, ground penetrating radar and electromagnetic have found wide applications in the probing of deep subsurface and near-surface for groundwater exploration and environmental purposes. Of the lots, none has found wide application in the probing of groundwater quality than the electrical resistivity methods, especially in developing countries, where it is one of the cheapest and cost effective geophysical methods that is readily available. The 2D electrical resistivity method is uniquely designed to discriminate freshwater from saltwater in coastal area on the bases of the aforementioned reasons (Loke, 2000). A mixing of infiltrated rainwater and saltwater below tidal creek was delineated by Acworth and Dasey (2003) with 2D ERT. Day-Lewis et al. (2006) has used same to reveal submarine groundwater discharge (SGD). Other studies involving the use of 2D ERT in saltwater intrusion in coastal aquifer in the Niger Delta includes Nwankwoala and Omunguye (2013) and Ohwoghere- Asuma et al. (2014). Currently the western region of the Niger Delta is devoid of literature involving the use of 2D electrical resistivity tomography (ERT) in assessing quality of groundwater beneath the high tide mark. The objective of this paper is to utilize 2D electrical resistivity tomography data to appraise the effect of saltwater inundation on groundwater quality beneath the high tide mark or upper shoreface.

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Description of study site

The study site, located in the coastal area of the western Niger Delta, situated about 40km from the oil city town of Warri and 15 km from Burutu. It is separated from Ogidigben by River Foracdos and bounded in the south by the Atlantic Ocean and the Forcados River in the North. It is an important hydrogeologic setting by the virtue of freshwater which flows from River Forcados and groundwater that empties and discharges into the Atlantic Ocean. It is an important community to the Nigerian Government as one of the major areas in the Niger Delta, where crude oil is being exported. For the above reason there are lots of oil and gas pipeline that transverses the area both underwater and on the surface. The south bank flow station of Shell is also located close to study area. The main occupation of the people is fishing and youth are employed in the Oil Company operating in the area.

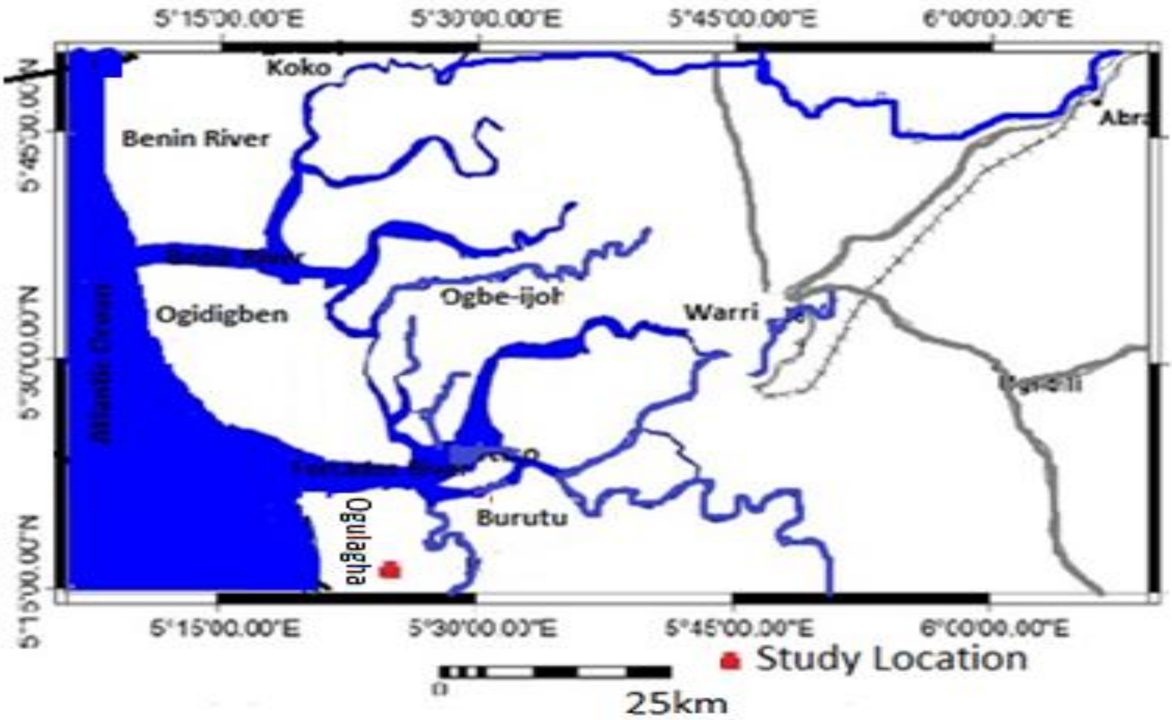

Figure. 1. Geographical location of Ogulagha and Study area

Geology and Hydrogeology

Fluvial and transitional environments influence the deposition of sands, clay and silts. The source of modern sediments supply is probably routed through Warri–Forcados and Niger River systems of the Niger Delta region. Adjacent to the Ocean are beaches consisting of sand dunes that separate the ocean from the land, which are products of marine environment. The operating process of waves and tide at the upper shore faces regime contribute to reworking of sediments deposited at the mouth of the Delta. It is believed that the modern influence of tide and waves may have also operated during the deposition of the Tertiary Niger Delta Basin fills in geologic past. The stratigraphy of the Niger Delta is subdivided into three groups (Figure 2);

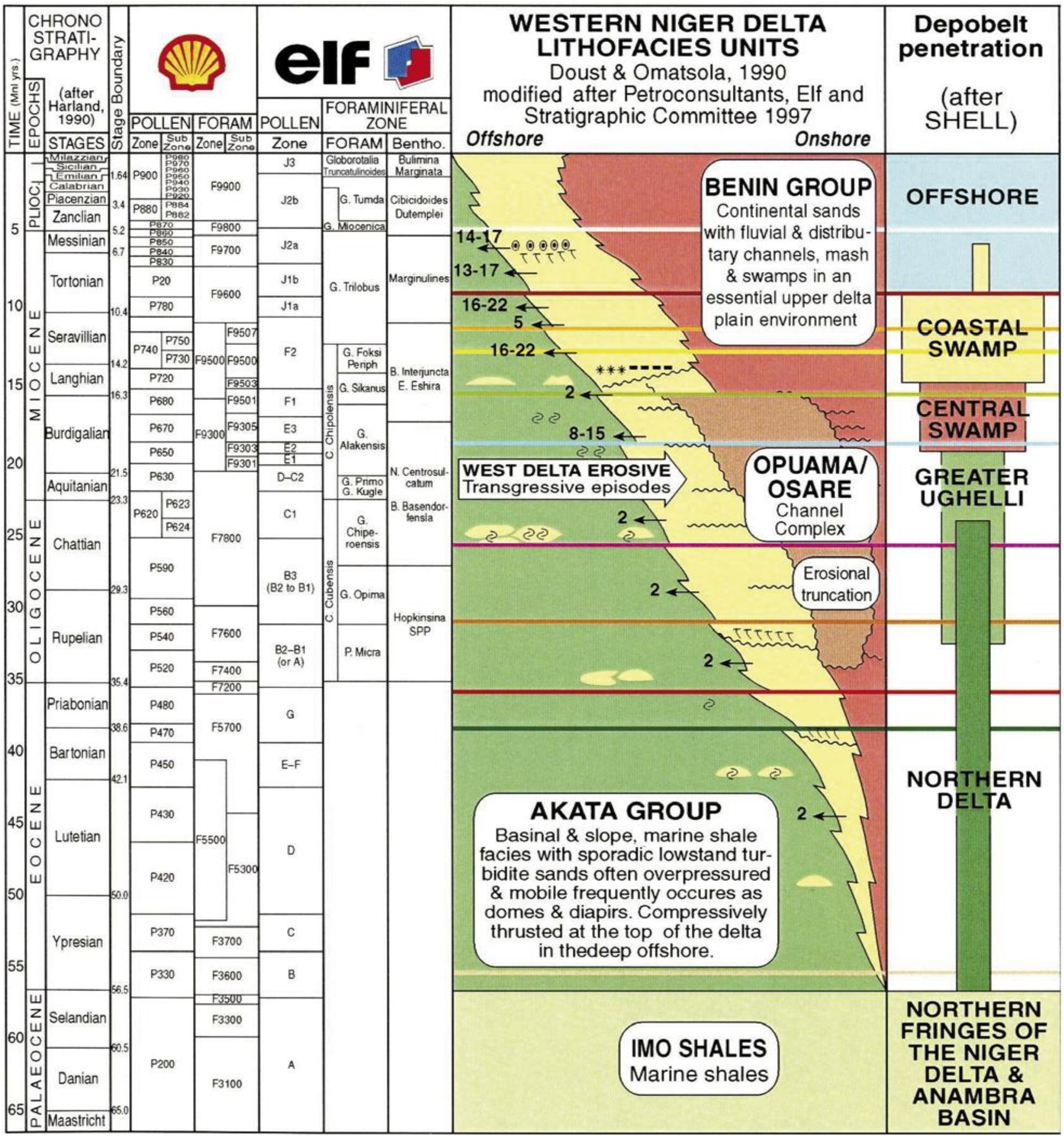

Figure 2: Detail Geology of the Niger Delta (Rejiers, 2011)

Benin, Agbada and Akata groups (Rejiers, 2011) in accordance with age. The prolific hydrocarbon bearing Agbada Group is sandwiched between the water bearing sand of Benin group and the highly pressured marine shale of the Akata group.

The deposits of the Benin group are solely the aquifers of the Niger Delta. The aquifer media are basically fine- to- medium coarse-grained sands and gravels, which are unconsolidated. Clay becomes predominant as environment of deposition tends to be transitional and more marine. In these environments, layers of clays and sand alternate each other giving rise to multiple aquifers in succession. The aquifer hydraulic conductivity is controlled by heterogeneity properties impacted by

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sandwiching of clays between sands horizons, termination of sand against clays, and intercalation of clays with sands. Hydraulic conductivity is also controlled by degree of grains sorting and environment of deposition. Beach sands are fine grain with good sorting and high yielding because of high energy of deposition. The high hydraulic conductivities which characterize beach sands encourage high infiltration of water into the aquifer underneath.

The watershed of the study area is drained by river Forcados, creeks and tidal inlets of the estuary. At the mouth of the Niger Delta basin, Forcados River empties into the Ocean. The river is more brackish, a characteristics of transitional environment. The saltiness of river Forcados is seasonally controlled; during dry seasons, it tends to be more brackish and less at wet seasons. Irrespective of the season the river water is always brackish and salty and is affected by 6 hourly tide.

Groundwater level measured around the south bank field ranges from 0.54-0.75m within domain of the study area. Groundwater is replenished by rainfall and groundwater stressing is through the deep confined aquifers pumping and evapotranspiration. Unlike most other coastal area the study area lacks hand-dug wells but has deep wells with depths greater than 400m deep. Rainfall is above 4000mm per annual and daily temperature varies from 24- 34 degree Celsius.

MATERIALS AND METHODS

Acquisition and Data Processing of 2D ERT

ABEM SAS 4000 Tarrameter equipment was utilized for the field investigation. The Werner configuration consisting of 64 electrodes spaced at minimum and maximum distance of 2.5 and 5m was used for the acquisition of ERT data. Each of the 64 electrodes as usual was driven into the ground surface and firmly secured in place. Electrodes were joined with some multicore cables to a switch panel. The current and potential terminals from switching panel were joined to the corresponding terminals of the Terrameter. The switching panel is made of sockets, which are coupled to electrodes by the multicore cable system. The arrangement of the whole system was such that there was continuous recording of apparent resistivity without movement of the electrodes. The terminals pins were fused with current source and they were retained inside the sockets. Acquired data were processed by smoothness-constrained least square inversion algorithm (RES2DINV) procedure of Loke and Barker (1996). The programme performs computation by forming grids. The finite-difference method suggested by Dey and Morrison (1999) was used in deriving apparent resistivity. The pseudosection contouring methods of Loke (2000) was also used to display apparent resistivity values. Furthermore, to reduce the difference between the measured apparent and calculated resistivity values to nearest minimum, the resistivity of the block was adjusted iteratively. The magnitude of the difference was measured by Root Mean-Squared-error (RMS). The computer iteration continues till RMS error was less than 5% or when RMS error values became inconsequential with successive iterations (Batayneh, 2006). Obtaining low RMS error may not actually always suggest an accurate model (Loke, 2000), but probably reveal unfeasible adjustment in the resistivity model.

RESULTS AND DISCUSSION

Figure 3 represents electrical resistivity tomography data acquired from the area opposite the Niger River mouth. This area represents where saltwater from the sea mixes with freshwater and its subsequent discharge into the sea. This profile clearly revealed the dominance of low resistivity images, which ranged from 0.146 to 9.43Ωm along the lateral extent of the entire topmost layer. Its occurrence is circumscribed to the first 4m of the subsurface. These ranges of resistivity image indicate continued inundation of the ground surface with saltwater when tides are high. Those images with resistivity values of 0.147 to 3.33Ωm are considered to be saltwater that infiltrated into fluvial and marine sand comprising the aquifer in this area. The Underneath layer is another resistivity layer which ranged from 9.33 to 74Ωm laterally, the layer may be described as region of mixing between freshwater that is probably discharging and seawater from the sea. The gradual increase in resistivity values according to depth is evidence of brackish water, which result from resultant mixing of both freshwater and saltwater. In this profile, the interface between freshwater and saltwater may be situated at about 10m depth. It may also represent region of groundwater discharge into the sea and recirculation of saltwater.

The saltwater/freshwater interface reflects gradual increase trend in resistivity with depth, an indication that the boundary is not sharp but a transitory in this profile. The transitory nature of the interface is controlled by diffusive mixing as result of dispersion of saltwater flow (Barlow, 2013). Laterally along the profile, resistivity values conspicuously increased from the right side to the left of the profile, an indication of the direction of how the saltwater will ingress towards the land should the freshwater be over-abstracted in the future.

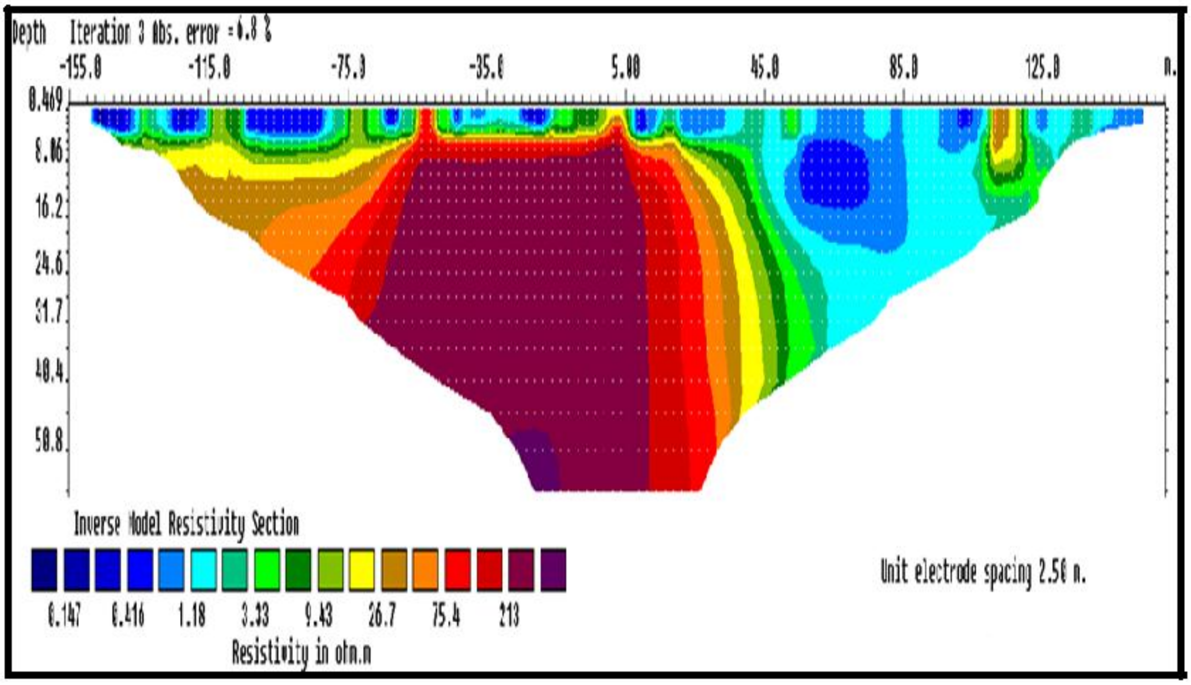

Figure 3: A Pseuduosection acquired from the mouth of River Niger

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Figure 4 is the electrical resistivity tomography data obtained at high tide mark from Ogulagha estuary. This profile is uniquely distinctive in possessing low resistivity values both laterally and vertically through the figure. The topmost layer revealed very low resistivity image values that vary between 0.375 and 1.06Ωm, with thickness approximated to be 7.0m. This layer is interpreted as moist fine marine sand. The low resistivity values associated with this layer evidently depicts saltwater inundating the high tide mark. The inundation is prompted by ocean tide and subsequently infiltrate into the marine sand. The amplitude of the tide is relatively lesser than 3.8m height required for tide to have significant effect on groundwater level fluctuation and on the thickness at the region of saltwater and freshwater mixing in coastal aquifers (Ataie-Ashtiani et al., 2001). This underscore the fact that tide of the ocean at the study site probably does not have affect on groundwater level and but impact seen is that from the inundation of the high tide mark with saltwater from the ocean. The other subsurface formations below this low resistivity layer are sequences of resistivity layer. They have resistivity values greater than 1.06Ωm and lesser than 4.2Ωm. These successive layers are mainly porous and permeable marine sand or reworked sand. These sands somewhat enhance continuous infiltration and percolation of saline water from the surface to topmost layer. The gradational decrease in the resistivity values with depth significantly suggests decreasing salinity of the groundwater aquifer adjacent to the Atlantic Ocean. Since the maximum resistivity image observed is less than 5Ωm, it actually suggests that the absence of brackish water at this location, but it rather indicates saturation with entirely saltwater. Conspicuously absent from the profile is freshwater/saltwater interface. The inability to reveal the interface in this profile is due to the electrode spacing which is designed not to exceed 5m. From the displayed of resistivity images with depth in this profile, there an indication that the interface is probably located deep down beyond what the profile revealed at depth 50.8m. From the resistivity image of this profile, it can be assumed that the saltwater interface is vertical at this region; the high-tide-mark is parallel to the ocean and not possible to show increasing freshwater towards the land. The assumption is evidently supported by the increase in the resistivity values from the top to the base as showed in Figure 3. In order to ascertain where the lateral interface between saltwater and freshwater is located, the profile is run perpendicular to the ocean, which I will investigate further in another study.

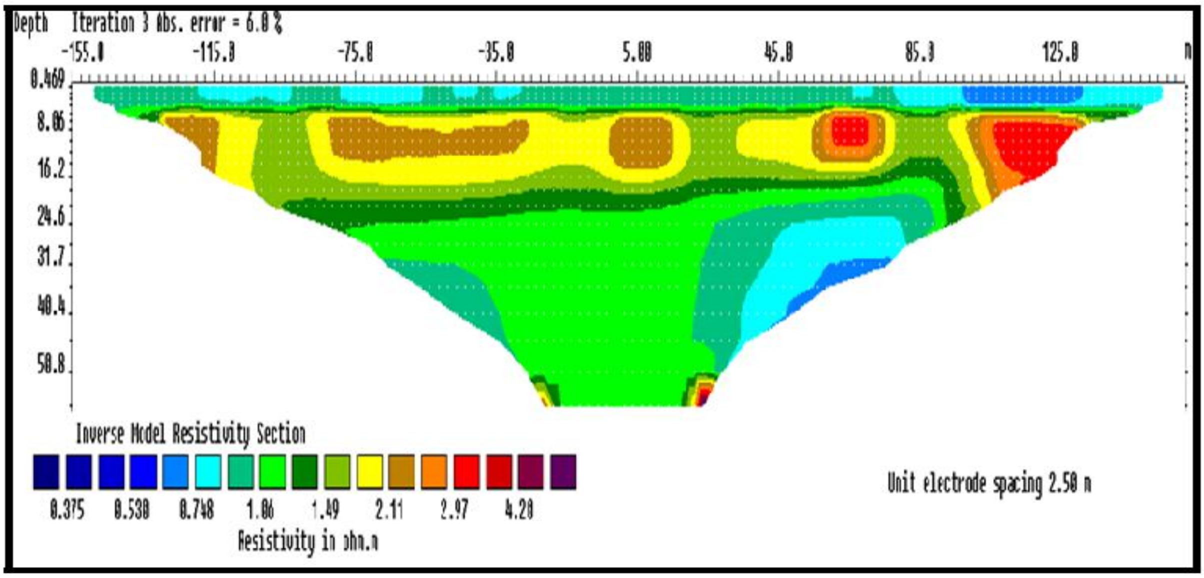

Figure 4: A Psedudosection obtained from the high- tide- mark

Figure 5 describes the electrical resistivity tomography data acquired from Ogulagha town. The uppermost layer is made up of resistivity images which range from7.4 to 70Ωm, the layer interpreted as clay. The moderate resistivity of the upper layer in this profile underscores the fact that saltwater is not present and as such not affected by tide. The nonexistence of saltwater in the uppermost layer of the profile is consistent with the fact that, the effect of tide on groundwater aquifer tends to wane with distance from the coastline (Turner et al., 1996; Sun 1997; Li and Jiao 2003). In addition, the absence of saltwater also points to the fact that the slope of the beach plays a significant role on how far the tide can affect inlands aquifers. This buttressed the fact that tide being experienced at the study site is of low amplitude and, as such could not affect aquifer in further inland from the high -tide –mark.

Underlying it, is a high resistivity images values with minimum of 123Ωm and maximum of 494Ωm, the layer is surrounded by a lesser resistivity image values of about 70Ωm. It extends from 80m to about 257m laterally along the profile but with variable thickness that is thin in some area and thick in others. This extensive layer is interpreted as sand saturated with freshwater lenses and the bounding layer as clay. Occurring below this layer at depth 49m is successive resistivity images of decreasing resistivity values, which are 60, 30.4 and 7.4Ωm respectively. Significantly, it probably suggests that freshwater/saltwater interface is situated at this depth. The decreasing resistivity images strongly specifies that the interface between the freshwater groundwater and saltwater is described as distinct boundary. The occurrences of freshwater lenses floating on top of saltwater represent stable condition. Development of this unconfined aquifer may precipitate the movement of saltwater from the saltwater zones considering the thin thickness of the lenses.

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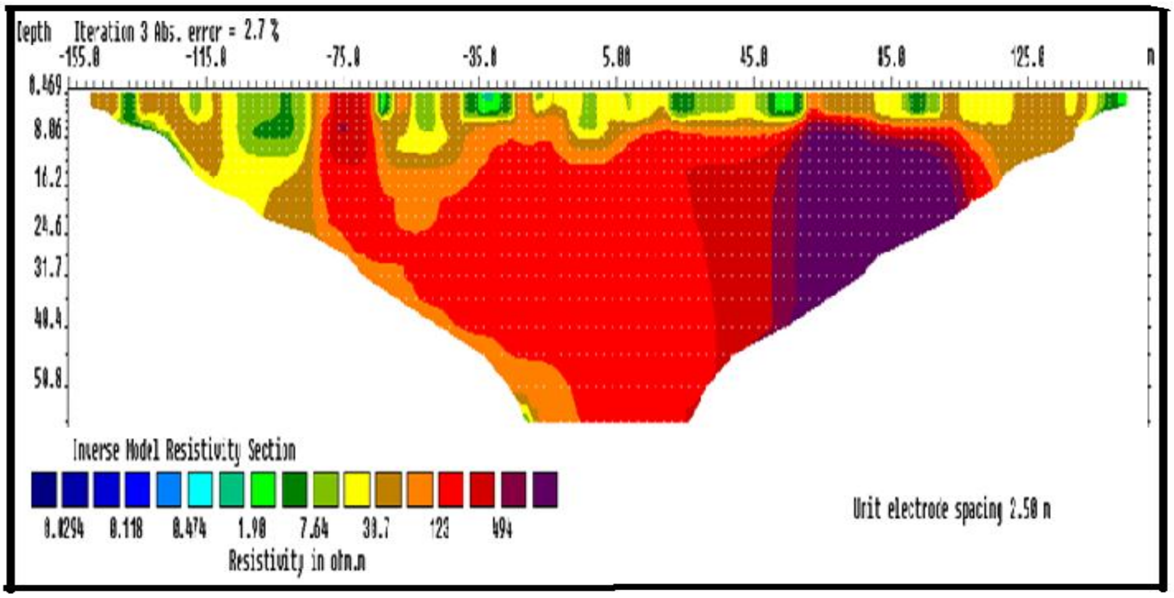

Figure 5: Psedudosection obtained from the Ogulagha town

2D Electrical Resistivity Imaging data acquired with a 64 multi-electrodes SAS 4000 ABEM Terrameter with 5m electrode spacing has been used to investigate the effect of tide on groundwater quality at the Ogulagha estuary. The effect of tide is most pronounced on the upper most geologic layers situated at the high-tide-mark but with no significant impact on aquifer situated further inland from the high- tide-mark. This points to the fact that the amplitude of tide being experienced at Ogulagha is not high enough to affect aquifers situated further inland from the high-tide-mark investigated in the study. The gradual decreases in resistivity with depth revealed in the study is due to mixing of saltwater with freshwater at the point of discharge and recirculation. The low resistivity of the upper most geologic layers is probably caused by the inundation of the high- tide- mark with saltwater. The infiltration of inundated saltwater into groundwater aquifer is responsible for the deterioration of groundwater quality. Moderate resistivity values of 2-4 Ωm of the underlying geologic layers indicated mixing of freshwater from inland aquifer and saltwater from the ocean.

The profile acquired from the high -tide - mark parallel to the ocean has a thick vertical zone of saltwater of 50.8m and believed to be deeper than what is revealed from 2D ERI data interpreted. It indicates that freshwater could be located at depth deeper than the depth probed in the study. The absence of saltwater zones in the profile from the Ogulagha town underscores the availability of freshwater and the position of the saltwater/freshwater interface is relatively deeper than revealed in the study.

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