



Time-lapse electrical resistivity investigation of seawater intrusion in coastal aquifer of Ibeno, Southeastern Nigeria

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Abstract

Saltwater intrusion, erosion, and periodic flooding during severe storms are some of the critical problems bedeviling the precarious coastal environment of Nigeria. A time-lapse study aimed at monitoring the dynamics of saltwater intrusion within the coastland surrounding Ibeno, southeastern Nigeria is presented. Three (3) vertical electrical soundings (VES) and four time-lapse electrical resistivity tomography (ERT) profiles with minimum and maximum electrode spacing of 5 m and 40 m and profile lengths of 120 m and 150 m respectively were acquired in 2016 and 2017 using the Wenner and Schlumberger arrays. Data acquired from the field surveys were modeled with WINRESIST and RES2DINV software to generate 1D and 2D resistivity images of the subsurface. The VES results with a maximum survey length of $AB = 300$ m revealed a four-layer KH curve. The 2D geo-electrical sections delineated contrast between the high resistivity values obtained for the saturated freshwater zones and the low resistivity values obtained for the saturated saltwater zone. Expectedly, the intrusion was dominant nearer the coastline than inland. The salinity changes are believed to have been caused by both incremental tides passing through highly porous materials in the active-salinity change area and over-pumping of groundwater. The time-lapse resistivity measurements showed significant, active lateral salinity changes rapidly intruding the freshwater aquifers. The study demonstrates the application of time-lapse 2D ERT and vertical electrical sounding in identifying the spatial and temporal changes of saltwater intrusion in the coastal aquifer.

Keywords Saltwater intrusion · Vertical electrical sounding · Electrical resistivity tomography · Coastal aquifers · Time-lapse ERT · Ibeno

Introduction

The economic significance of coastal regions and its consequent rapid increase in population cannot be overemphasized as major cities of the world are situated there. The need for their development has led to increasing emphasis on developing available resources including groundwater (George et al. 2014). The southern part of Akwa Ibom State

in Nigeria, which harbors more than 30% of Nigeria's crude oil resources, is presently experiencing an increase in human population and industrialization (Edet and Okereke 2001a, b). The availability of groundwater resources in this area has never been in doubt, because geologically, the study area comprises highly productive aquifers (Edet 2017). The challenge, however, has been that of poor groundwater quality due to increase in rate of potable water abstraction and uncontrolled land-use practices among others. These practices have negative impact on groundwater quality, and one of such is saltwater intrusion (Edet and Okereke 2001a, b; Udom et al. 1999, 2002).

Saltwater intrusion is a global environmental phenomenon that affects the chemical composition of the coastal groundwater and this may be more critical in the near future due to the increasing sea level rise associated with climate change (Antonellini et al. 2008). Furthermore, growing water demands and manipulation of natural hydrologic systems have led to saltwater intrusion being considered a

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significant future threat to coastal freshwater resources globally (Kinzelbach et al. 2003; Barlow and Reichard 2010; Werner et al. 2013).

Delineation of marine intrusion in coastal aquifers has traditionally relied upon observation wells and collection of water samples (George et al. 2015; Mahjoub et al. 2017). This study area is not an exception. Several studies on saltwater intrusion or contamination in the southern Akwa Ibom area mostly deal with water quality and geochemical assessment (Edet and Okereke 2011a, b; Inim et al. 2017; Edet 2017; Affiah et al. 2018). Measurements made in wells provide point data, which may fail to capture the spatial complexity in subsurface conditions. Improving the spatial coverage with additional wells will attract additional cost. Time-lapse geo-electrical surveying attempts to detect variations in the electrical properties of the subsurface with time, introducing an additional dimension into the data collection (Giordano et al. 2017; Loke et al. 2017; Du et al. 2018; Shin et al. 2019). This technique can be carried out over short time periods (e.g., several days with readings taken every few hours) and has been used for the evaluation of the migration of contamination plumes (Chambers et al. 2004; Radulescu et al. 2007), early detection of dam failure (Shin et al. 2019) the detection and monitoring of concentration of conductive contaminants within aquifers (Chambers et al. 2004; Cassiani et al. 2006; Oldenborger et al. 2007), the quantification of superficial water infiltration rates into the subsurface (Barker and Moore 1998), and tracer test monitoring (Monego et al. 2010; Ward et al. 2010). Long-term time-lapse resistivity surveys have been applied in the monitoring of seasonal variations on seepage rates (Johansson and Dahlin 1996; Sjö Dahl et al. 2008) and the monitoring of salinity within aquifers in coastal areas (Leroux and Dahlin 2006; de Franco et al. 2009; Ogilvy et al. 2009).

Coastal regions in Nigeria are affected by saltwater intrusion. Although studies have been carried out in other parts of the country to investigate the extent of the problem, this study is the first in Ibeno area, a major oil-producing area in Nigeria. There has been very limited research on the problem of saltwater intrusion in the region, but the problem is expected to worsen in the future as a result of coastal erosion, climate changes, increase in sea-level rise, and increase in human population (with a corresponding increase in the demand for potable water). A deeper knowledge of the problem is important to help the government plan for the future.

Saline water intrusion does occur naturally but mostly becomes a problem when freshwater is pumped from the aquifer. Pumping of freshwater reduces the aquifer's hydraulic head. This causes reduction in the elevation of the water table and enables the seawater to move inland. Another problem associated with overexploitation of groundwater is upconing, and this occurs when saltwater from the surrounding underlying saltwater wedges are drawn up a well, causing a

contamination of the freshwater resources. Increases in sea-level rise, extreme weather events, reduced natural recharge from rainfall, can all cause an inland shift of the saltwater–freshwater interface, contaminating freshwater sources and aggravating the problem of saltwater intrusion. In the study area, the occupants use wells to pump freshwater to the surface, and this aggravates the problem of salt water intrusion. As it so happens in this densely populated locality, more freshwater is typically withdrawn than the aquifer can supply, leading to pumping out of saline water, and a consequent abandonment of the well.

According to IPCC (2007), climate change will lead to increase in sea level rise, changing precipitation patterns, extreme weather events, and coastal erosion within the coastal areas. This will make water supplies even more vulnerable to saline water contamination especially for people living along the coastline. IPCC (2007) has predicted that by year 2100, the sea will rise to values ranging from 18 to 59 cm globally. As alarming as such predictions are, Rahmstorf (2010) has predicted even greater levels of sea-rise (values twice more than that predicted by IPCC.) This rise will definitely lead to increases in the rate of seawater intrusion along the coastline and will affect infrastructure and residential areas in areas close to the coastline. This study aimed at assessing seawater intrusion using the time-lapse electrical resistivity approach to understand the spatial and temporal changes for better planning and management of groundwater resources. Data acquired from the field surveys were modeled with WINRESIST and RES2DINV software to generate 1D and 2D resistivity images of the subsurface.

Setting of study area

The study area (Ibeno) which is located in the coastal area of Akwa Ibom, southeastern Nigeria, lies between Latitudes 4°30'N and 4°36'N and Longitudes 7°48'E and 8°18'E. The area is drained mainly by Imo River, Kwa Iboe River, and Cross River together with their tributaries (Fig. 1).

The area is characterized mostly by flat lying sandy deposits, while the main landforms are mangrove swamps and floodplains with recent alluvial accumulations, beach ridges, and mangrove mudflats (Petters 1989). The area experiences two seasons: wet season (April–October) and dry season (November–March), while the average annual rainfall is about 3000 mm characterized by humid tropical climate. Geologically, the study area is underlain by Recent to Tertiary sediments belonging to the Benin Formation of Niger Delta. The grain size of these sediments ranges from coarse to fine in texture and are poorly sorted. They have great thickness and minor intercalations of clay, silts, and sandstones with alternating sequence which builds up multiple aquifer systems with various thicknesses. The major

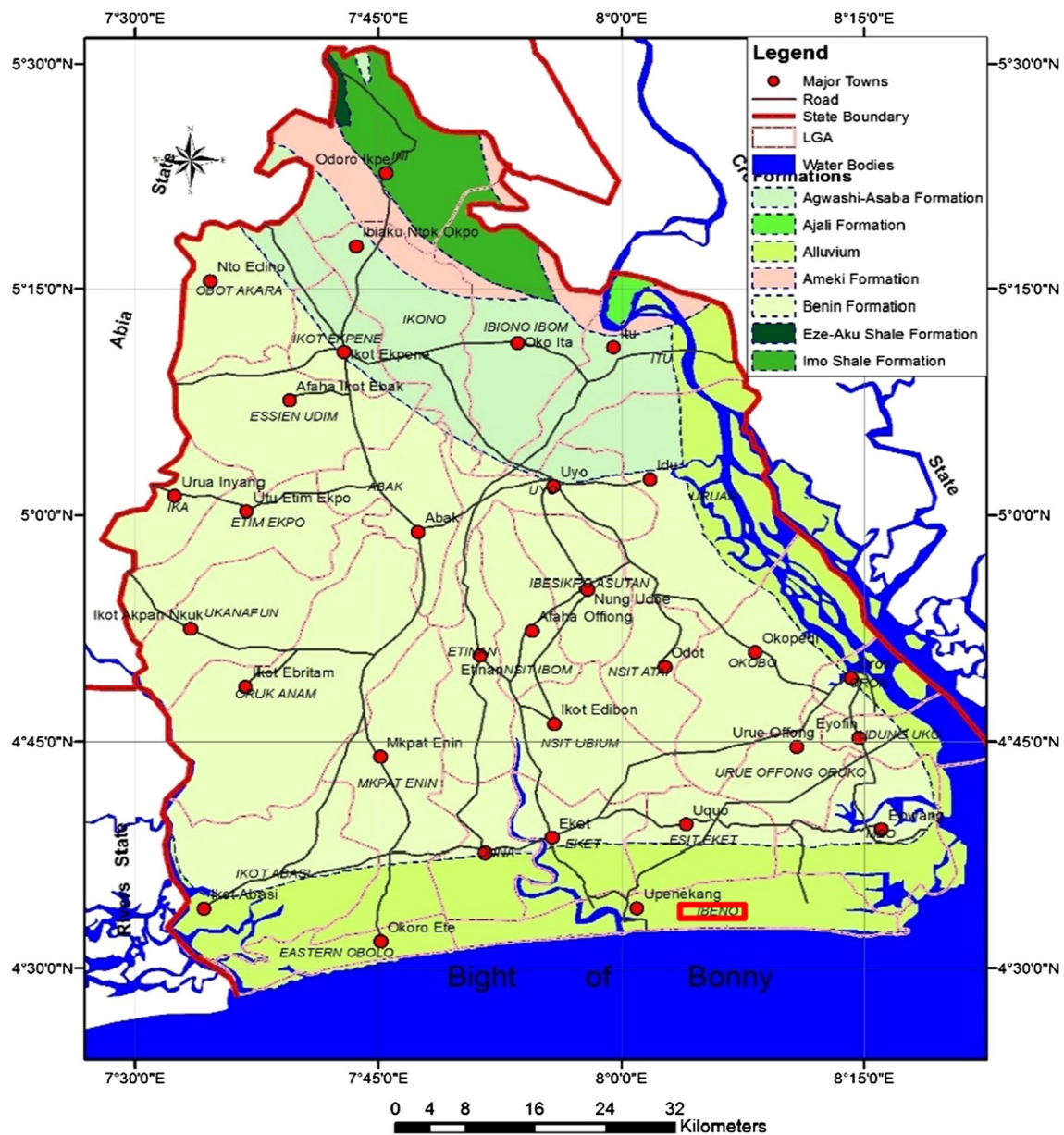


Fig. 1 Geologic map of the study area

hydro-stratigraphic units within the study area are the upper sandy aquifer comprising recent alluvial material and the coastal plains of Benin Formation (Esu et al. 1999). These Coastal plain sands are mostly made up of unconsolidated sands and gravelly sands with clay intercalations, while the Alluvium comprises gravels, lateritic sands, fine to medium grained, and carbonaceous sand (Esu et al. 1999). The upper sand aquifer has the following characteristics: thickness 20–200 m, saturated thickness of aquifer 39–100 m, static water level 1–55 m, yield 316–530 m³/d, transmissivity 200–8300 m²/d, hydraulic conductivity 2–28 m/d,

drawdown 1.2–42.5 m, and storage coefficient 0.10–0.30 (Esu et al. 1999).

Materials and methods

An ABEM terameter was used to collect vertical electrical sounding (VES) and time-lapse electrical resistivity tomography (ERT) data. The VES method, employing Schlumberger electrode configuration, was used to obtain three profile lines. The maximum current electrode separation was 100 m for VES line 1, 150 m for VES line 2 and VES line 3.

The WINRESIST software was used to generate logarithmic curves of apparent resistivity against AB/2.

Data acquired from the VES field survey were modeled with WinResist software to generate VES resistivity images of the cross section of each profile line. The ERT survey was carried out along four profile lines: ERT Line 1, ERT Line 2, ERT Line 3, and ERT Line 4 (Fig. 2). Along ERT Line 1 and ERT Line 2, the profile length was 120 m. Along ERT Line 3, the profile length was 135 m, and along ERT Line 4, the profile length was 150 m. Minimum and maximum electrode spacing of 5 m and 30 m was used in the ERT surveys. The Wenner configuration was used due to its high sensitivity to horizontal structures, low sensitivity to geological noise, and strong signal strength which is useful in areas with high background noise. Data acquired from the field survey were modeled with RES2DINV software from Geotomo to generate 2D resistivity images of the cross section of each profile line. Time-lapse ERT surveys were undertaken in March 2017 (12 months after the initial survey in 2016).

Results and discussion

VES and ERT survey

Qualitatively, the VES curves revealed a KH type for which $\rho_1 < \rho_2 > \rho_3 < \rho_4$, while quantitatively (interpreted using existing borehole lithology log within the study area) (Fig. 4b), it revealed (Fig. 3, 4a), from top to bottom the following layers; lateritic top soil with resistivity and thickness ranging from (180–280 Ωm) and (0.5–1 m), respectively, freshwater sand with resistivity and thickness ranging from (340–1667 Ωm) and (1–6 m), respectively, and saline sand with resistivity and thickness ranging from (14–112 Ωm) and (4–13 m), respectively. Underlying the saline sand is clayey sand with resistivity values ranging from 560–2500 Ωm with infinite depth.

The four ERT sections delineated contrasts between the high resistivity values obtained from the saturated freshwater zones and the low resistivity values obtained from the

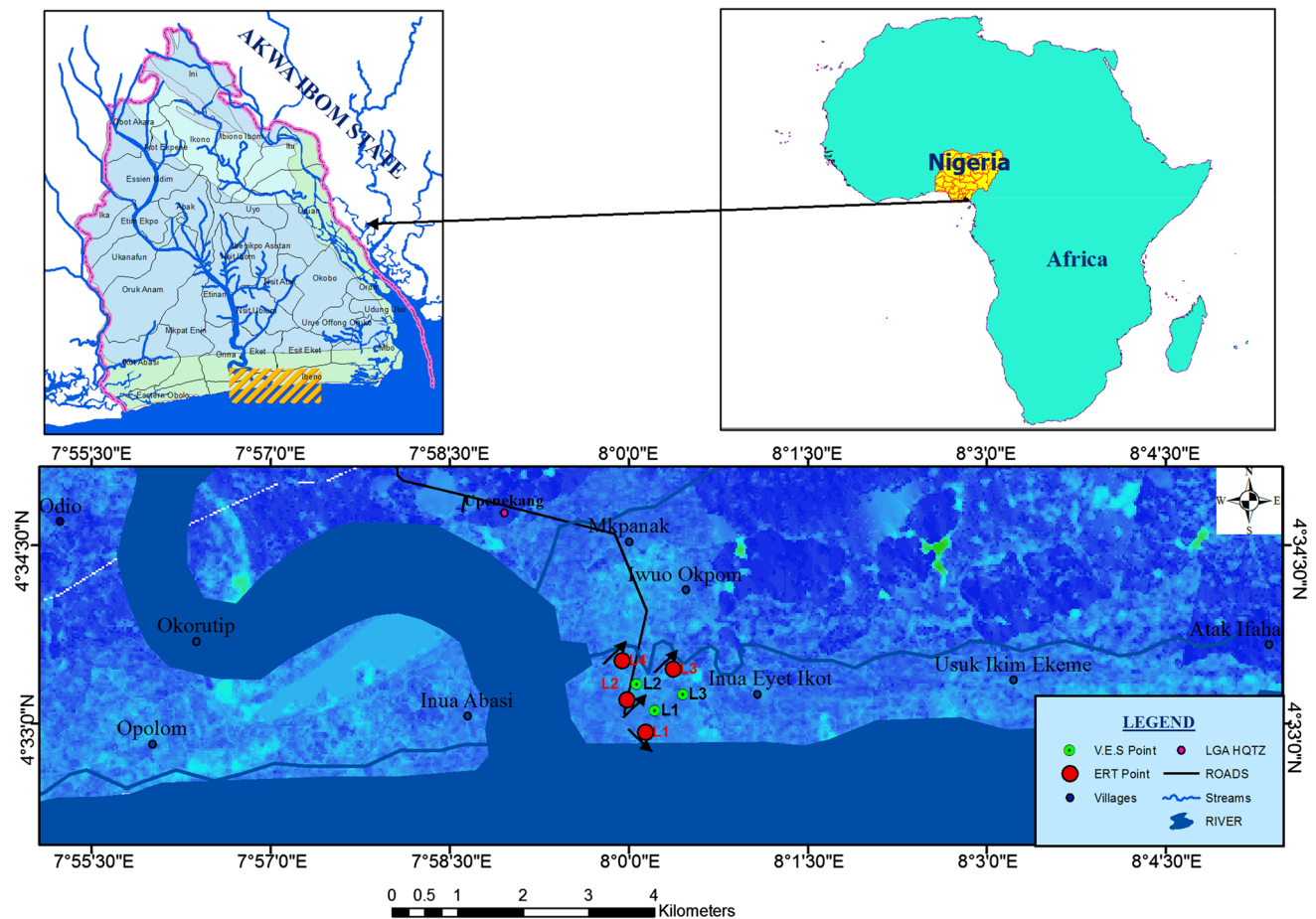


Fig. 2 Map of the study area showing survey lines

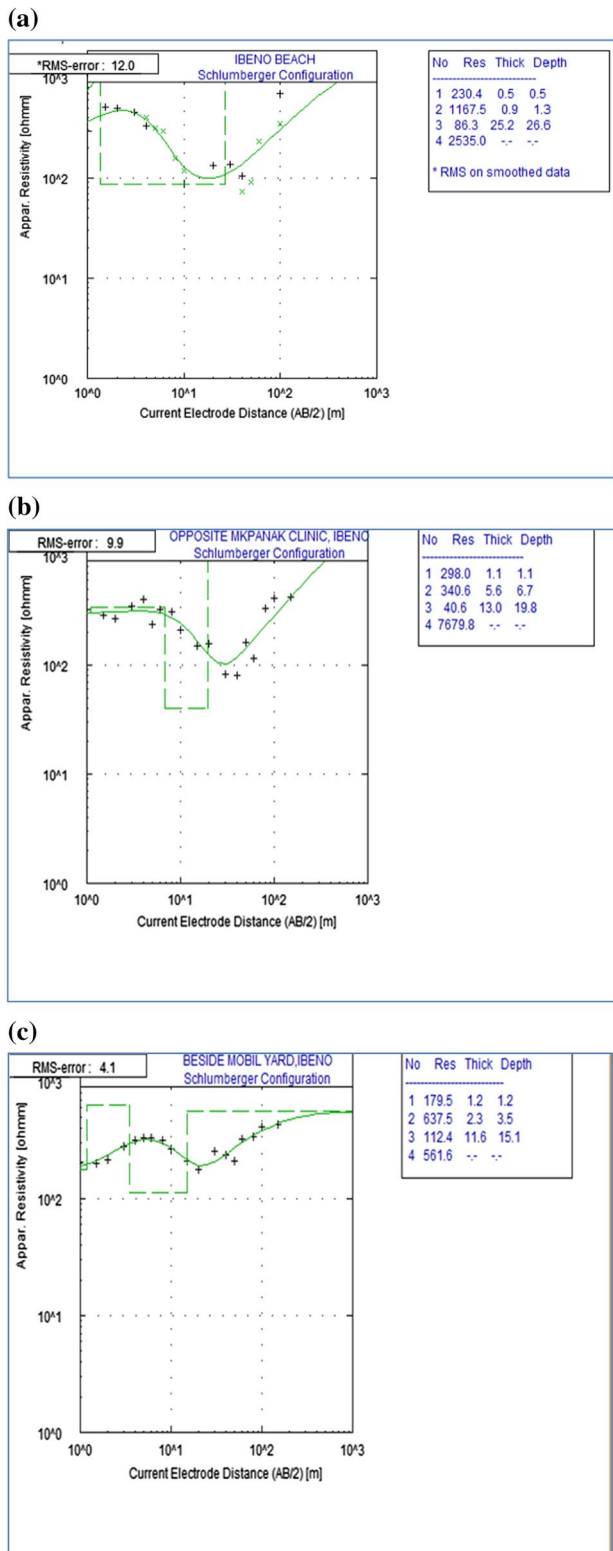


Fig. 3 Resistivity profiles generated from vertical electrical sounding data. **a** VES 1, **b** VES 2, **c** VES 3

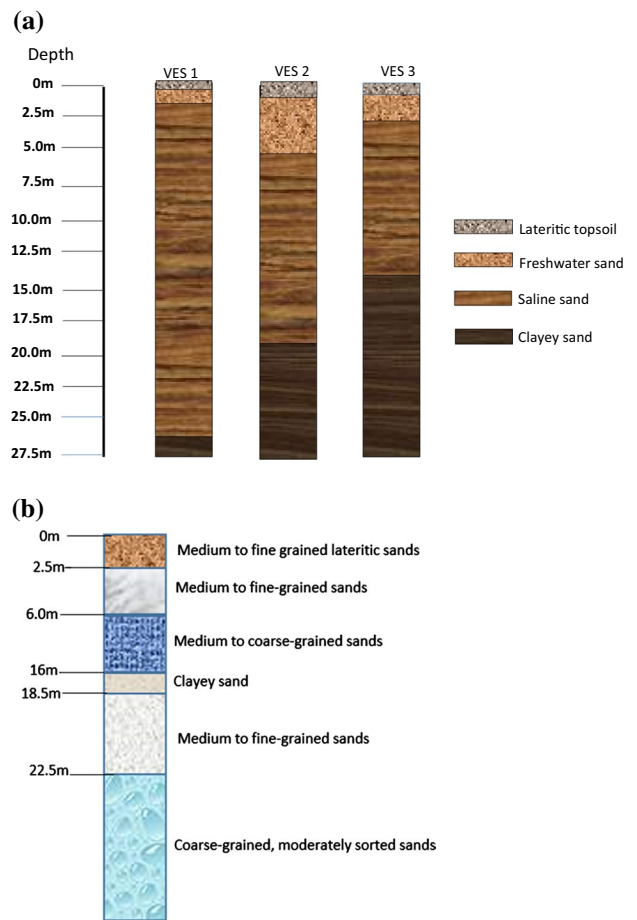


Fig. 4 **a** Qualitative interpretation of VES model obtained, **b** bore-hole lithology logs

saturated saltwater zone and revealed three distinct resistivity zones. The first ERT profile, ERT1, acquired in 2016 which runs NW–SE; upland to coastline (Fig. 5a) shows a top layer of high resistivity ranging from 140 to 300 Ω m with approximately 4 m vertical extension which corresponds to unconsolidated sand (top soil). This is underlain by a layer of low to medium resistivity (10–100 Ω m) with a depth range of 4–18 m. This second layer corresponds to the sandy aquifer which is intruded by saline water. Underlying this aquifer is another higher resistivity zone (300–800 Ω m) which represents the consolidated clayey sand formation.

The second ERT profile, ERT2, acquired in 2016 runs in SW–NE direction (Fig. 5b) and reveals a medium resistivity zone on the top that corresponds to the sandy clay unit. The region of low resistivity values (below 153 Ω m) underlying the sandy clay unit of the profile corresponds to the sandy aquifer intruded by saline water, and it extends from depth 8 m to more than 20 m. The sandy aquifer intruded by saline water is underlain by a high resistivity layer which corresponds to a sand pocket with resistivity values above 390 Ω m with depth ranging from 19 m to more than 30 m.

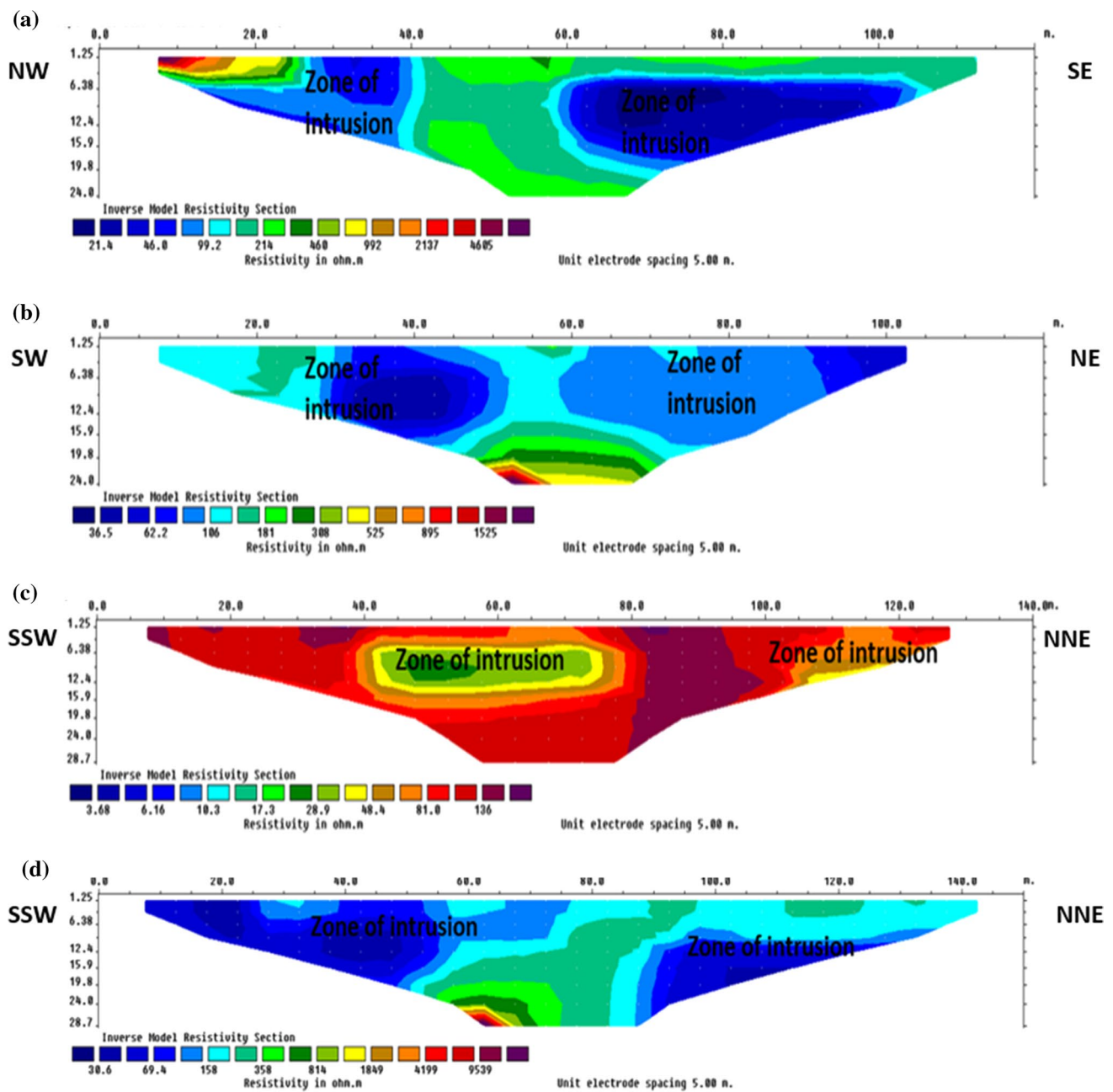


Fig. 5 ERT profiles obtained in 2016 a ERT 1 profile, b ERT 2 profile, c ERT 3 profile, d ERT 4 profile

The third ERT profile, ERT3, acquired in 2016 runs in SSW-NNE direction (Fig. 5c). The first zone with resistivity values ranging from 80 to 100 Ω m and depth of 2 m represents the top soil. Underlying it is the saline water intruded sandy aquifer with resistivity values ranging between 17 and 50 Ω m and depth range of 2–25 m. The third zone representing consolidated clayey sand shows resistivity values greater than 200 Ω m at depths ranging from 20 to 30 m.

The fourth ERT profile, ERT 4, acquired in 2016 profile runs in SSW-NNE direction (Fig. 5d). The first zone with resistivity values ranging from 150 to 300 Ω m and depth of 2 m represents the top soil. Underlying it is the saline water intruded sandy aquifer with resistivity values ranging between 30 and 150 Ω m and depth range of 2–20 m. The third zone shows resistivity values ranging between 800 and 1500 Ω m with depth range of 20–30 m representing consolidated clayey sand.

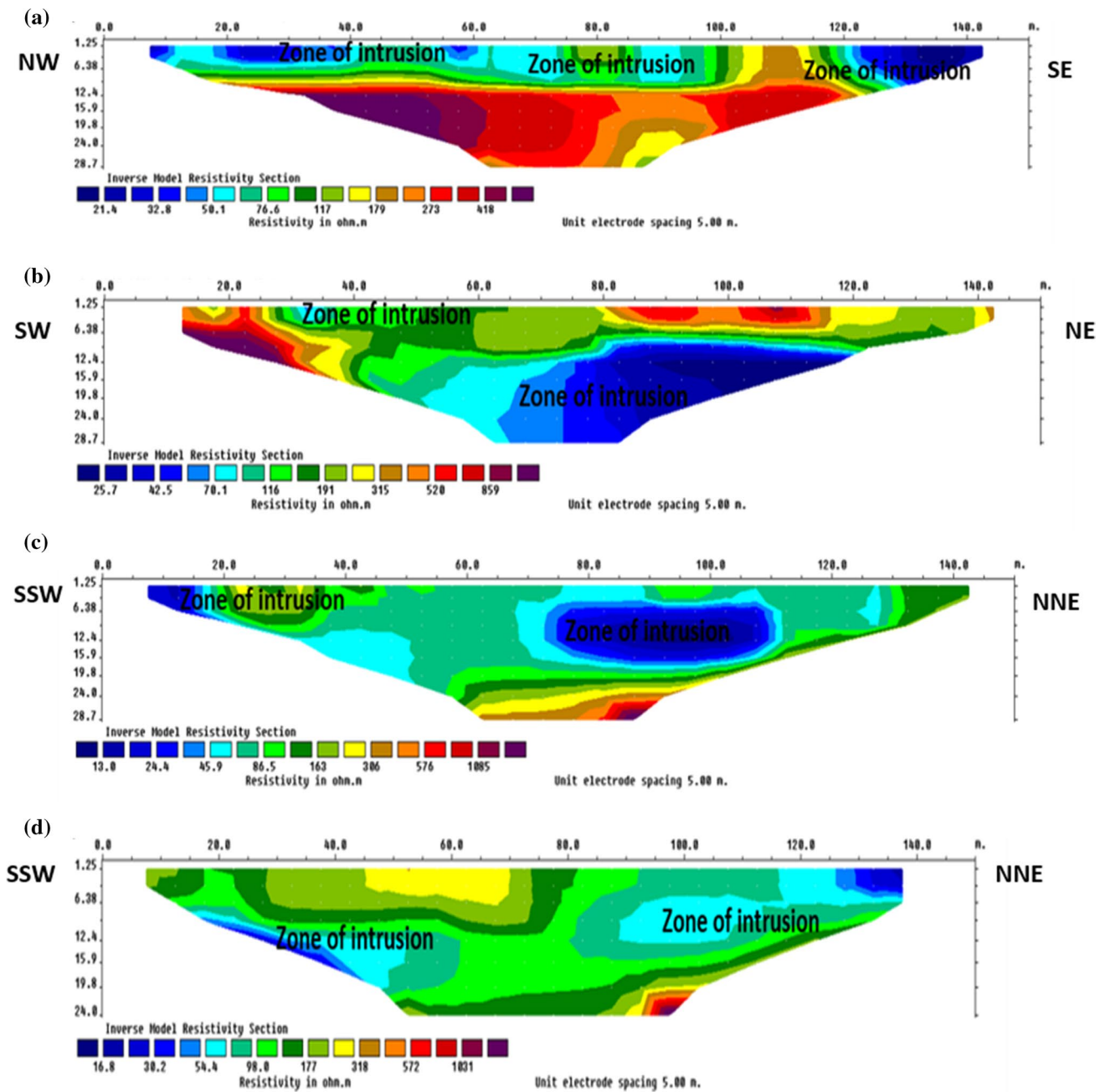


Fig. 6 ERT profiles obtained in 2017 **a** ERT 1 profile, **b** ERT 2 profile, **c** ERT 3 profile, **d** ERT 4 profile

In 2017, ERT data were again acquired at the exact locations and profile lines as those previously obtained in 2016 (see Fig. 6a–d). This was to enable the determination of the extent of saline intrusion.

Figures 5 and 6 show that the saturated freshwater zones are denoted with high resistivity values. The high resistivity values denote the near surface unsaturated zone, which decreases gradually. The reduced resistivity values indicate the presence of saltwater at depths between 0.5 and 20 m

(Figs. 5,6). The saltwater–freshwater interface appears to occur at depths as shallow as 10 m, and since it is rarely a sharp boundary, the interface does extend on some of the profiles downwards to depths as large as 18 m (e.g., Fig. 6c). It can be seen that the boundary between the freshwater and the saline water is not static, but transits seasonally depending on climatic conditions. This interface, as obtained in this work (see Figs. 5,6) is not a sharp boundary, but a gradual zone of transition (otherwise called zone of dispersion) where the salt water mixes with freshwater water. During

the rainy season, there is a greater supply of freshwater in the study area and consequently, the freshwater–saline water interface shifts towards the sea which is the case in this study area. During such months, the extreme salinity is reduced. On the other hand, during the dry season, there is generally less supply of groundwater, and more salt water shifts inland from the sea.

Time lapse images

The difference map images were further obtained by subtracting raw resistivity values obtained on the field in March 2017 from raw resistivity values obtained on the field in March 2016, profile line by profile line. The difference values served as input for inversion with RES2DINV to generate the time lapse images shown in Fig. 7. The high resistivity values on the time lapse images indicate greater increase in salt-water intrusion. In other words, the resistivity values obtained in 2016 were lower than those obtained in 2017. The difference between those values would indicate the extent of intrusion.

In the case where the difference between resistivity values obtained in 2017 and 2016 is minimal, the time-lapse or difference images would show low resistivity values (and this would indicate reduced rate of intrusion). Where the difference between resistivity values obtained in 2017 and 2016 is large, the time-lapse or difference images would show large values of resistivity values and this indicates increased rate of intrusion. The latter is the case at the study area.

The results show that the extent of intrusion is increasing with time. The time lapse for the profile lines shows positive resistivity values ranging from 0.112–45 Ωm with significant higher values inland, which indicates more conductive zones the subsequent year.

The difference map from profile line 1 (ERT1) (Fig. 7a) shows a top layer with resistivity values ranging from 20 to 60 Ωm with a vertical extension of about 20 m, indicating a large difference between saline intrusion in 2016 and 2017. The large difference in resistivity values indicates that there is high increment in intrusion with time within the top soil between the two consecutive years. This is attributed to anthropogenic factors such as over-pumping (which comes as a result of increase in population with time), climate changes, increase in sea-level rise, and seasonal tidal influence. The second layer has medium resistivity (1.5–20 Ωm) with a depth range of 1–12 m. These medium values of resistivity within the sandy aquifer zone indicate increased intrusion in 2017 compared to that in 2016, though lesser than that within the top soil.

The difference image from profile line 2 (ERT2) (Fig. 7b) shows a top layer with resistivity ranging from 20 to 40 Ωm with vertical extension of about 20 m. The difference in the resistivity values indicates greater intrusion between 2016

and 2017 within the top soil. The top soil overlies another layer with medium resistivity (1–20 Ωm) with a depth range of 1–12 m. The medium values of resistivity within the sandy aquifer zone indicate intrusion though lesser than that within the top soil. The difference images shown in Fig. 7 are similar, indicating greater intrusion in 2017 compared to 2016 within the top soil, the sandy aquifer, and the consolidated clayey sand.

The results obtained in this work complements that of Nowroozi et al (1999) who used resistivity imaging to study the extent of saltwater intrusion into the freshwater aquifer in the eastern shore of Virginia and that of Khalil (2006) where resistivity imaging was used to evaluate geo-electric parameters of the aquifer in the Abu Zenima area, West Sinai, Egypt. Yet another work that used resistivity to investigate the extent of saltwater intrusion was that of Choudhury et al. (2001) where resistivity imaging and seismic refraction were used to investigate the extent of intrusion in the alluvial belt of Digha, East India. Similar to our work, geophysics was able to delineate the geo-stratigraphic units and also showed that the saline zone decreased as one moved away from the shore. Safe zones for water exploitation were delineated on the basis of results obtained from geophysics, and unsafe zones not recommended for exploitation were also delineated. Their work also confirmed that geophysics was an extremely useful tool for investigation and delineation of salt water intrusion even when thick clay formations exist. Yet another work that illustrates salt-water intrusion mapping by geoelectrical imaging surveys is Nassir et al. (2000) where the geo-electrical method was used to map the freshwater–saline water boundary in Yan, State of Kedah, north-west Malaysia. The resistivity sections obtained from their work corroborated the results obtained from borehole and geological information gotten from the site. A sampling of some recent work (Giordano et al. 2017; Loke et al. 2017; Du et al. 2018; Shin et al. 2019) also illustrates that the resistivity method is a fast and efficient method with which to map the interface in an area.

The problem of salt water intrusion in the area is expected to worsen due to compounding factors like climate change and consequent increase in sea level rise, overpumping, increase in human population. Past work in the southern Akwa Ibom region focussed on water quality and geochemical assessment (Edet and Okereke 2011a, b; Inim et al. 2017; Edet 2017; Affiah et al. 2018) which only give point data about the given area in question. Though drilling measurements provide point data, they may fail to capture the spatial complexity in subsurface conditions. Drilling methods have been found to be a costly and formidable undertaking. In many cases, expensive and time-consuming pump tests, borehole drills and core analysis are carried out. This led to the search for economical and undemanding methods of quantifying saline water intrusion. A surface geophysical

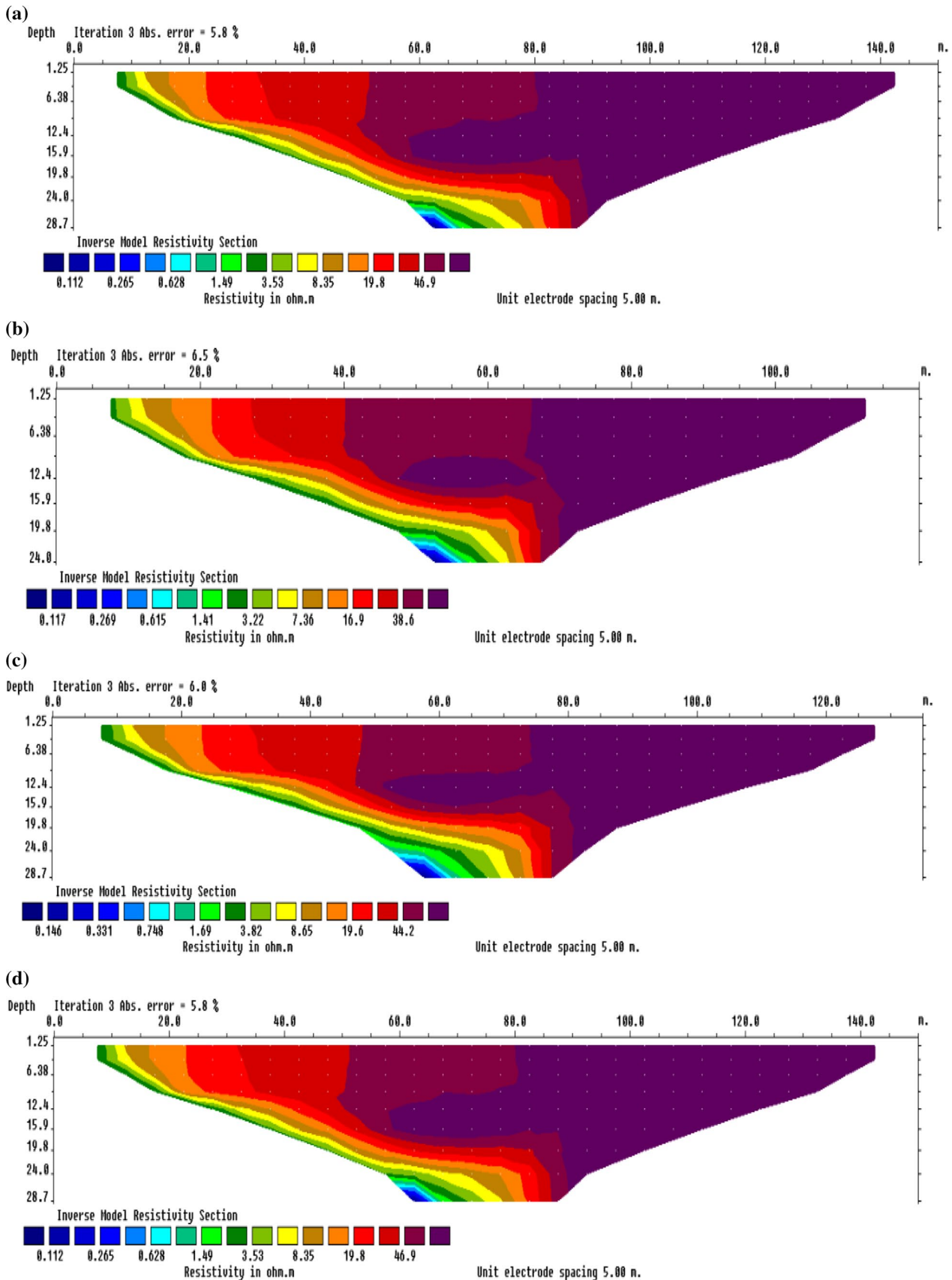


Fig. 7 Plot of difference (time-lapse) in resistivity values between 2016 and 2017, a TL_ERT1, b TL_ERT2, c TL_ERT3, d TL_ERT4

method, the resistivity technique, has been found to have the advantage of operational ease, speed, accuracy, noninvasiveness, and inexpensiveness. Time-lapse resistivity surveying attempts to detect variations in the electrical properties of the subsurface with time (Giordano et al. 2017; Loke et al. 2017; Du et al. 2018; Shin et al. 2019). The time-lapse electrical resistivity surveying carried out in the work has been shown in previous work to be a powerful tool for monitoring saline intrusion at different periods in time (Slater et al. 2002; Singha and Gorelick 2005; Cassiani et al. 2006; Leroux and Dahlin 2006; de Franco et al. 2009; Ogilvy et al. 2009).

Conclusion

In conclusion, time-lapse ERT and VES survey were conducted in Ibeno, South-East of Nigeria, to determine the extent and rate of saltwater intrusion within the coastal aquifer. DC resistivity surveys were carried out in 2016 and 2017 to delineate the lateral and vertical variations of the salt water interface in Ibeno area in South-East of Nigeria. The resistivity surveys were used to detect changes in pore-water resistivity. In areas where low resistivity values ($< 2 \Omega\text{m}$) were detected, this indicated the saltwater intrusion into the surrounding groundwater. The VES data generated a geoelectric model having between three and four layers. The 2D imaging of the subsurface variations in the resistivity/conductivity vividly reflects different lithologies and fluid content. Other than the top soil, the subsurface lithologies consist of prolific sands with intercalations of clayey sands. The silty sands and coarse-sand layers constitute the coastal aquifer units within the area with varying ground water yield as a result of variation in porosity and permeability. Some of the aquifer was contaminated with saline water (lateral encroachment) from tidal influence and/or the increase in groundwater abstraction causing a reversal in the natural groundwater gradients. This work has shown that the salt water has intruded into the freshwater aquifer down to a depth of over 20 m. The time-lapse ERT (2016 and 2017) measurements showed significant, active lateral, and vertical salinity changes rapidly intruding the freshwater aquifers. Area that were previously not intruded are experiencing intrusion while those already intruded are experiencing higher concentration. This increase in intrusion implies a decrement in the amount of potable water for inhabitants of the area (which has led to public health problems) and a continual encroachment and deterioration of the region as a result of saline intrusion.

This work is the first to characterize saline water intrusion along the coastline of Ibeno, a major oil-producing region in Nigeria, with geophysical techniques in order to quantify the extent of saline intrusion in the region rather than with

time-consuming and expensive methods such as chemical analysis of groundwater samples, well-logging, profiling of temperature or chloride concentration, which only give point data about the location in question. Results obtained from the geophysical investigations undertaken correspond to those obtained from geochemical analysis of water samples at the site, showing that resistivity imaging is a useful tool for determining the extent of saline intrusion and the pattern of saline water flow. Though geochemical analysis gives accurate results at a given point, geophysical investigations generates superior results because it measures the trend of saline intrusion over a large expanse of the region and this information can be obtained at a faster rate than with the alternative techniques. Geophysical investigation provides more information faster than the drilling techniques. Subsequently, geophysical methods have become more important for saltwater intrusion monitoring.

This research, like previous work on saline water intrusion (Nowroozi et al. 1999; Nassir et al. 2000; Choudhury et al. 2001; Khalil 2006; de Franco et al. 2009; Kazakis et al. 2016; Giordano et al. 2017; Loke et al. 2017; Du et al. 2018; Shin et al. 2019), shows that resistivity imaging is a powerful tool for quantifying the extent of saline water intrusion within a coastal region in the absence of geochemical information.

The study demonstrates the applications of time-lapse two-dimensional electrical resistivity tomography and vertical electrical sounding in identifying temporal and spatial changes of saltwater intrusion in the coastal aquifer. It is recommended that Government legislations be enacted to regulate pumping rates and locations of abstraction points. The problem of salt water intrusion in Ibeno should be placed high on the priorities of the local and state governments as the presence of saline water intrusion poses a threat to the life and well-being of the community. Consistent geophysical surveys for different years will help to establish a trend and eventually predict the rate of intrusion. Ibeno has major economic significance to the country Nigeria, and this work will provide useful information to researchers working in the region.

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Statement on compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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