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Electrical Resistivity Tomography and Conceptual Hydrogeological Modelling of Saline Water Intrusion and Groundwater Development Potential in Burutu Island, Coastal Niger Delta, Nigeria

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Abstract: In coastal area of the Niger Delta, Nigeria, where shallow aquifer is predominant source of domestic water supply, saline water intrusion is a very serious problem to groundwater resources. The research in this project attempts to determine the degree of saline water intrusion and to map sustainable groundwater development zones on Burutu Island with the aid of Electrical Resistivity Tomography (ERT) and hydrogeological conceptual modelling. 5 dipoles were deployed along five traverses to perform two-dimensional ERT surveys and the resulting resistivity sections were interpreted using known coastal resistivity classification techniques to identify the freshwater, brackish and saline water zones. ERT results show significant resistivity variations laterally and vertically over the study area. Deeper subsurface layers in certain areas of Traverses 1 and 2 are dominated by low resistivity (<15 Ωm) interpreted as saline to brackish water intrusion, while higher resistivity (>70 Ωm) values are present in the freshwater bearing sand and gravel units in Traverses 3 and 4. The result of this geophysical interpretation has been verified by hydrochemical data from hand duged wells, taken from a past study within the region. The electrical conductivity and TDS values are quite similar to World Health Organization (WHO) guideline values, and zones with low resistivity indicate saline intrusion in the affected areas, and the zones of high resistivity indicate low salinity groundwater. Based on the ERT interpretation and supporting hydrochemical evidence, an integrated conceptual hydrogeological model is presented to illustrate the encroachment of saline wedges into the freshwater aquifers from inland areas. The results show that sustainable exploitation of the groundwater resources on the Burutu Island is limited to shallow to intermediate depth in the high resistivity zones with saline water intrusion at deeper depths.

Keyword: *Saline Water Intrusion, Conceptual Hydrogeological Model, Coastal Aquifer, Groundwater Development, Niger Delta, Burutu Island.*

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I. INTRODUCTION

Due to the growth rate of population, urbanization, industrialization, and rising agricultural activities, global demand for freshwater is still growing. The coastal areas have generally adequate water resources, but potable groundwater is a challenge. saline water intrusion into freshwater aquifers is the main cause of poor quality of groundwater (Subasinghe and Jinadasa, 2012).

The rapid population growth and unplanned urbanization in Nigeria has resulted in serious deterioration of groundwater quality, especially in coastal belt region of Niger Delta region. Saline intrusion and anthropogenic activities such as over extraction, industrial effluents and improper waste disposal are major threats to groundwater reservoirs in coastal sedimentary basins (Abdul *et al*., 2000; Batayneh, 2006; Amadi *et al*., 2012). As a result, many boreholes sunk for access to freshwater have been abandoned

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as they became saline which is becoming common in Nigeria (Oyedele and Momoh, 2009).

Water found below the land surface in saturated geologic material (aquifer) from which it has been removed in response to gravity, and where the hydrostatic pressure is equal to or higher than atmospheric pressure. It is one of the resources most essential to humanity and socio-economic development. The development of civilizations in the past has been closely related to the availability of groundwater. Sustainable extraction of groundwater and appropriate management of saline groundwater intrusion have become more important because about 70% of the world's population live in coastal areas (Bear *et al*., 1999).

Saline water intrusion is one of the major concerns for almost half the world's population relying heavily on groundwater resources (Zawawi *et al*., 2011). Intrusion is when the salinity of groundwater is greater than the requirements for drinking, agricultural and industrial purposes. This is mainly attributed to freshwater/saline water system hydrostatic imbalance (often due to anthropogenic activities) (El Yaouti *et al*., 2009). The major drivers for saline water intrusion are: over-exploitation of groundwater, heavy agricultural use, industrial dumping, natural geologic processes, sea-level rise and climate change (Duque *et al*., 2008). The over pumping reduces the fresh water level, and saline waters move inland and upward into the fresh water aquifers, displacing fresh water resources (Balasubramanian *et al*., 2018; Baba and Gündüz, 2017).

The delineation of freshwater/saline water boundary has been subject of many hydrogeological and geophysical studies in the few decades (Lee and Cheng, 1974; Barlow and Reichard, 2010; Hassan *et al*., 2017). Saline groundwater is usually believed to have high concentrations of dissolved salts, often of sodium chloride (NaCl), which affects the electrical properties of the aquifer. Groundwater is one of the vital freshwater sources in many developing nations such as Nigeria. Saline water intrusion is among the most serious problems impacting the quality of groundwater in coastal areas (Todd and Mays, 2005; Hu *et al*., 2011). Groundwater is the primary source of water supply in Burutu Island, Delta State for drinking, and other domestic use.

There are concerns over the depletion of resources and salinization of aquifers in Burutu Island, Delta State. Numerous boreholes which were originally drilled for freshwater have been replaced by saline water in a short time. The uncontrolled exploitation of unconfined and confined aquifers, combined with the close proximity of tidal river systems are responsible for this problem in large part (Lee and Song, 2007).

The rapid expansion of the major cities of the Niger Delta like Warri, Port Harcourt, and Bonny, worsens the situation. Since most of the populations are relying on groundwater resources, knowledge of the spatial information on freshwater, brackish water and saline water is crucial to groundwater management and mitigation of saline water intrusion (Post, 2005; Hassan *et al*., 2017).

The usage of Electrical Resistivity Method (ERM) in this study, includes Two-dimensional Resistivity imaging (2-D Resistivity) using Dipole–Dipole array, together with the physicochemical analysis was used to delineate saline water contaminated zones, identify freshwater to saline water interface and characterize subsurface geological formations in Burutu, Burutu Local Government Area of Delta State, south of Nigeria. Results of the study will provide empirical data for groundwater development, management and mitigation for saline water intrusion in the area under study.

➢ *Geology and Hydrogeology*

Burutu Island is found a few kilometers off the Atlantic Ocean between latitude 5º 34’ 80.8’’N to 5º 35’49.8’’N and longitude 5° 50’29.6’’E to 5° 51’24.3’’E at an average height of 22m above sea level. The basic sediments of the island are reworked by the ocean tides and waves, which are deposited by fluvial and transitional sediments from the Warri and Forcados and Niger River systems. The hydrodynamic processes are similar to those which created the Tertiary Niger Delta Basin. The river at Burutu is brackish, the salinity of which changes from time to time, more so during the dry season. Somebreiro-Warri Deltaic Plain deposit is made up of unconsolidated fines (clay, silts, sands) and overlies the water-bearing Benin Formation. The shallow aquifers, less than 200 m deep, found in the Deltaic Plain are iron rich, which is an issue of groundwater quality. The sole aquifer for the whole Niger Delta is the Benin Formation which consisting of sands, silts, clays and gravels, the sand and gravel layers being the aquifers, and sometimes the clays and sands interact with each other creating heterogeneity. The rivers of the region especially in the west constitute subcatchments in the Niger delta basin. Forcados River, at Burutu, is also affected by a well-marked 6 hourly tidal influence with low and high river stages, of 0.4 m and 1.2 m respectively, respectively, but the tide at the river does not have significant effects in the groundwater stage. Sources of groundwater recharge are mostly precipitation infiltration and the sources of groundwater discharge are mostly pumping, evapotranspiration and river discharge. Seasonal variations affect groundwater levels between 0.2 to 1.2 m, and generally groundwater flows towards Forcados River (Ohwoghere-Asuma, et al., 2014). The mean annual precipitation is in excess of 3000 mm and precipitation is quite heavy during the wet season.

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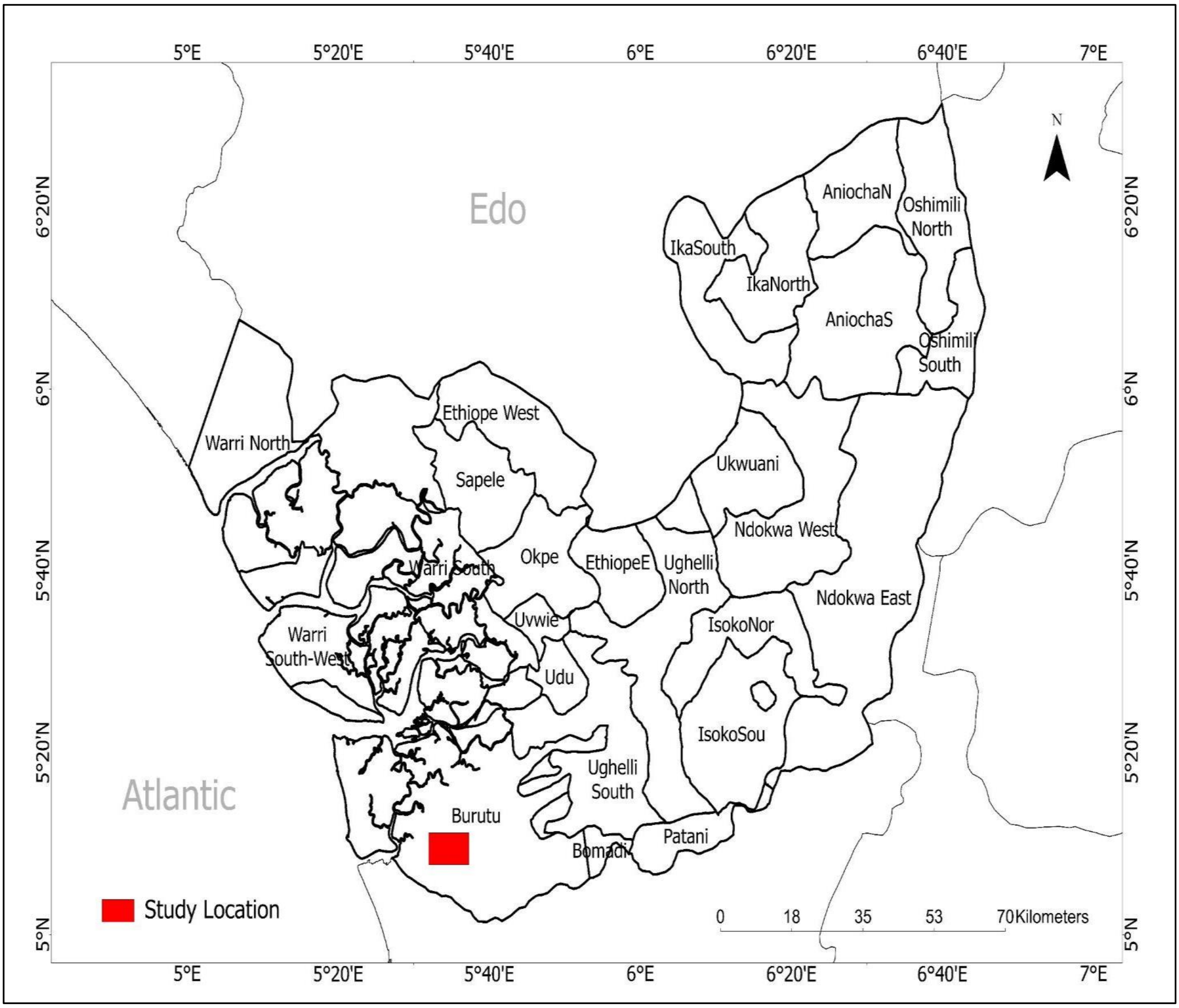

Fig 1 Map of Delta State Showing the Study Area

II. MATERIALS AND METHODS

Two-dimensional Electrical Resistivity Tomography (PERT) surveys took place, using a dipole-dipole array configuration on the PASI Earth Resistivity Terrameter (16GL model), due to its sensitivity to both lateral and vertical variations of resistivity around saline intrusion which is common to coastal aquifers. The maximum investigation depth was approximately 25 m as five traverses were acquired with 31 electrodes spaced regularly at 10 m. Apparent resistivity data was processed, inverted using RES2DINV software developed by Loke (1999), which uses the smoothness-constrained least-squares inversion scheme developed by Loke & Barker (1996) that can be used to transform apparent resistivity values into true subsurface resistivity distribution. The inverted resistivity sections were interpreted using standard classification of coastal sediments (Zohdy & Martin, 1993; modified by Ibrahim, 2008) to separate freshwater, brackish and saline water zones. ERT data was supplemented with existing hydrochemical data collected from previous groundwater quality assessment carried out in Burutu Town by Esi et al. (2013) for strengthening the interpretation and minimising ambiguity. However, using secondary water-chemistry data is justified because the hydrogeological setting, lithology, and groundwater abstraction conditions that existed at that time are similar to those of the present study area. Key salinity indicators such as Electrical Conductivity and Total Dissolved Solids was used to validate geophysically inferred saline intrusion zones. A conceptual hydrogeological model that incorporates both the ERT interpretations and hydrochemical evidence was also created to represent saline water intrusion and groundwater development zones. Sketching the conceptual model using an AI-assisted visualization tool with detailed descriptions by the author for the subsurface layering, geometry of the saline wedge, and groundwater flow pattern, is a simplified model for the saline intrusion processes and for groundwater development in the area of study.

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III. RESULTS

> *2-D Electrical Resistivity*

- *Traverse 1*

The resistivity values in the near surface layer are between 30 and 100 Ωm and in some places above 100 Ωm to a depth of approximately 3-5 m. This layer is described as that of sand and gravel with low to no clay content, which is a partially to unsaturated coastal sand deposit. The relatively good resistivity values are most associated with freshwater conditions and there is no evidence of any significant saline water intrusion at shallow depths. In the subsurface from 6 m to 22 m, a low-resistivity zone exists where the resistivity varies between 0.5 and 4.5 Ωm. The values represent a typical highly porous sand or salt-saturated clay. This unit represents the main saline water intrusion zone on Traverse 1 (fig. 2a). Resistivity values of <4.5Ωm are the minimum limit above the saline intrusion found between chainage 40 m and 260 m, which is considered to have a lateral extent of approximately 220 m and a vertical thickness of 15-18 m, from 7 m to 24 m depth. The continuity and thickness of this low resistivity zone suggest that saline water is active in the subsurface. At depth within the saline intrusion zone (measurements were taken from 0 to 700 m), there are localized areas of intermediate resistivity (10–30 Ωm) above and along the margins, specifically between V = 160 m and 200 m between depths of 5–10 m. These zones are considered as sandy clay to sandy gravel units with brackish ground water and due to the close hydraulic relationship with the underlying saline zone, they are considered to be highly vulnerable to further salinization.

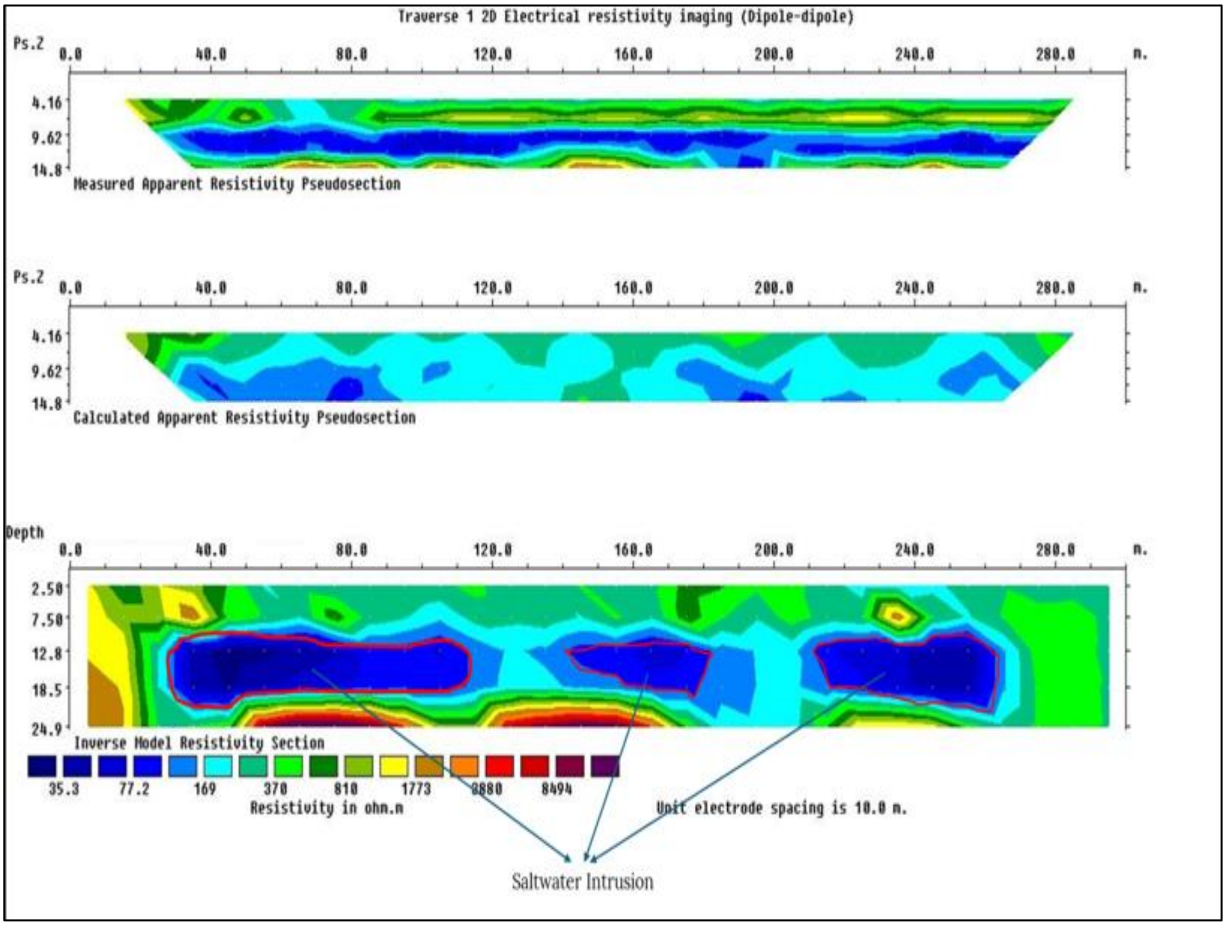

Fig 2a 2-D Inverted Section of ERT Along Traverse 1

- *Traverse 2*

Generally good conditions for groundwater are suggested by the high resistivity values of Traverse 2 (fig. 2b). The near surface layer extends from the ground surface to 4-6 m and has moderate to high resistivities (60-500 Ωm). This layer is considered to be sand and gravel and low to no clay, as being shallow sandy deposits under freshwater conditions and low saline influence. The high resistivities (more than 100 Ωm, and even more than 1000 Ωm locally) dominate the subsurface between the depths of 6 and 15 m and it is characterized by a high resistivity unit. This unit interpreted as clean coarse sand and gravel which is a productive freshwater aquifer. Traverse 3's continuity and thickness make it ideal for groundwater development. Moderately high resistivity (88-128 Ωm) are found at depths of 15-25 m, mainly from chainage 60-140 m and 200-260 m. These zones are considered to be sandy clay or clayey sand with a relatively wet, but still within the freshwater resistivity zone. No very low resistivity zones (less than 30 Ωm) are seen along the traverse indicating that no saline and/or brackish water intrusion exists in the area of study in depth range investigated.

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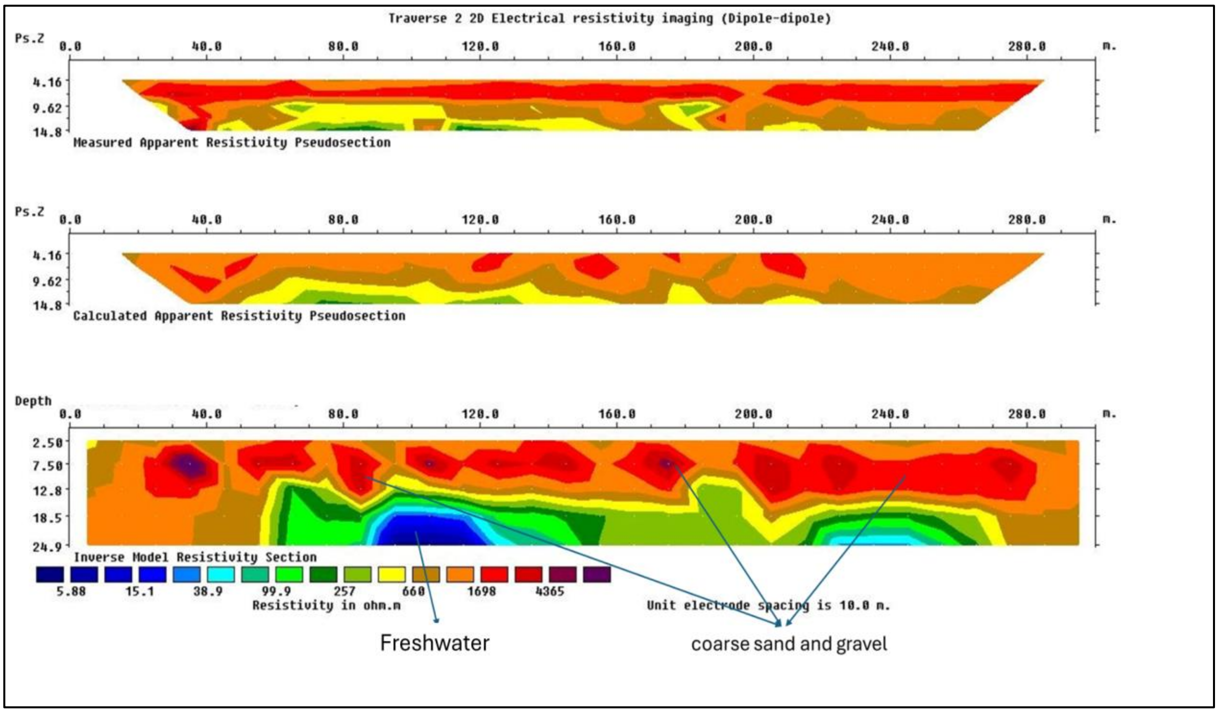

Fig 2b 2-D Inverted Section of ERT Along Traverse 2

- *Traverse 3*

There were three zones geographically defined for traverse 2 (fig. 2c). The shallow layer is located from the surface to 4-6 m deep. It has moderate to very high resistivity values (70 – 1000 Ωm) with a few areas showing higher resistivity values that can exceed 4000 Ωm. This is reported as coarse sand and gravel having low to no clay content, corresponding to very low to moderately saturated, freshwater deposits of sand. A moderate-resistivity unit (30-70 Ωm) can be found beneath the layer at depths of 6-12 m along the traverse. This unit is described as sand and gravel containing some clay – this is an interpretation of intermediate freshwater conditions. Its proximity and close vertical relationship to lower-resistance zones, although quite young, suggests its susceptibility to saline intrusion. At deeper depths the low resistivity zone is located at depths of 10–24 m, and in some places it has a lower resistivity (5.8–15Ωm), and even lower than 10Ωm. This zone is believed to be the zone of saline to brackish water intrusion into sandy or sandy clay body. Saline intrusion is most evident at the chainages from 80 m to 160 m, and is 80 m wide and 12-14 m thick. A secondary low resistivity pocket between 220m and 260m is present and is indicative of localized saline encroachment.

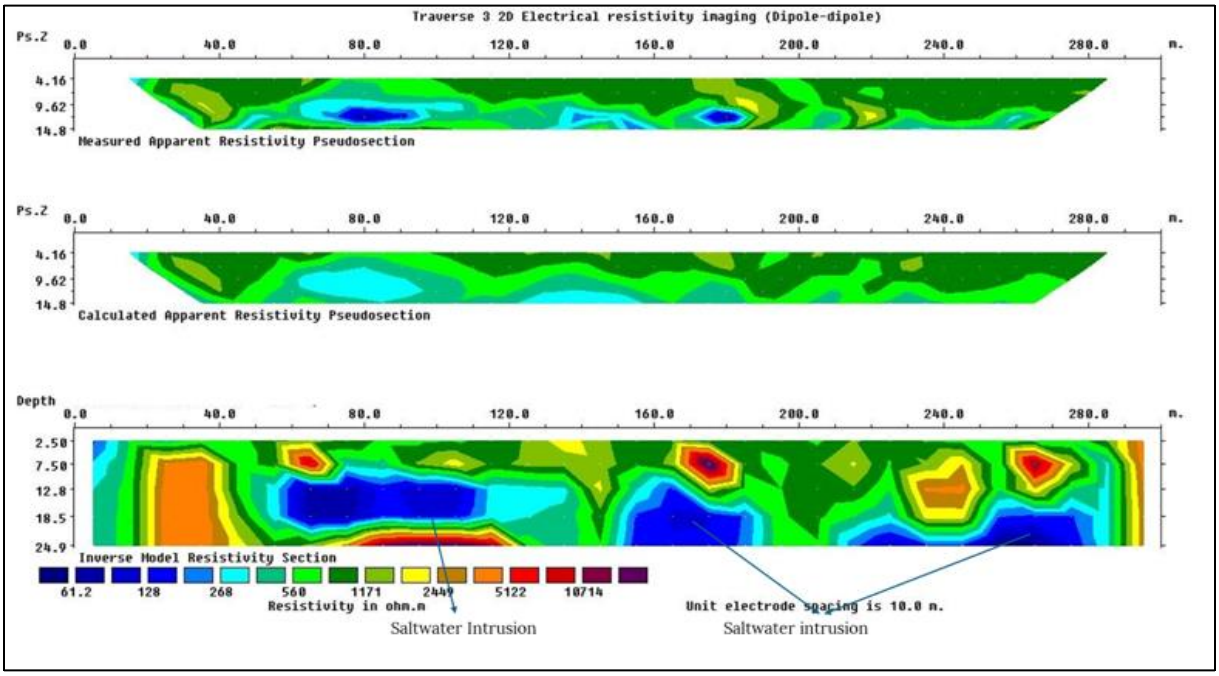

Fig 2c 2-D Inverted Section of ERT Along Traverse 3

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- *Traverse 4*

The shallow layer (fig. 2d) with moderate to high resistivity values (60-200 Ωm) extends from ground surface to depths of 3-5 m. This resistivity range is representative of materials ranging from sandy to gravelly, with a low percentage of clay, typical of near surface deposits that have little salt-water influence. The region of moderate resistivity (30-70Ωm) provides a zone between 5-10m with a thickness of approximately 10m from the base and extends throughout the chainages 40–200 m. Moderate resistivity values represent a transitional subsurface unit, between the shallow and deeper, resistive zones. These deeper layers (8-18 m) show bodies of high resistivity, over 100 Ωm and locally over 1000 Ωm. The anomalies, mostly situated between chainage 60-80 m, 120-140 m, and 160-200 m, are interpreted as low clay content localized coarse sand and gravel units. There are no very low resistivity zones <30Ωm present at traverse 4 and these zones are typically associated with saline or brackish water intrusion. The resistivity values for the sections where z is >58 Ωm do not show the presence of highly conductive saline zones. Below 18 m depth, there is a small relatively low resistivity zone to the west (0-20 m) of the profile.

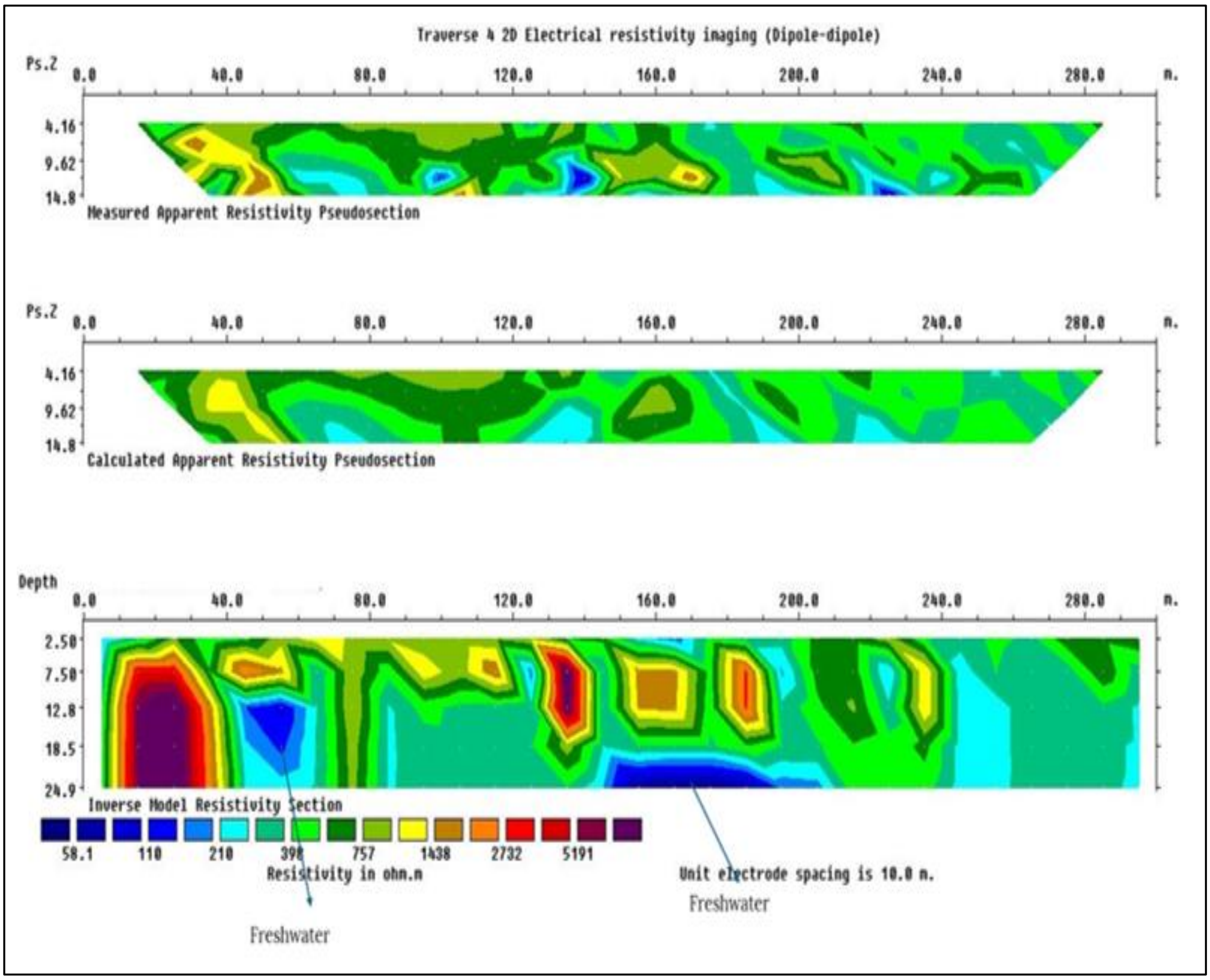

Fig 2d 2-D Inverted Section of ERT Along Traverse 4

- *Traverse 5*

The shallow layer, which lies between the ground surface and 3 to 5 m depth has medium to high resistivity (50-200 Ωm). This layer consists of near surface sandy deposits, low salinity. Between 5 m and 12 m, resistivity values are high, above 1000 Ωm and up to 8000 Ωm. This zone is considered to be coarse sand and gravel, low to very low in clay content, from about 12 m to 25 m. A decrease in resistivity is seen (48–113 Ωm) especially from chainage 80 to 200 m. These are higher than the saline levels usually encountered in such water but a marked reduction in comparison to the overlying high-resistance unit. The lower-resistivity zone is about 120 m wide and 10-13 m thick. A lack of very low resistivity (<30Ωm), along the traverse, suggests that there are no strongly saline conditions in the investigated depth range.

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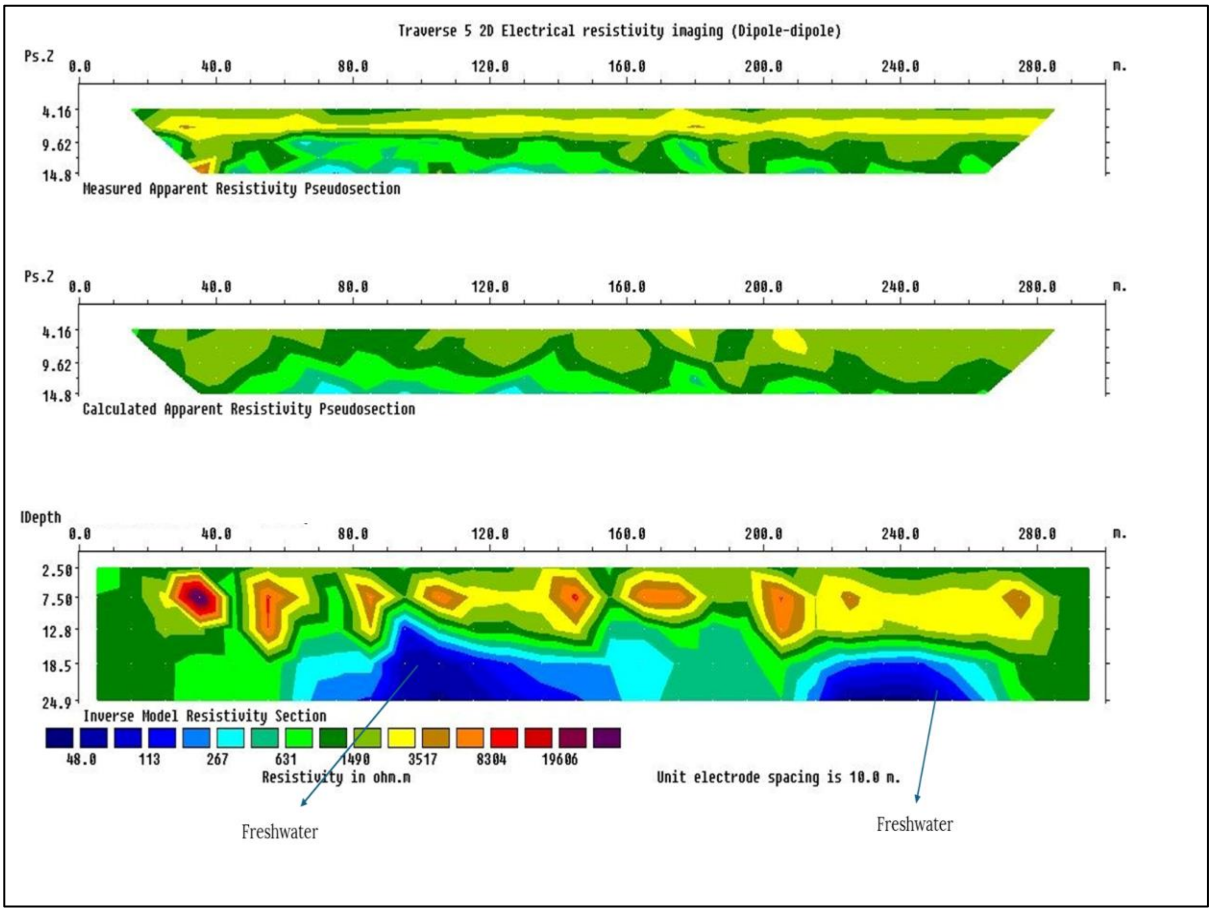

Fig 2e 2-D Inverted Section of ERT Along Traverse 5

➢ *Integration of Hydrochemical Data with ERT Interpretation*

The hydrochemical data from hand-dug wells in Burutu Town were also combined with the results of the Electrical Resistivity Tomography (ERT) to test inferred geophysical patterns of saline intrusion. Groundwater quality data was obtained from a previous work by Esi et al., (2013) which sampled groundwater from several quarters namely, Desomatec, Amber, Kalaroo, Chicoco and Okorodudu. Secondary hydrochemical data were used in this study, but it is justified because the data are from the same coastal hydrogeological environment and from groundwater that is influenced by similar lithological, tidal, and salinity effects, enabling meaningful comparison between the use of these data. New water samples often cannot be collected in coastal groundwater research in certain areas due to logistical and/or temporal limitations, or in areas with very little data, and so the integration of legacy hydrochemical data from the past with geophysical surveys has become increasingly common (Zebaze et al., 2025; Sarr et al., 2025). When combined, these approaches give knowledge of the distribution of subsurface salinity and help identify fresh/saline boundaries compared with assessments using single methods (Obakhume et al., 2022).

Groundwater samples from Burutu Town showed that there were variations in the water quality from one point to the other in the town (i.e. distribution of TDS and electrical conductivity from sample to sample (Figs. 3 and 4). The electrical conductivity values are ranging from 45 to 1870 µS/cm, TDS is ranging from 20 to 1140 mg/l, which shows a wide range of fresh to saline groundwater condition. World Health Organization (WHO) guideline values indicate relatively fresh groundwater conditions as seen in the locations of Desomatec, Amber, Kalaroo and Chicoco which have groundwater values higher than the WHO guidelines, while Okorodudu shows groundwater values consistently below the WHO limits. The spatial distribution of the hydrochemical plots closely resembles that seen by the ERT. The EC–TDS relationship in the scatter plot (Fig. 5) is positive, with good correlation that was often seen in the saline intrusion in coastal aquifer. Kidorudu plots in low conductivity, low TDS, showing a region of fresh water, whereas the data points for Desomatec and Amber fall above the WHOs threshold levels, separating the saline affected areas from the fresh water areas. Additional information about the overall salinity condition of the shallow aquifer system is provided by the mean groundwater quality values (Fig. 6). The average value of TDS is 614 mg/L which is higher than WHO recommended limit of 500 mg/L, and the mean electrical conductivity is also above the recommended levels. The Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD) are pointers of anthropogenic activity as opposed to salinity levels, however their high levels observed in certain areas (Desomatec and Kalaroo) indicate low natural protection and vulnerability of shallow aquifers.

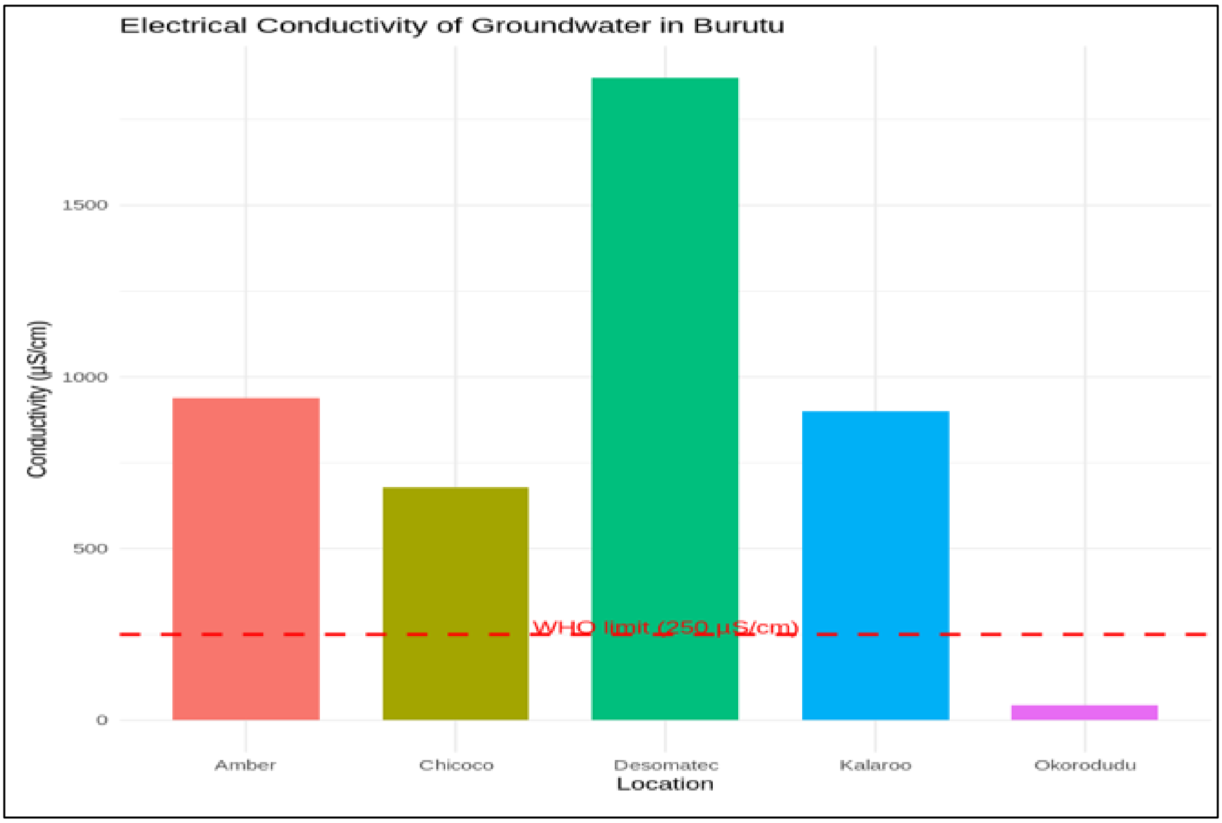

Fig 3 Electrical Conductivity

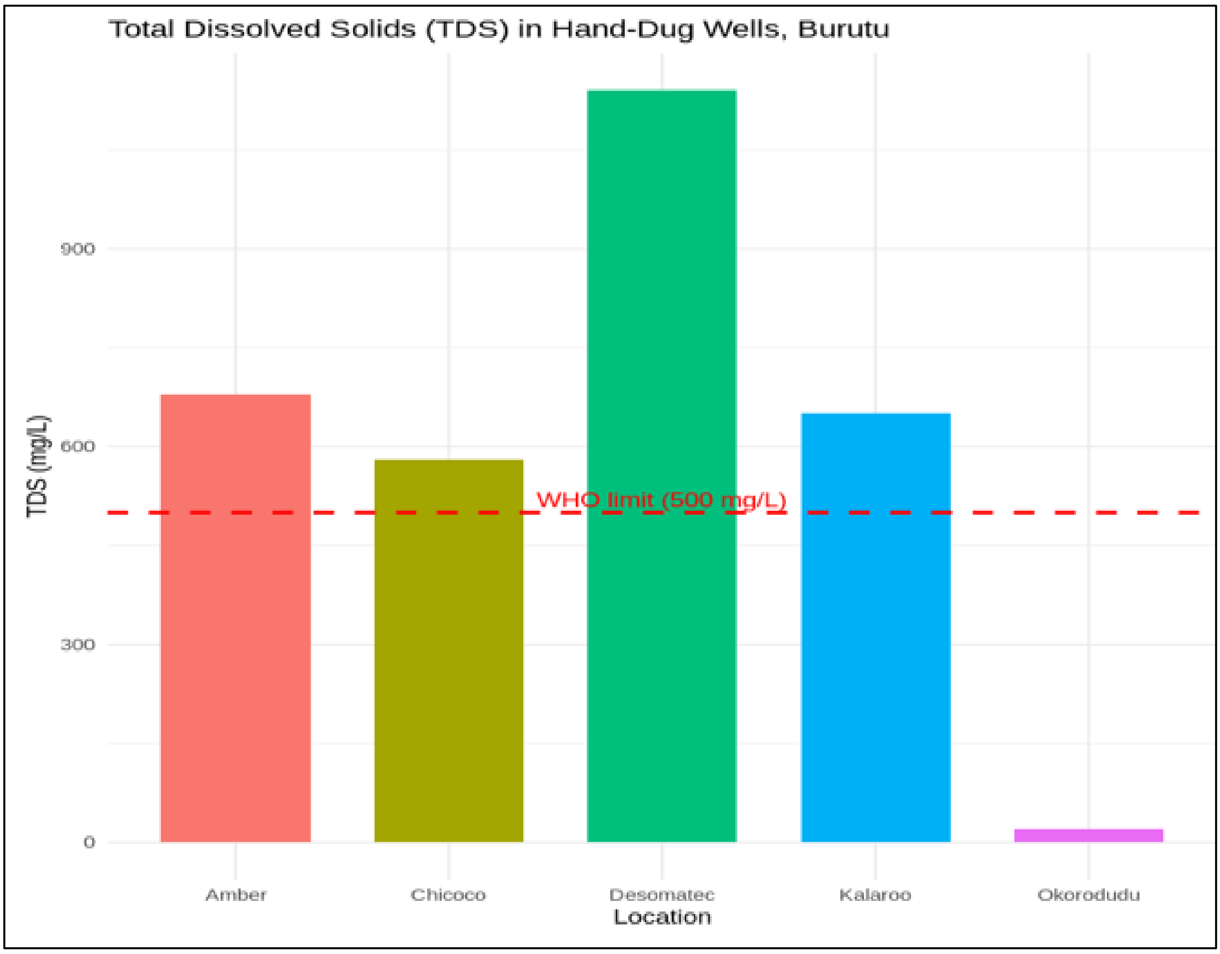

Fig 4 Total Dissolved Solids (TDS)

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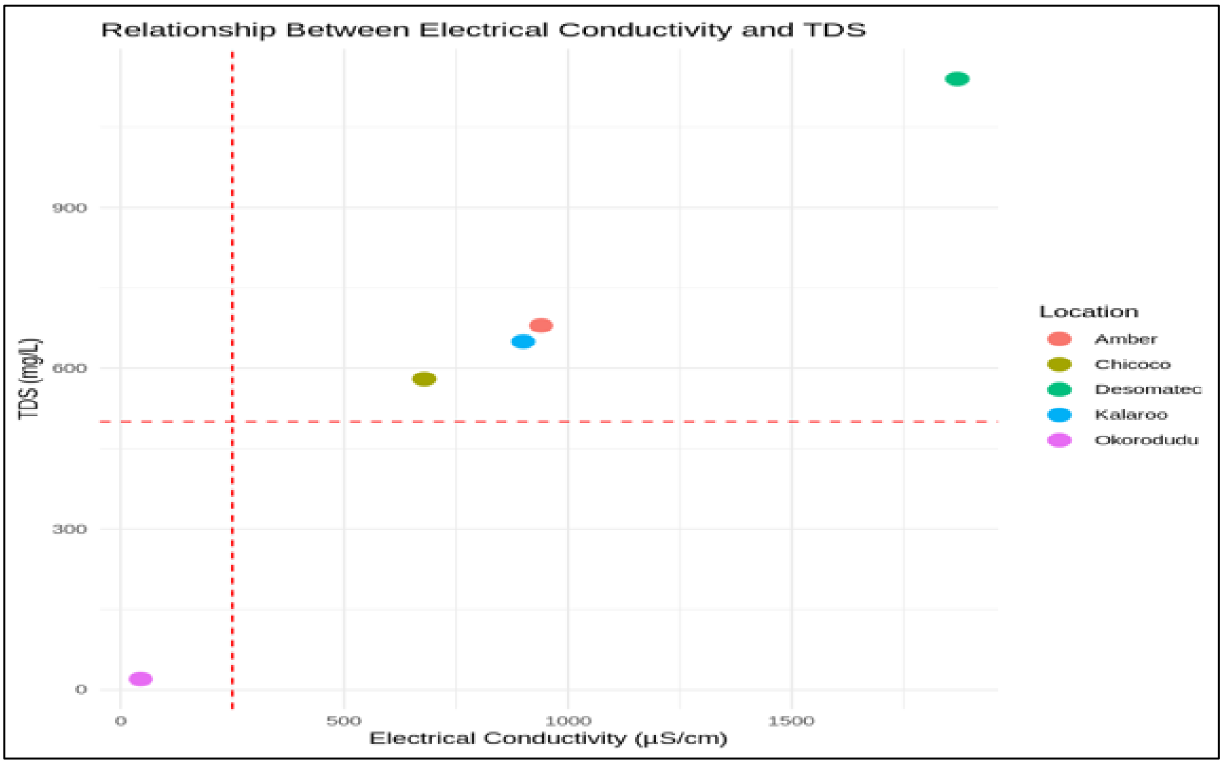

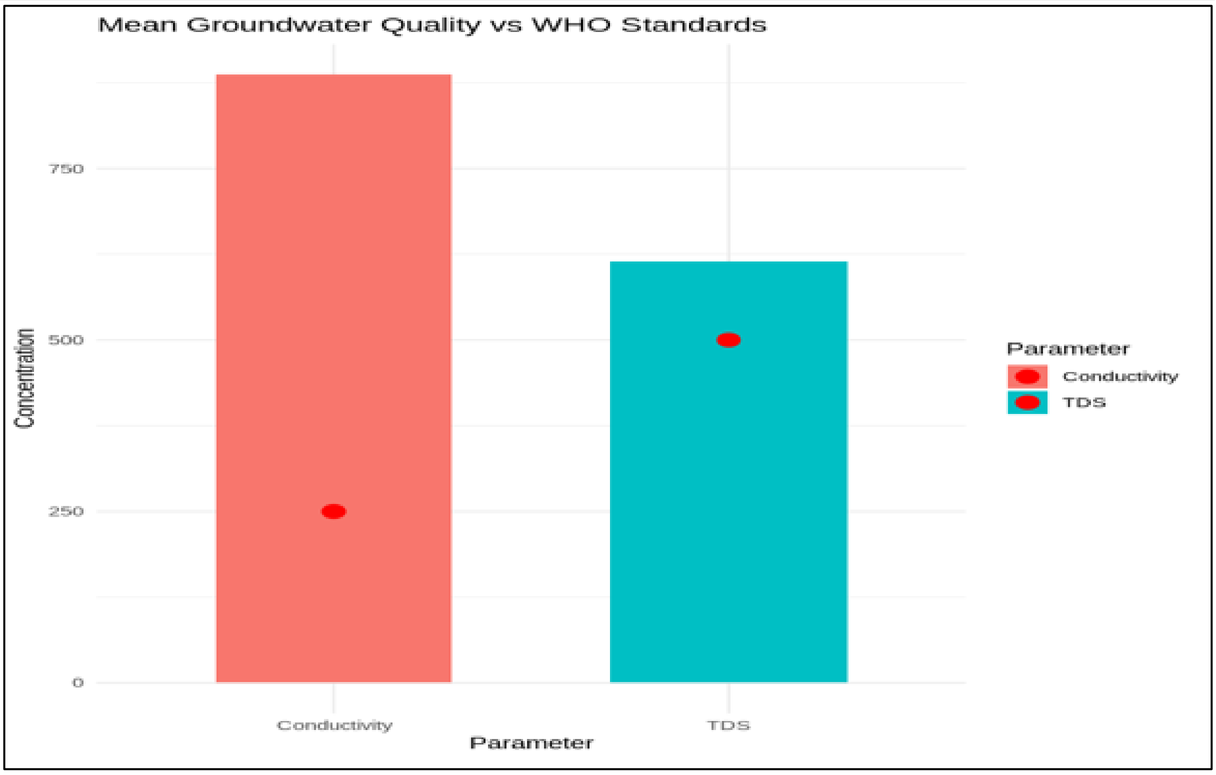

Fig 5 & 6 Scatter Plot of Electrical Conductivity vs Total Dissolved Solids; Mean Concentration Quality Versus WHO Standards

- *Conceptual Hydrogeological Model of Saline Intrusion and Groundwater Development*

Based on the integrated interpretation of 2D ERT profiles, a conceptual hydrogeological model indicating saline water intrusion and groundwater development on Burutu Island was obtained and shown in Figure 7. The model summarizes shallow freshwater aquifer and underlying transition (mixing) zones and saline water units identified throughout the study area. The fresh water-bearing sands are found at shallow to intermediate depths, and are underlain by a saline intrusion zone that penetrates inland from the coast as a wedge. The model also shows how these are hydraulically connected and emphasizes the susceptibility of the shallow aquifers to saline upconing from the groundwater abstraction. The conceptual model overall represents a simplified relationship between the ERT-generated resistivity signatures and the groundwater flow conditions and is used to identify areas for sustainable groundwater development.

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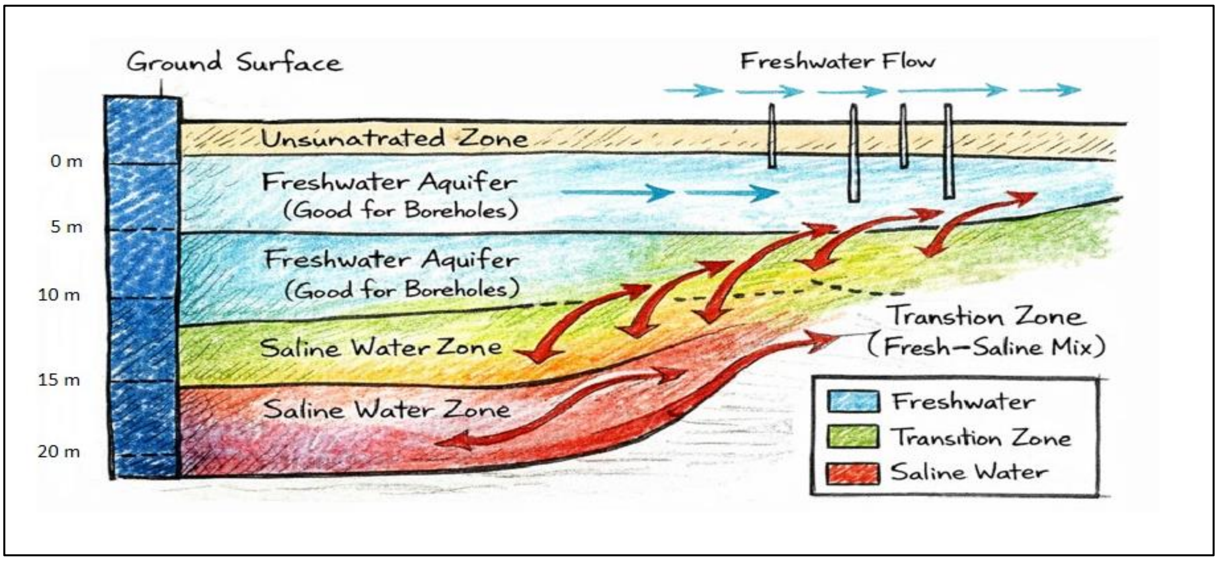

Fig 7 Conceptual Hydrogeological Saline Intrusion Model for the Buruttu Island based on 2D ERT and Water Chemistry

IV. DISCUSSION

The ERT surveys showed significant lateral heterogeneity and vertical resistivity variations throughout the study area indicating differing hydrogeoelectric units. High resistivity (>70 Ωm) in the sand and gravel horizons in Traverses 3 and 4 are associated with fresh water; low resistivity (<15 Ωm) in Traverses 1 and 3 are associated with saline water saturated sediments that are likely to have been invaded. The coastline site of the salt intrusion is consistent with the behavior of coastal saline intrusion in similar deltaic settings (Eyankware *et al*., 2025; Ayolabi *et al*., 2022) because it was found that the salt water creeks forced the landward intrusion of landfals where freshwater lenses were formed due to tidal fluctuation and hydraulic gradient.

The interpretations in geophysics are corroborated independently from hydrochemical data obtained from hand dug wells. Groundwater samples with high electrical conductivity and Total Dissolved Solids (TDS) are believed to reflect areas with low resistivity and saline intrusion on the ERT in some parts (Desomatec and Amber). The mean TDS (~614 mg/L) is also higher than WHO guidelines for drinking water which also indicate significant salinity stress in these aquifer areas (Esi *et al*., 2013). Conversely, areas with a steady decrease in conductivity and TDS values are associated with high-resistivity zones in Okorodudu indicating areas of relatively fresh groundwater.

These outcomes are also incorporated on the conceptual hydrogeological model to form a model framework focusing on the vertical assembly of deeper saline units, transition zones, freshwater aquifers, and unsaturated sands. The model simulated the inland migration of a saline wedge from the coastal boundary, a response that is commonly observed in coastal aquifers and that occurs when the coastal boundary or the sea is subjected to a specific stress that reaches the outer edges of the aquifer, resulting in a balance between coastal movement of seawater and flow of freshwater toward the coastal boundary (Werner et al., 2013). The zones of transition (mixing) occurring beneath the freshwater aquifers indicate very high susceptibility in brackish zones to pressures from pumping. Aquifer susceptibility to human activities is suggested by high BOD_5 and COD concentrations in some wells, which can further exacerbate salinity migration by altering aquifer flow pathways and reducing aquifer natural attenuation capacity (Werner & Simmons, 2009). The zones of fresh water identified in this study are suitable for sustainable groundwater development and provides a sound demarcation of saline intrusion boundaries using a combination of geophysical and hydrochemical approach. These zones, along with sea level rise due to climate change, are known to increase the risks associated with saline intrusion, and therefore are important to delineate for groundwater management purposes (Taylor *et al*., 2013; Werner *et al*., 2019). Results show that deepest abstraction in low and moderate resistivity is not recommended due to concerns of saline upconing and water quality degradation. However, an alternative approach to sustainable groundwater development on Burutu Island is to target shallower to intermediate depths (approximately 6–15 m) in high-resistivity, sand and gravel units. Both hydrochemical thresholds in relation to WHO guidelines and geophysical signatures support this recommendation.

V. CONCLUSION AND RECOMMENDATIONS

This work demonstrates that the integration of Electrical Resistivity Tomography (ERT), hydrochemical data and conceptual hydrogeological modelling is a powerful tool in assessing saline water intrusion and groundwater potential in coastal environment in Burutu Island. The ERT results are clearly able to distinguish saline intrusion areas of low resistivity and shallow to medium depth, lateral continuity of fresh water-bearing sand and gravel units. There are hydrochemical indicators, including high electrical conductivity and Total Dissolved Solids concentrations in available data of groundwater quality in the study area, which support these geophysical interpretations. The conceptual hydrogeological model uses data sets and highlights salinity wedge intruding into inland freshwater aquifers, and the very sensitive transition zones where groundwater abstraction will

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affect the development of the saline wedge. The sustainable use of the groundwater resources on Burutu Island should only be utilized in shallow and intermediate wells that lie within the high-resistivity fresh water units, typically from 6 to 15 m in depth. In saline-prone areas, avoid deeper abstraction where saline upconing may occur, and may lead to long-term water quality degradation. The study highlights the need of integrating the geophysical and the hydrochemical approaches with properly selected secondary data in order to efficiently manage a groundwater system in data-poor coastal settings. The integrated methodology proposed is recommended to be extended to other similar deltaic and coastal aquifer system in the Niger Delta and beyond.

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