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Surficial Survey of Unstressed Aquifers for Saltwater-freshwater Interaction using 2D Inverse Resistivity Model and Saltwater Markers in the Coastal Area of Ogheye in the Niger Delta Basin, Nigeria

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Abstract

The flow and interaction of freshwater and saltwater have a significant impact on how much freshwater is available in coastal aquifers. For effective management of groundwater resources in aquifers adjacent to the sea, identification of the saltwater-freshwater interface position is necessary. The objective of the study is to define the salinity of aquifers by integrating a 2D resistivity model of the subsurface with total dissolved solids (TDS), electrical conductivity (EC), molar ratios of Na^+/Cl^- and Mg^{2+}/Ca^{2+}. The geologic models created from the resistivity data revealed a gradual increase in resistivity both laterally and vertically as the distance from the sea increases. The saltwater-freshwater interaction zone is located between 415 and 485m and also at 735 and 885m from the coast. Near the sea, saltwater extends to a depth of 24 meters, below which there is likely an uninvaded zone. Geochemical indicators of groundwater from 37m and 69m depths indicated no significant evidence of saltwater incursion. Interaction between freshwater and saltwater is evident in aquifers between 2.3 and 4.3m depths with TDS and EC exceeding 3000 mg/l and 5000μS/cm, as well as ratios of Na^+/Cl^- between 0.54 and 0.64 and Mg^{2+}/Ca^{2+} between 4.1 and 4.5. Without extensive active pumping, geogenic factors are probably responsible for the salinization of aquifers in the areas. The backwater influx of saltwater into shallow aquifers during the dry season is attributed to the intrusion of aquifers. The existence of a clay layer of considerable thickness under the saltwater zones provides adequate protection against groundwater from 38 to 69m depths, respectively.

Keywords: *Coastal aquifers; Resistivity imaging; Ionic ratios; Saltwater intrusion; Saltwater/freshwater interface, Benin Formation*

1. Introduction

The Benin Formation beneath the Niger Delta coastal region is characterized by an abundance of groundwater resources. The salinization and proximity of aquifers to the seashore hinder the availability of freshwater in the coastal regions. The groundwater in most estuary environments, where continental groundwater mixes with saltwater from the sea are under serious threat from intrusion. The threat may emanate from geogenic factors and overstressing of coastal aquifers (Abam 2001; Post 2005). As a result, coastal aquifers are frequently contaminated by saltwater and the attendant effect is groundwater quality degradations (Batayneh 2006) and also, reduction in freshwater quantity. The salinization of coastal aquifers in the Niger Delta has been a cause of concern, but decision-makers and groundwater resource managers have not taken it seriously. Boreholes in these regions are frequently abandoned few months after drilling, owing to seawater intrusion (Ohwoghere-Asuma et al. 2017) and lack of proper geophysical investigation.

Fresh groundwater supply for home and industrial use is dwindling and increasingly becoming more expensive to harness as a result of intrusion. The impact of intrusion extends not only to groundwater but also to soil fertility. Excessive pumping, geologic formation, hydraulic conductivity, and recharge influence the degree to which salinization impacts coastal aquifers (Abd-Elaty and Zelenakova 2022; Urish and Frohlich, 1990; Frohlich et al. 1994; Freeze and Cherry, 1979; Choudhury et al. 2001). The influx of saltwater into freshwater aquifers leads to a significant reduction in the resistivity of groundwater. The presence of discernible contrast between the resistivity of freshwater and saltwater is utilized to delineate one from the other (Griffith and Barker, 1993). Electrical resistivity techniques have gained enormous interest globally and have been successfully utilized to detect the freshwater/saltwater interface in coastal aquifers (Barker, 1980) and delineation of potential aquifers in both basement complexes and sedimentary environments (Okogbue and Ukpai, 2013; Al-Amoush et al., 2017). Various researchers have used electrical resistivity surveys to analyze saltwater intrusion in various coastal places across the world (Yang et al. 1999; Batayneh, 2006; Bauer et al. 2006; Choudhury et al. 2001; Kruse et al. 1998; Nowroozi et al. 1999; Ohwoghere-Asuma et al. 2017; Ohwoghere-Asuma and Essi, 2017; Ohwoghere-Asuma, 2017a and b).

Furthermore, geochemical characteristics of groundwater have been employed as saltwater indicators in addition

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to electrical resistivity in the delineation of intruded from non-intruded aquifers. Saltwater substantially has higher concentrations of Na^+, Cl^-, total dissolved solids (TDS), and electrical conductivity (EC) than freshwater. Since seawater is characterized by high concentrations of Na^+, Cl^-, and TDS, it is generally denser than freshwater in the same aquifer. The core driving force behind intrusion is the density contrast between freshwater and saltwater. When an aquifer is pumped intensively, intrusion frequently begins by either migrating laterally from the sea or an underlying aquifer (upconning). In upconning, freshwater occurs floating on top of saltwater in the aquifer (Ohwoghere-Asuma (2017a, b). The molar ratio of Na^+ to Cl^- concentrations in seawater is 0.86, indicating that the Cl^- is considerably in excess of Na^+ and hence the fraction is less than unity (1). Furthermore, the Mg^{2+} to Ca^{2+} ratio ranges from 4.5 to 5.2 (Jones et al. 1999), indicating that Mg^{2+} concentration in seawater is substantially greater than Ca^{2+} concentration. Freshwater aquifer experiencing interaction is often characterized by TDS in excess of 200mg/l, Cl^- in excess of 100mg/l, and EC in excess of 3000S/cm (Karahanoglu, 1997). These critical criteria have necessitated their use as a proxy for delineating freshwater from intruded aquifers, especially the interface between them.

The accurate prediction and monitoring of freshwater/saltwater interface movement in response to both natural and anthropogenic forcing, including aquifer over-pumping, is required for the successful management of coastal groundwater resources. The study area is thinly populated and therefore lacks adequate conditions consequential for the over-pumping of shallow aquifers. In this context, the objective of this study is to use 2D electrical resistivity tomography and validated by lithology and geochemical indicators, to determine the intrusion saltwater and the relative position of the freshwater/saltwater interface in the subsurface aquifers adjacent to the sea.

1.2 Location, Geology, and Geomorphology

The area under investigation consists of three communities of Ogheye-Eghoroke, Ogheye-Orere, and Ogheye- Dimigu, they are situated on both sides of the Benin River and facing the Ocean, the Gulf of Guinea. This area is the region of the western Niger Delta where the Benin River discharges into the Gulf of Guinea. The location of the area under investigation on the Niger Delta region coordinate can be found on the latitude that ranges from 05°46′21.1″ to 05°46′48.5"and longitude that ranges from 05°04′2.2″ to 05°04′15.6″ (Figure 1). It is bounded in the west and east by the ocean and networks of tidal inlets and distributaries of the Benin River respectively. In terms of topography, annual rainfall, and temperature, the area is not distinctive from other parts of the coastal Niger Delta. It consists dominantly of the saltwater mangrove swamps of the four geomorphologic units of the Niger Delta.

The Niger Delta was formed as the result of the building up of fine-grained sediments eroded and transported by the River Niger and its tributaries which began in early Paleocene times. The Niger Delta is composed of three subsurface lithostratigraphic units; Akata, Agbada, and Benin Formations (Reyment, 1965; Short and Stauble, 1967). The basal Akata Formation was deposited in the marine environment during low stands. It consists of thick shales with minor clays, silts, and occasionally turbidite sand lenses.

The Formation which has a relative thickness of 20,000ft (5882m) is rich in organic matter and is the source of oil in the Niger Delta basin. The Agbada Formation which overlies the Akata Formation was deposited under a transitional environment, with a composition of alternating parallic sequences of sands and shales. The upper portion is predominantly sand with clays increasing with depth. The Benin Formation (2100m thick), which caps the sequence in the region and comprises over ninety percent (90%) fine–coarse-grained sands with intercalations of clay/shale interbeds.

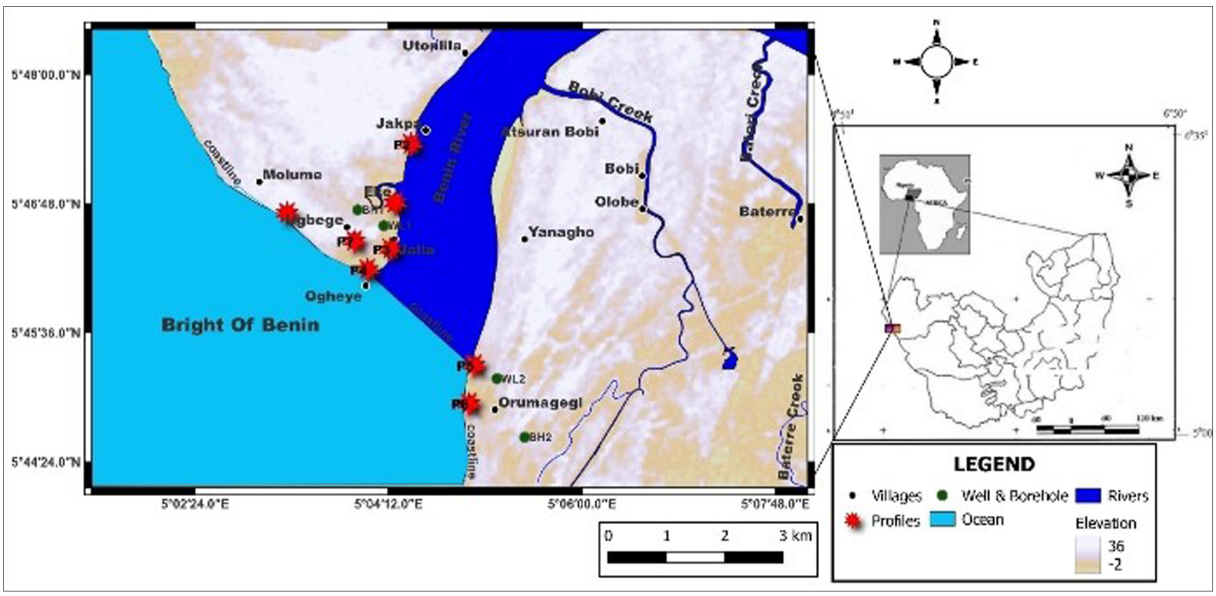

Figure 1. Map of the study area showing profiles and groundwater samples locations.

The Niger Delta is characterized by four (4) major intergradational geomorphological units (Etu–Efeotor and Akpokodje, 1990). These units occur from sea to land as abandoned and active coastal islands; beaches; saltwater mangrove swamps, estuaries, creeks, and lagoons; extensive freshwater swamps and meander belts, dry deltaic plains with rare freshwater swamps.

2. Materials and methods

Using the ABEM SAS 4000 Tarrameter in the Wenner setup with a current electrode separation of 5m, eight (8) electrical resistivity tomographies (ERT) were acquired. The roll-along approach was used manually to acquire 2D resistivity data. RES2DINV, an iterative forward modeling tool, was used to invert the measured apparent resistivity data (Loke, 2000; Loke and Barker, 1996). The program generates a two-dimensional resistivity model of the subsurface based on the measured resistivity data provided. The first stage of processing involves the creation of pseudosections, which are preliminary images of the subsurface, while the second stage involves the transformation of measured apparent resistivity values into computed resistivity values using a quick inversion method (Loke, 2000). The subsurface geology is divided into rectangular blocks using an inversion routine based on the smoothness-constrained least-squares optimization method. The model block resistivity is adjusted to minimize the discrepancy between the measured apparent resistivity and the computed values. The RMS (root mean square) error quantifies this disparity (Loke and Barker, 1996; Sasaki, 1992). Tying lithologic logs from BH1 and BH2 (Figure 2) that are close to profile locations aided in the delineation of geologic information from resistivity models.

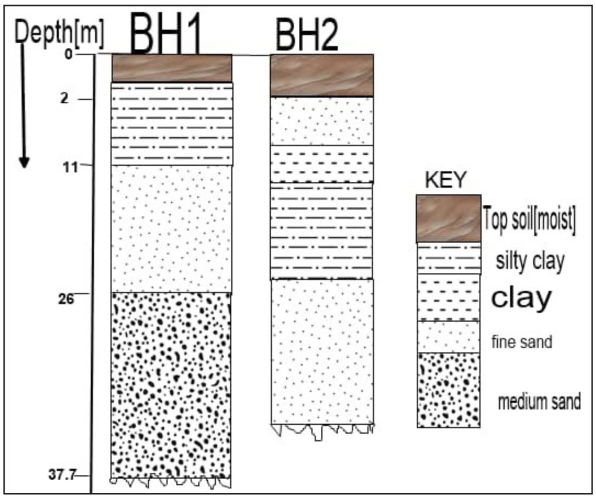

Figure 2. lithology logs depicted the subsurface geology of Ogheye-Eghoroke and Ogheye-Orere.

2.1 Groundwater collection and laboratory analysis

Four groundwater samples were collected from 2 hand-dug wells and two boreholes, as well as river samples. Groundwater data are insufficient and restricted to only four samples due to the logistic transportation of drilling equipment to the coastal region of the Niger Delta. The boreholes were logged, and depths and lithologies were tied to and aided the interpretation of 2D resistivity data. The water samples were collected from Ogheye-Eghoroke and Orere. They were collected with one-liter plastic containers, and except for those for anions analysis, a specified volume of HNO_3^- was added to samples for major cation analysis. At the time of collection, samples were stored in the field with an ice cooler box and refrigerated at 4^0 degrees Celsius before being transported to the laboratory for analysis.

Unstable parameters of TDS, pH, and electrical conductivity (EC) were measured in situ with a Hanna hand-held H19831 model and pH meter. Others, such as Ca^{2+}, Na^+, Mg^{2+}, and Cl^-, were determined in the laboratory. These ions were chosen because they contain saltwater intrusion markers such as Cl^-, Ca^{2+}, Na^+, TDS, and EC. The major cation was examined in the laboratory using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), whereas the anion was analyzed with Ion Chromatography. The results of the laboratory analysis were subsequently compared with national and WHO drinking standards (NSDQW 2007; WHO 2017).

3. Results and discussion

Table (1) and Figures (3and4) show the summarized interpretations of 2D resistivity structures and pseudo sections for the eight profiles. In general, all profiles demonstrated lateral and vertical variation in resistivity. Lower electrical resistivity values were found on the profile's western (sea) sides. This could be attributed to saltwater-saturated underlying strata intruding the aquifers from the sea. Resistivity increases immediately to the east, which is typical of freshwater aquifers located further inland from the coast.

The low and gradational resistivity zones revealed by the geologic models of the subsurface seen in models 2,3, and 5-7 in Figure 3 above strongly suggest groundwater undergoing marine incursion into inland freshwater aquifers. Due to intrusion, the groundwater in the area is evolving from freshwater to saltwater type. The trend of resistivity values laterally and vertically reflects the different groundwater types identified. This evolution can also be explained by the interplay of the freshwater/saltwater interface with the nearby aquifer (Walraevens and Van Camp, 2004). The end outcome is a degradation of groundwater quality due to intrusion, which has been shown to diminish with distance from the land. The vertical thickness of salt water appears to be thicker than 24m near the sea and reduces significantly to around 12m landward (Figure 3), which illustrates the geometry of the aquifer adjoining the sea that is experiencing intrusion. Laterally, saltwater is about 100m away, while freshwater is around 600m away. Geogenic processes and artificial abstraction are both known to contribute to the salinization of the aquifers next to the sea (Basack et al. 2022; Aladejana et al. 2020; Post, 2005; Urish and Frohlich, 1990). The most known important factor causing the saltwater intrusion is overstressing of coastal aquifers through severe pumping (Nowroozi et al. 1999; Post, 2005). The low resistivity zones seen in the area are most likely caused by geogenic processes rather than aquifer overstressing. This assertion is supported by evidence revealed from the groundwater flow and simulation of saltwater intrusion into aquifers (Ohwoghere–Asuma et al. 2021).

Table 1. Summary of interpretation of 2D pseduesections and geological inferences of profiles 1 to 8.

Location	Profile No.	Resistivity (Ωm)	Lateral distance	Depth (m)	Inference
Ogheye-Eghoroke	1	2.13-3.05	5-50	1.2-24	Saline water
		3.05-6.69	75-105	7-24	Saline water
		76-125	185-585.8	1.25-24	Saline water
		3.21-5.29	5-85	1.2-24	Saline water
	2	5.29-18.9	85-245	1.2-24	Saline water
		81-111	325- 725	1.2 – 14	Freshwater
		4.21-7.17	5-165	1.25-14	Saline water
	3	12.2-20	85-325	12.4 -24	Saline water
		75-126	45-725	1.25-24	Freshwater
		0.72- 3.67	5-325	1.2-12.4	Saline water
Ogheye -Orere	4	8.26-18.6	85-415	12.4-15.6	Saline water
		94-212	85-485	12.4- 24	Freshwater
		0.32- 4.47	5- 405	1.3 – 10.2	Saline water
	5	5- 23.1	5-485	1.25-19.5	Saline water
		0.85-5.57	5-165	1.25-19.5	Saline water
	6	10-36.4	645-735	15.9-19.8	Saline water
		78-119	485-885	20-24	Freshwater
Ogheye-Dimigu		0.89-5.24	5-245	1.25-10.5	Saltwater
	7	9.81-34.3	245-385	1.25-9.37	Saline water
		70-108	485-895	9.25-24	Freshwater
		1.13-2.78	5-165	1.15-9.25	Freshwater
	8	6.92-23.2	65-405	1.15-24	Saline water
		77-100	405-485	1.25-24	Freshwater

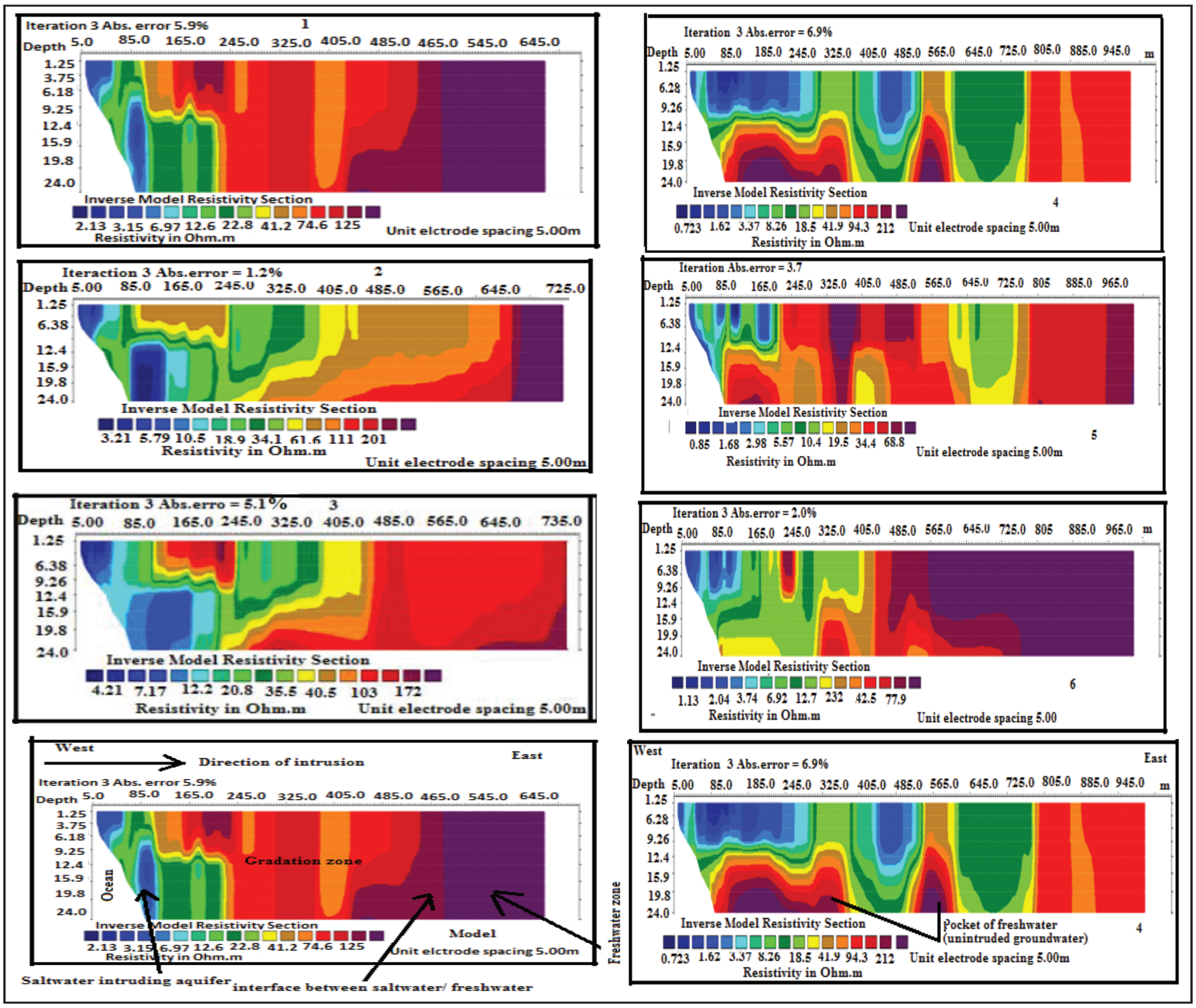

Figure 3. 2D electrical resistivity models of profiles 1-4 and 4-6 and subsurface geologic models for Ogheye–Eghoroke (right) and Ogheye- Orere (left).

Using various scenarios that reflected realistic and unrealistic water demand in most settlements along the Niger Delta coast revealed that groundwater demand is on a small scale. Pumping groundwater from these locations is not sufficient to drive intrusion. The reason is that the population in these areas is thinly populated as compared to the landed regions of the Niger Delta, which are profoundly populated. The effects of sea level rise and ocean tides on saltwater intrusion into coastal aquifers are also well documented (Panthi et al. 2022) may be responsible for the intrusion observed in the area. During transgression, marine water normally migrates towards the continent, resulting in seawater contamination of aquifers.

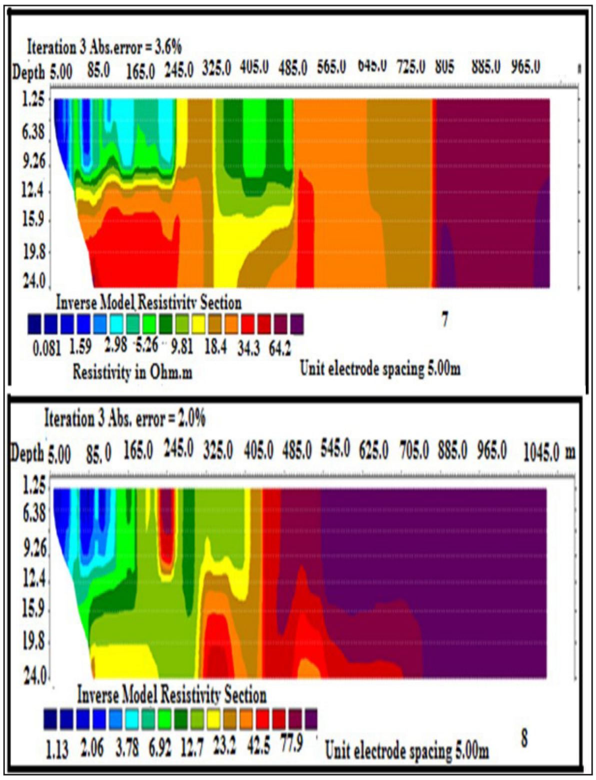

Figure 4. 2D electrical resistivity models of profiles 7-8 and subsurface geologic models for Ogheye–Dimigu.

A cursory analysis of Figures 3 and 4 reveals zones of low resistivity, which are most likely saltwater leftovers from the last time transgression. Similar low resistivity groundwater has previously been observed at shallow depths near the Lagos coastal area (Oyedele, 2001) and the Escravos area of the western Niger Delta (Ohwoghere-Asuma, 2017a), both were assumed to have been caused by marine transgression. The aquifer directly adjacent to the ocean was primarily affected by tide-induced intrusion, particularly at the high tide mark of the beach. In such cases, the high tide mark (upper shoreface) is flooded with a significant amount of seawater intermittently during high tide, which then infiltrates into the subsurface to contaminate groundwater. As demonstrated by Ohwoghere-Asuma (2017a) for the Escravos area, this is common in most upper seashores of the basin. Aside from flooding at the high tide mark, saltwater seepage from the Benin River into the underneath aquifer is possible. This is further demonstrated by the change in water quality inside the tidal reach that is dependent on the makeup of the original river water and the seawater. A zone of mixing and diffusion migrates up and down the river, generating a cyclic diurnal change in water quality, with the most saline contamination occurring during high tide and the least contamination occurring during low tide. During the dry season, when river levels are at their lowest ebbs owing to a lack of rain, rivers in estuaries are salinized by tides induced by an influx of seawater upstream (Abam, 1999). The water quality appears saline and further inland in the lower region of the estuary than in primary freshwater. The distances salinized upstream typically range from less than 1km to tens of kilometers, so saltwater is confined to the riverbank. When aquifers in coastal areas are hydraulically connected to rivers within the estuarine reach of the stream, saltwater may encroach into the underlying freshwater aquifers depending on the relative positions of the water table and the river stage; this is most likely reflected in the subsurface geologic models depicted in Figures 3 and 4. Because of the huge discharge of freshwater that dilutes intruded aquifers during the rainy season, the influence of tides on water quality is negligible during the rainy season. As a result, it is assumed that the saltwater seen near the river bank is caused by tidal influences.

3.1 Geochemical markers

Ambiguity is frequently encountered while inferring geologic information from subsurface resistivity investigations, highlighting the importance of subsurface lithology for effective resistivity data interpretation. Subsurface geology is frequently used to evaluate 2D resistivity interpretations to avoid ambiguity with an adequate depiction of the subsurface. To correlate the salinity of groundwater with depths explored with 2D resistivity data, groundwater geochemical facie was used to determine whether or not aquifers have been intruded with saltwater from the neighboring marine environment. As a result, four groundwater samples from two boreholes and two dug wells were tested for intrusion markers. The pH values shown varied from 6.3 to 7.4 (Table 2), indicating that the groundwater is moderately acidic and slightly neutral. This is typical of most aquifers in the Niger Delta basin, as groundwater from these locations is typically fresh, somewhat acidic, and has a high dissolved Fe^{2+} concentration.

Table 2. Physiochemical composition of the groundwater and Benin River of the study areas.

Sample	pH	EC (µS/cm)	TDS (mg/l)	Ca^{2+} (mg/l)	Na^{+} (mg/l)	Mg^{2+} (mg/l)	Fe^{2+} (mg/l)	Cl^{-} (mg/l)	Depth (m)
HDW1	7.4	8100	4000	34.42	102.68	93.96	0.02	264.	2.30
BH1	6.3	267	135	13.41	15.6	12.20	0.01	12.18	37. 18
HDW2	6.7	8000	4000	31.88	88.92	79.29	0.02	234.90	4.60
BH2	6.5	1432	715	16.68	98.64	18.21	0.03	67.82	68.78
Benin River	7.4	84000	4000	69.74	246.67	89.45	0.03	456.89	

The parameters of EC, TDS, and Cl^-, which are commonly utilized as proxies for saltwater intrusion are defined by concentrations that are more than the Nigerian and WHO standards for drinking water (NSDQW, 2007; WHO, 2017). Kim et al. (2003) discovered that aquifers that have been intruded by saltwater typically exhibit ECs above 5000S/cm. Furthermore, the mixing of freshwater and saltwater in the aquifer can be deduced from EC values greater than 3000μS/cm (Karahanoglu, 1997). Table 2 exhibited EC values ranging from 267 to 8400μS/cm. Those above 5000μS/cm are from dug wells with ECs of 8100 and 8000S/cm, respectively. This could indicate that these shallow-dug wells have been subjected to intrusion. Backwaters with direct access to the sea may be a source of intrusion, especially during the dry season. This backwater influx is confirmed in October 2021, when the levels of EC and TDS of HDW1 measured were observed to decrease from 81000S/cm and 4000mg/l to 2217S/cm and 1093mg/l, respectively. The decrease in values is caused by a large input of freshwater from the landward side, which forces saltwater inward into the sea during the wet season. Elango and Manickam (1987) and UNDP (1987) provided a similar argument for the Bay of Bengal and the Buckingham Canal.

TDS levels greater than 2000mg/l indicate that saltwater has intruded the freshwater aquifer. The TDS values shown in Table 2 for dug wells are significantly greater than those for boreholes, ranging from 235 to 4000mg/l. HDW1 and HDW2 are with values that exceeded this, except BH1 and BH2, respectively. The ionic ratios of Na^+/Cl^- and Mg^{2+}/Ca^{2+} have been used to distinguish between freshwater and saltwater aquifers. A non-intruded freshwater aquifer is characterized by having $Na^+/Cl^- > 1$ and an intruded aquifer is 0.86 (Vengosh and Rosenthal, 1994). The Na^+/Cl^- for HDW1 and HDW2 are 0.64 and 0.58, respectively, and those for the BH1 and BH2 are 1.97 and 2.24, respectively. The ratios of Na^+/Cl^- of groundwater from HDW1 and HDW2 are lesser than 0.86 required for aquifer experiencing intrusion. The low ratio values that are lesser than 0.68 is suggestive of the initiation of salinization of groundwater from HDW1 and HDW2. The Na^+/Cl^- of groundwater from BH1 and BH2 exceeded one (1) required for a coastal aquifer to be regarded as freshwater. Again, this indicates that BH1 and BH2 with depths of 37m and 69m, respectively, are freshwaters and therefore have not experienced intrusion.

Mg^{2+}/Ca^{2+}ratio in freshwater aquifers intruded by saltwater ranges between 4.3 and 5.2 (Jones et al., 1999). The Mg^{2+}/Ca^{2+}ratios of BH1 and BH2 are 1.5 and 1.8, respectively, while HDW1 and HDW2 are 4.5 and 4.1, respectively. These values are consistent with the Na^+/Cl^- ratios as well as the TDS and EC values; however, the high TDS, EC, and ratios of Na^+/Cl^- and Mg^{2+}/Ca^{2+}values show that the quality of water in the dug wells have been compromised by intrusion whereas the boreholes were not. These indicators appear to have verified the subsurface geology model in that intrusion is significantly limited to shallow aquifers with depths ranging from 2.3 to 4.3m. Although the depth inferred from the 2D resistivity model is 24m, it is shallower than the depths of 37m and 69 meters for the borehole whose water is fresh. These depths are comparable to those found in Ohwoghere-Asuma's (2019) previous investigation using vertical electrical sounding. This aquifer could have been protected by a thick layer of clay, which could have served as a barrier to intrusion. Since the geochemical markers of the groundwater from these boreholes are below allowable limits, the intrusion does not affect aquifers in these communities located 400 to 500 meters from the sea.

4. Conclusions

The underlying geology revealed by borehole lithologic logs and interpreted 2D resistivity data indicates a lithostratigraphy of silty clay, clay, fine sand, medium, and coarse sand. Saline water is restricted to depths ranging from 2.3 to 4.6 meters due to silty clay. Groundwater geochemical markers from these depths strongly indicated intrusion. At depths near the upper shoreface, saline water can be found at 24m, although it decreases to 12m as the distance from the coast increases towards land, whilst water at this depth is fresh further inland.

The current study was successful in displaying electrical resistivity tomographies of the subsurface geology, which aided in the establishment of saltwater-freshwater interaction and delineation of the interface, which is located between 415 and 485m, and 735 and 885m from the sea at Eghoroke and Orere, respectively. The resistivity model displays a strong trend of increasing resistivity landward from the ocean, indicating that groundwater salinity is decreasing. Groundwater in the studied area was classified into three types and three distinct zones based on resistivity image values: very low resistivity zones suspected to be areas affected by intrusion located near the ocean, mixing (transition) zones of salt water with fresh water, and a zone of only freshwater.

The validation of the 2D electrical resistivity data with lithologic logs and total dissolved solids (TDS), electrical conductivity (EC), and molar ratios of Na^+/Cl^- and Mg^{2+}/Ca^{2+} of groundwater from boreholes in the study has significantly increased the likelihood that intrusion is on a very small scale and limited to shallow aquifers. In this study, the small scale of intrusion discovered is substantially adduced to the lack of intensive pumping, which could lead to a drop in the hydraulic heads of aquifers on the landward side of the ocean. However, the intrusion is caused and controlled by the influx of backwater from the sea into the freshwater aquifers during the dry season, when the Benin River discharge is relatively low.

Based on the information presented in the paper, we recommend that groundwater development for optimal freshwater abstraction be located at least 450m away from the ocean, and monitoring wells be drilled to depths of 38 to 70m deep to monitor intrusion. Groundwater from these proposed drilled wells should be tested for physicochemical characteristics to determine water quality frequently.

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