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Fresh Water Depth Determination and Mapping of Saline/Fresh Water Interphase Using Geographical Logs in Coastal Aquifers of Niger Delta, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors contributed to the conception and design of the study. Authors TM, JK and EEE were responsible for material preparation, data collection, and analysis. Author JK wrote the first draught of the manuscript, which was reviewed and redrafted by authors TM and EEE. All authors read and approved the final manuscript.

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ABSTRACT

The introduction of salt/saline water into boreholes has been a major issue in groundwater utilisation in the Niger Delta.
Aim: The study was aimed at determining the depth of saline/saline water and freshwater aquifers in the region.
Study Design: The study was designed to use combined geophysical borehole logs to delineate saline water and fresh water aquifers by determining the depth of such aquifers.
Place and Duration of Study: Research took place in 7 locations within the Southern Niger Delta between March 2021 and November 2021.

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Methodology: This involved the interpretation of downhole electrical resistivity, natural gamma ray and spontaneous potential logs using the difference in their values in different lithologic formations.
Results: Two levels of fresh water zones (a shallow unconfined aquifer between 0 and <150m and beyond) were revealed. Both are separated by a zone of saline water. The freshwater aquifers are mainly sand and gravel, while the saline zone has clay, sandy clay, and silt mixed in various proportions. However, some areas have multiple freshwater aquifers while some do not have a shallow freshwater zone. The variation in depth at various locations could be due to differences in lithology and the rate of abstraction.

Keywords: Geophysical borehole logs; groundwater; coastal aquifers; saline-fresh water interface.

1. INTRODUCTION

Because freshwater is a basic necessity of life, men have worked throughout history to locate and develop it. Human civilization has been centred on the availability of water resources. Water occurs either as surface water or groundwater. Over ninety percent of the freshwater that is available at any given moment on the earth lies beneath the land surface [1]. Groundwater is the most important source of fresh water resources for domestic and industrial uses in coastal regions [2]. However, its availability is hampered by a lot of factors, such as subsurface structural conditions, movement of water within geologic formations, the environment, and climatic conditions. Groundwater is found in sedimentary aquifers and in the cracks and fissures of rocks. An aquifer is a water-bearing formation or stratum capable of transmitting water through its pores at a rate sufficient for economic extraction by wells [3,4]. Because groundwater is widespread and less prone to pollution, it has become a major source of water supply. More than 90 percent of the population in the Niger Delta depends on groundwater for its water supply [5]. This is because of the availability and cost of developing and treating portable surface water. The rapid population increase and urbanisation have put so much pressure on the water resources of the area, especially in the coastal areas. This has offset the freshwater-saline water balance, resulting in the movement of saline waters into coastal aquifers [6,7].

The movement of saline waters into coastal aquifers saline water instruction into the coastal aquifer has become a major concern as it constitutes the most common of all pollutants in freshwater in the coastal areas of the Niger Delta. Saltwater intrusion could be described as the movement of saline water into freshwater aquifers. It is a process by which sea water infiltrates into coastal aquifers, leading to contamination of water sources for various uses. A major cause of saline water intrusion is excessive extraction of water from coastal aquifers. Other causes include changes in the sea level due to dredging and other human activities. Overpumping reduces the hydraulic head of the aquifer, thus slowing or stopping the southward flow of freshwater, which allows saltwater to move further inland [8]. Excessive extraction of groundwater induces upconing, whereby deeper saline waters from the underlying saltwater wedge drain towards a pumping well. A reaction in the recharge rate of an aquifer due to precipitation or an increase in sea level often leads to a change in the saline water/fresh water dynamics [1,5]. A detailed hydrogeophysical study is therefore necessary to understand the saline water and fresh water dynamics in the area and also to determine the depth of freshwater aquifers and the saline water interface. This is with a view to providing good-quality portable water for various uses in the area.

In this study, geophysical logs (electrical resistivity and gamma ray) were used to capture the salinity situation in some coastal aquifers in the Niger Delta, Nigeria. Based on the resistivity values of the formation, detailed mapping of saline water and freshwater boundaries was completed. Geophysical logs have distinctive configurations for certain beds or horizons whose characteristic forms correspond to lithologic changes, hence electrical resistivity, spontaneous potential (SP), and gamma ray logs.

Resistivity logs measure the effect of an artificial electric current produced and transmitted to a subsurface through electrodes. Several studies have used electrical resistivity logs to interpret rock types, aid in correlation, and estimate the chemical nature of a deltaic environment [9][10][2]. The electrical resistivity geophysical method has the advantage of sub-surface electrical properties. Also, the interpretation is straight-forward, and the equipment is simple. However, the measurement is not an intrinsic characteristic of the material since it is not possible to determine the length or cross-sectional area of the current [4][11].

1.1 Geology of the Area

The Niger Delta, which is Eocene to Recent in age, is a region of redistribution of waters of the River Niger into the Gulf of Guinea. The development of the Niger Delta has been dependent on the balance between the rate of sedimentation and the rate of subsidence, resulting in a succession of transgression and regression of the sea, giving rise to three main subsurface lithostratigraphic units. These units, in ascending order, are the Akata, Agbada, and Benin formations [13][14].

The Akata formation is made up of marine shale. The Agbada formation is characterized by sandstone and sand beds alternating with shale. The sands are salt water-bearing with formation resistivity up to 2 ohm, except those containing hydrocarbons [6][1]. The third in the sequence is the Benin formation, which is predominantly sand and gravel with local shale intercalations. The sands are highly porous and permeable, while the localized shales are impermeable. Quaternary deposits of about 100 m in thickness comprising recent deltaic sediments made up of sand, silt, and clay beds overlie the Benin Formation in the swampy deltaic areas [5][15].

1.2 Hydrogeology of the Area

Groundwater recharge is mostly through infiltration from precipitation and rivers/lagoons at the surface. The Benin Formation is the dominant freshwater aquifer in the Niger Delta. It consists mostly of sand, clay, and silt. These materials are believed to have been deposited in a fluviatile to deltaic environment. The clays are of various thicknesses, up to about 20 m.

Fig. 1. World Map [12]

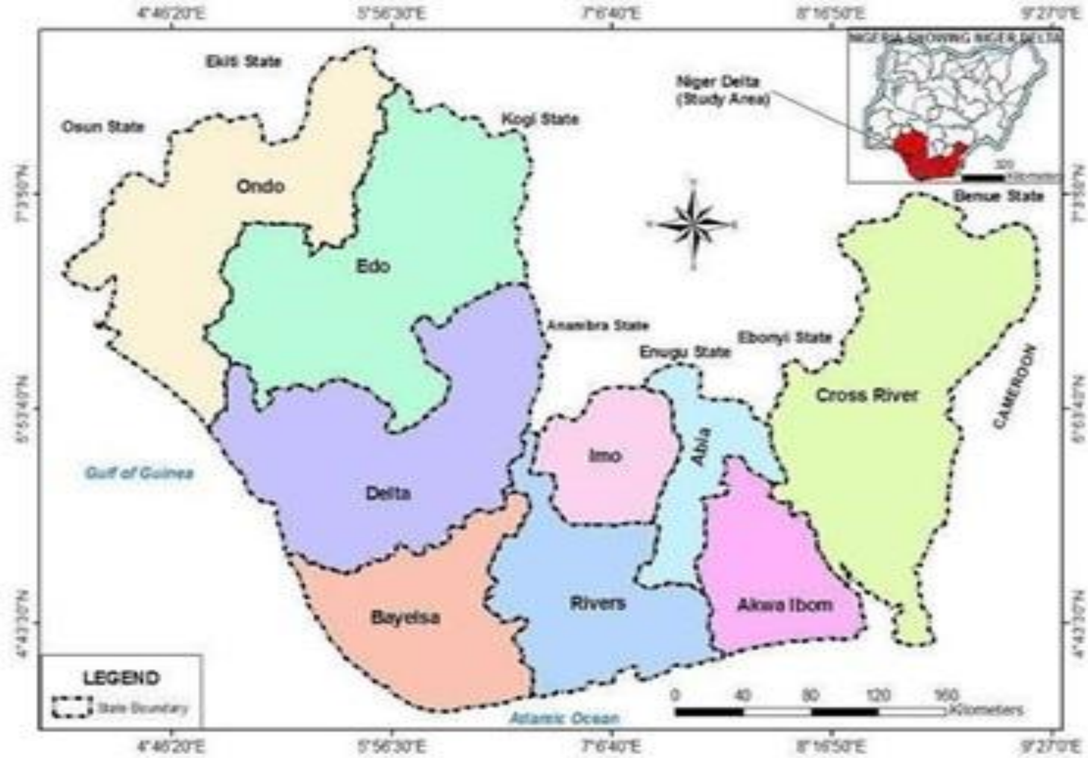

Fig. 2. Location map

Logging of existing boreholes showed deep sandy units in parts of the area with some unconfined and confined aquifers. The deltaic aquifers are classified as unconfined because they are recharged directly by infiltration from precipitation and base flow. Their water table is very shallow, between 0 and 90m below ground level. They have little variation due to heavy rainfall ranging from 2400 mn to 4800 mn all year [6][16]. The confined aquifers consist mainly of very coarse-to medium-grained sands. They are confined by a clay layer up to 40 m thick. Their average thickness is about 100m. The aquifers increase in thickness toward the continent while the confining clay thins out [2] [17].

There is observed irregular alteration of aquifers and aquitards which make up the aquifer system. They occur at various depths and are of varying thicknesses. The aquitards are mainly shale or clay and are usually 3–15m thick, capping the aquifers.

2. MATERIALS AND METHODS

Data for the study consists of lithostratigraphic and down-hole geophysical logs from recently drilled deep water boreholes. The wells were drilled using a rotary method commonly used in the Niger Delta. The down-hole geophysical logging was carried out using mount sop equipment in 8 water boreholes in Ndoni, NLNG–Amadi Creek, Bonny and Onne, all in the Niger Delta (see Fig. 3). The spontaneous potential (SP), resistivity, and gamma ray logs were used for the study.

The resistivity logs gave information on both the rock units and the quality of the water content in the invaded zone, while the SP and Gamma logs provided information on the different rock unit penetrated in the boreholes. Spontaneous Potential (SP) and Electrical Resistivity (ER) logs also enabled the demarcation of saline and fresh water zones penetrated in a borehole.

The electrical resistivity (ER) is interpreted based on the fact that high ER indicates the presence of fresh water, while low ER is an indication of saline water or brackish water. The ER and the lithologic samples were matched to map out fresh water horizons and likely saline water aquifers. A deflection of ER to the right (high ER) indicates fresh

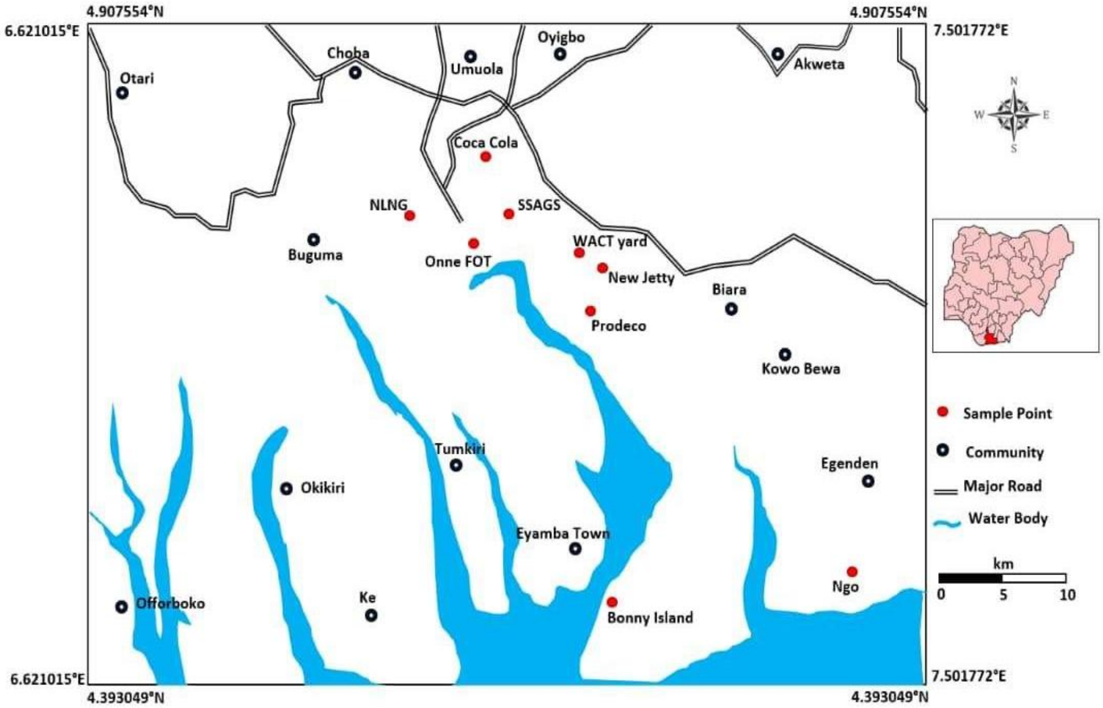

Fig. 3. Sample Location Map

water; a deflection to the left (low ER) indicates saline or salt water horizon. This was correlated with the litho-log to know the type of formation, whether sand, clayey sand, gravel, clay, etc.). This way, areas likely to have fresh water, salt or saline water were demarcated.

3. RESULTS AND DISCUSSION

A careful analysis and interpretation of each log was done to separate sand from clay, fresh water-bearing sand from saltwater-bearing sand. With this, the interphase between fresh water and saline water was determined in the area. Representative geographical logs of the boreholes and the strata logs were presented in Figs. 4-7. Below is a detailed description of four boreholes considered representative of the study area.

Both the geographical and lithologic logs show that the subsurface stratigraphy of the area consists of various thicknesses of alternating layers of sand and clay, sometimes combined in various proportions (Figs. 4-7). This is in line with other studies in the Niger Delta [13,14,5,11]. Following the method of Jimoh et al. [14][19], thick sand units that are separated by thin clay/clayey sand/sandy clay layers are merged and considered as a single uniform and continuous sand unit (Fig. 5). Furthermore, where there is no thick continuous sand layer, clayey sands and/or sandy clay are the primary water-bearing units (Fig. 4).

3.1 Borehole 1 (BH1)

Between 0–20 m and 40 m to about 165 m, there is a high resistivity value (> 100 ohms). These regions correspond to fresh water-bearing layers. From 20m to 40m and 165m to 195m, the resistivity is much lower (80 ohms). These correspond to saline/brackish bearing layers, while from 20m to 40m, the resistivity is between 80–100 ohms. This indicates the salt/saline water to fresh water interface.

Looking at the subsurface strata, 0 – 20 is a sand layer with minor clay intercalations; also, the interface of 30 – 40m corresponds to the sandy clay/clay sand logs as shown in Fig. 4. The freshwater-bearing structures are the sand units, with intermittent clay units at various points.

Table 1. Summary of studied boreholes in the Niger Delta

S/N	BH No	Location	Depth (m)	Depth logg ED (m)	Coordinates	
					Northing	Easting
1	1	Ngo Andoni LGA	220	200	5.3998^o	6.6211^o
2	2	WACT yard FOT Onne	200	200	4.7238^o	7.1516^o
3	3	Onne FLT/Prodeco	165	156	4.6872	7.1547^o
4	4	ONNE FOT	200	190	4.74434^o	7.035316^o
5	5	Coca Cola Plant Port Harcourt	300	300	4.81351^o	7.0443^o
6	6	Onne FLT/New JETTY	214	211	4.71803^o	7.15412^o
7	7	IMT/OSB	350	350	4.76997^o	7.06438^o

Table 2. Data summary from the studied location's logs

S/N	Location	Borehole depth (cm)	Types of logs	Depth range of surface aquifer (1μg)	Saline/fresh water interface (1μg)	Confine fresh H_2O depth
1	Ngo, Andoni LGs	200	EP Gamma SP	0 – 20	20 – 40	40 – 165
2	Wact Yard, FOT, Onne	200	EP Gamma SP	0 – 3		
3	Onne, FLT/Prodeco	165	EP Gamma SP	0 – 70	70 – 98	≥ 115
4	IMT/OSB, Bonny	350	EP Gamma SP			
5	Coca-cola, PH plant	300	EP Gamma SP			
6	Onne FOT	200	EP Gamma SP	0 – 28	60 – 125	150 –

3.2 Borehole 2 (BH2)

The resistivity value from 0 – 30m is very low and falls to about 0 – 10 ohms. This region therefore corresponds to the saline water-bearing layer. There is, however, shallow fresh water between 30 and 50 metres deep. Between 50 and 70 m, there is a zone where fresh water meets salt water. This is indicated by the near-zero values of the resistivity. Another saline layer is identified at a depth between 75m and 125m, with a resistivity value of about 10 ohms as indicated in Fig. 7. From observation (and confined by strata log), these regions correspond to clay and silt/sandy clay layers. Sand/silt units with intermittent clay units at various points form the saline water-bearing structure.

3.3 Borehole 3 (BH3)

There is a high resistivity value (about 250 ohms) between the upper 15 and 70. From 70 to about 98 m, the resistivity falls to about 5 ohms. From 98 m to 150 m, the resistivity is much higher (See Fig. 6). These regions correspond to the fresh water bearing layer, whereas resistivity between 8 and 10 ohms indicates the salt/saline water to fresh water interface between 70 and 98 m. Observing the subsurface strata, the 0–70m are sandy clay and clay sand layers. Also, the interface of 70 to 98 m is a sandy clay layer without clay intercalations as shown in Fig. 6. The fresh water-bearing structure is the sand units with intermittent clay at different points.

3.4 Borehole 7 (BH7)

The resistivity values between 15 and 19 ohms and from 40 to about 80 m are very low (between 0 and 10 ohms). This indicates that the region corresponds to saline water-bearing layers. This is below a high resistivity surface layer of about 500 ohms. From the strata log, this region corresponds to clay and silty clay layers (Fig. 7). Three other salt/saline to fresh water interphases were recognized from the logs at 110 and 120m, and about 150 and 190m. This is confined by the resistivity values of 40 ohms as indicated in Fig. 7. There is therefore a shallow surface of fresh water up to a depth of 15m. The saline water-bearing structure is the intercalated sand with clay units at different locations. Fresh water zones are indicated between 100 and 110m, 120m and 150m, 155 to 190m and at depths of 190 to >240m.

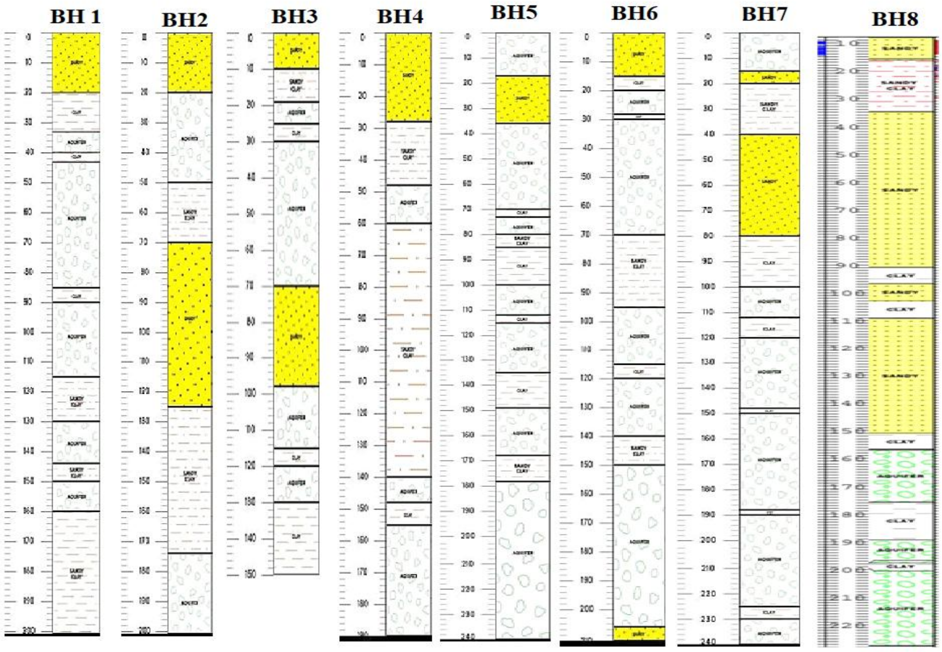

Fig. 4. Summary of Stratigraphic Logs

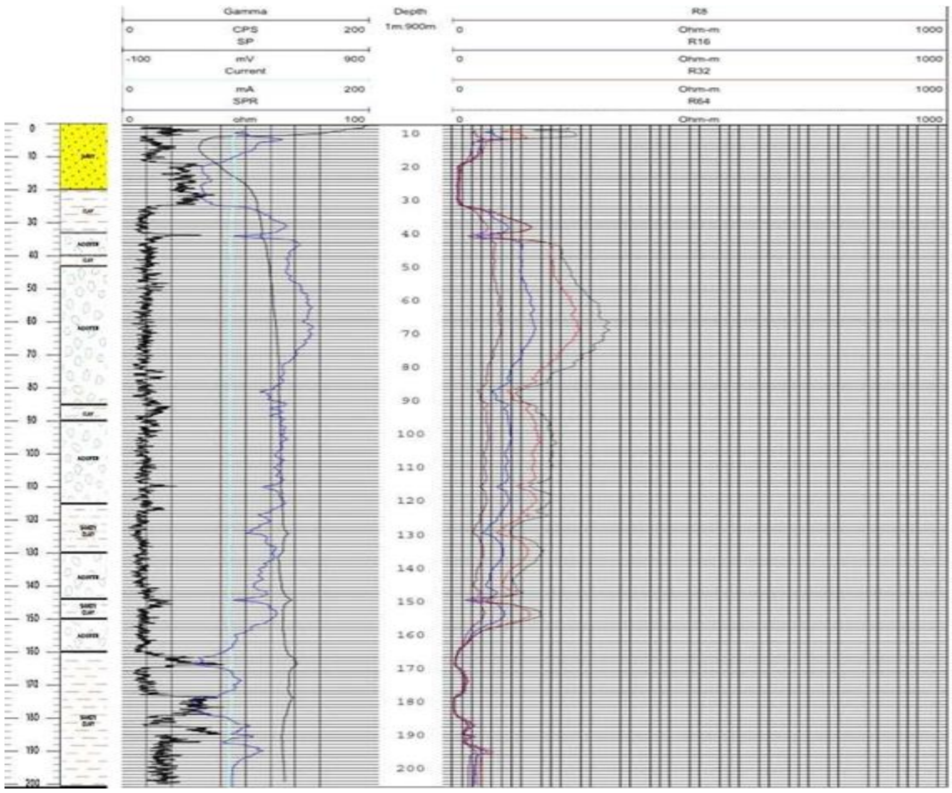

Fig. 5. Geophysical Log of a Borehole at Ngo, Andoni LGA

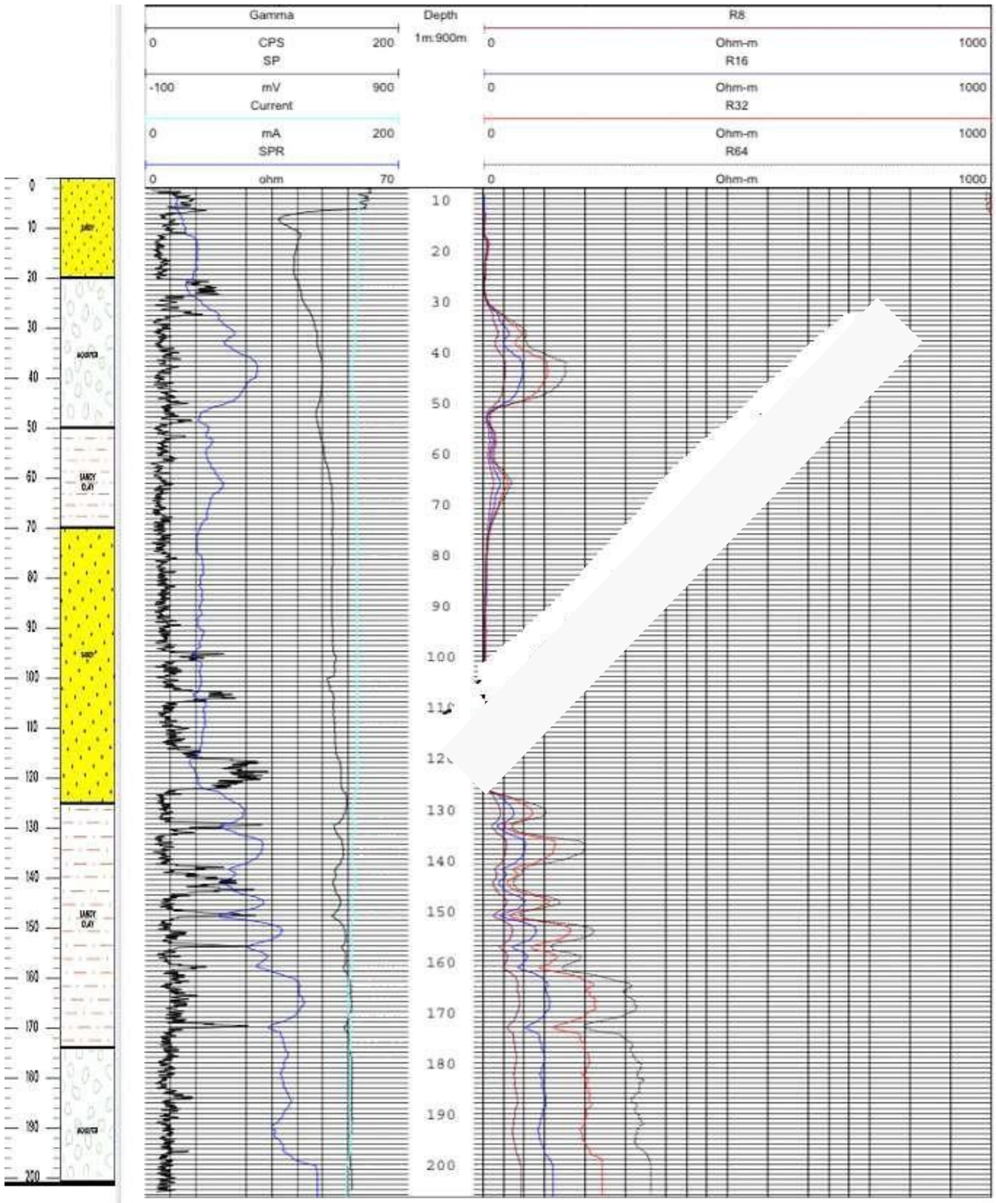

Fig. 6. Geophysical Log of a Borehole in Wact Yard FOT Onne

4. DISCUSSION

The coastal plain sands of the Benin formation are indicated as the main aquifers in the study area and the Niger Delta at large. There are 100-meter-thick quaternary deposits of recent deltaic sand sediments. [1][2]. The measurement of electrical resistivity shows values that vary with certain aquifer characteristics. Clean sand saturated with freshwater shows relatively high resistivity, while dirty sand, shale, and clay show low resistivity. Those variations in resistivity values of various earth materials were used to identify various formations and water boundaries. As a result, high-resistivity sands and water boundaries exist. This high-resistivity clay gravel was differentiated from low-resistivity clay and shale. In some way, freshwater horizons of high resistivity were delineated from salt /saline water horizons.

The aquifer system and groundwater types were established by an integrated interpretation of the lithologic and downhole geophysical logs (gamma and electrical resistivity logs). The number of aquifers appears to increase from the uplands towards the coast. They are of varying thickness and occur at different depths within the region.

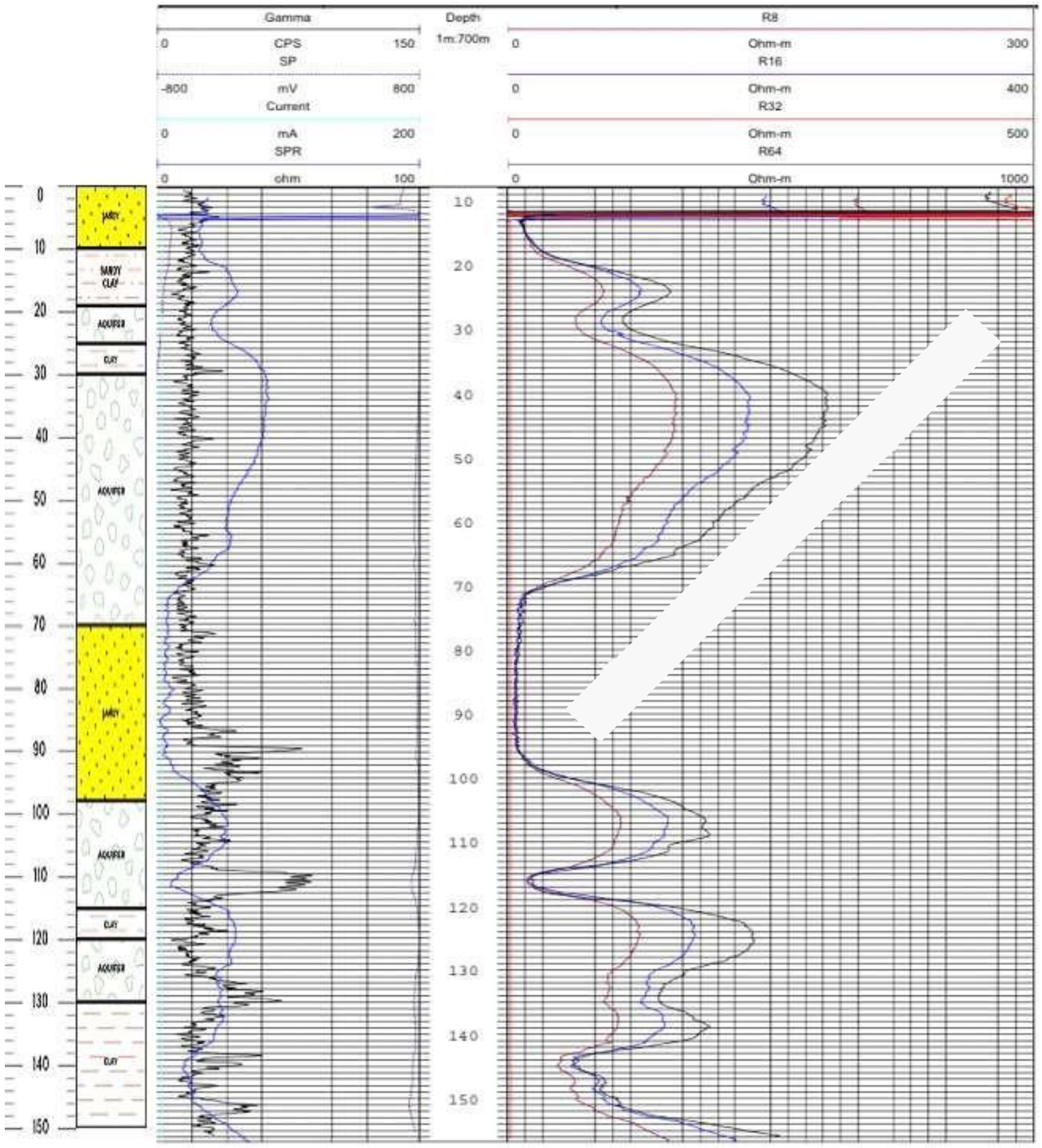

Fig. 7. Geophysical log of a borehole at Onne Flt/Prodeco

The first freshwater zone is the high-resistivity unconfined surface aquifer, which is shallow and at varying depths (from about 0 to 50m). This shallow, unconfined surface aquifer is not detected in some areas (Figs. 5,6). This may be a result of a lack of suitable water bearing aquifers, bearing in mind the presence of numerous aquitards and aquicludes in the deltaic sands and Benin formation of the Niger Delta. Such aquitards are mainly shale or clay and usually 3–15 m thick; however, they appear to be localised as they are not laterally continuous over long distances [10]. Many authors [8][10] have cautioned against groundwater extraction for domestic uses from this shallow surface aquifer, citing the potential risk of contamination through human activities and saltwater infiltration as reasons.

The second freshwater horizon is indicated between 90 and 250 meters, depending on location, with an increase in resistivity values. Here, the resistivity values are higher as one moves up, indicating a seaward movement of freshwater because of the hydraulic head difference. This is in line with the natural geodynamic equilibrium between freshwater and salt or saline water [18][11][10]. In between these two horizons of freshwater is a transition zone or an interface of saline / saltwater and freshwater, whose thickness is variable depending on location. The resistivity values in this zone are between 50 ohms and 100 ohms. This contact between the freshwater and saline water interfaces is not sharp but gradual. The interface fluctuates due to tidal and potentiometric local changes. As a result, mixing of saline and freshwater occurs primarily due to deposition and less significantly due to molecular diffusion in a limited zone near the interface. Numerous studies have focused on the movement of saline water in coastal aquifers of the Niger Delta [10][9][13]. Some of the reasons are an increase in groundwater abstraction in coastal areas, changes in sea level, and the absence of a shallow unconfined aquifer in some locations (Fig. 5), which may be attributed to changes in sea level, which can lead to changes in the direction of groundwater flow in a coastal aquifer [16][8][20].

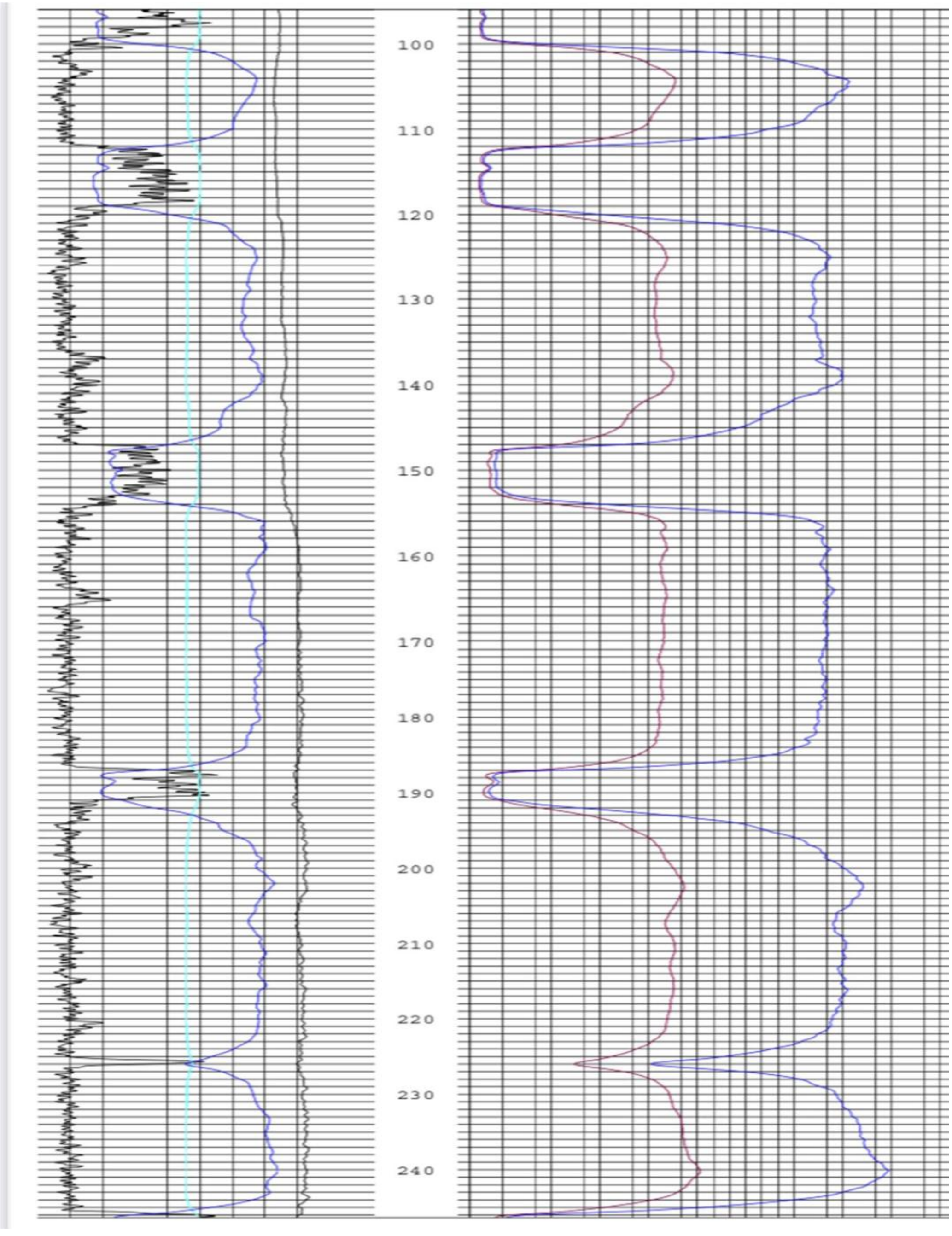

Fig. 8. Geophysical Log of a Borehole in IMT/OSB

Amechi et al [1] attributed the saline water in the coastal area of the Niger Delta to connate water (water trapped during the transgressive phases of the delta formation) The reason has been that groundwater development in the Niger Delta is in its infancy, and there is no over development of the aquifers that could have led to recent saltwater intrusion.

Salt in the groundwater of coastal aquifers may come from natural and anthropogenic sources, but significant contamination at levels high enough to impair its usefulness often comes from natural sources [17][18]. Natural sources include saline seawater intrusion, tidal oscillation, and induced enlargement of saltwater zones leaching from saline confining beds [1] Under normal condition, the inland extent of salt water is controlled by the higher pressure exerted by the freshwater column. Groundwater extraction often lowers the level of the freshwater table, allowing the denser saltwater to move inland laterally. This can also contaminate the groundwater well by causing the upwelling of saltwater.

5. CONCLUSION

Using geographical and lithostratigraphic logs, the subsurface stratigraphy of the study area was delineated. Also, the various aquifers and their dept demarcated using electrical resistivity (ER), spontaneous potential (SP), and gamma ray (GR) logs, aided by the strata logs. Two fresh water zones (0–70m and 150m), depending on location, were delineated using their resistivities. In between these zones are the transition zones of the fresh water/salt water interface. The first freshwater zone is shallow and unconfined and is recharged directly from infiltration. It is therefore alienable to surface contamination. The second fresh water aquifer is confined and is therefore recommended for fresh water extraction. It is believed that there are deeper aquifers in the area. This calls for further studies. The findings of this study have provided an effective strategy for reducing the number of abandoned water wells in the study area and the Niger Delta as a whole.

THE FUTURE

Geophysical logs have proven to be valuable tools in well design because they can pinpoint the exact depths and thicknesses of the right aquifers (permeable zones) where quality groundwater is available and substantial enough to be screened for extraction. The findings of the preceding study should be taken into account in any ground water development programme in the Niger Delta and beyond. When studying coastal aquifer characteristics of saline / fresh water interactions, a detailed hydrological study is strongly recommended.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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