*Original Research Article*

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


## ABSTRACT

The introduction of salt/saline water into boreholes has been a major issue in groundwater utilisation in the Niger Delta.

**Aims:** 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.

**Methodology:** This involved the interpretation of downhole electrical resitivity, 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.




## INTRODUCTION

Groundwater is found in sedimentary aquifers and in the cracks and fissures of rocks. An aquifer is a water-bearing geologic formation or stratum capable of transmitting water through its pores at a rate sufficient for economic extraction by wells [17]. Because groundwater is widespread and less prone to pollution, it has become a major source of water supply. More than 90% of the populace in the Niger Delta depends on groundwater as their source of water supply. This is because of its readily available nature and the cost of developing and treating portable surface water. The rapid population increase and urbanization of the Niger Delta as a result of industrialization have put so much pressure on the water resources of the area, especially in the coastal areas. This has resulted in the movement of saline waters into coastal aquifers, offsetting the freshwater-saline water balance.

Saline water intrusion into coastal aquifers has become a major concern as it constitutes the most common of all pollutants in fresh water in coastal areas of the Niger Delta [13]. Salt water intrusion could be described as the movement of saline water into a fresh water aquifer. It is the process by which seawater infiltrates coastal aquifers, contaminating water sources for a variety of uses. A major cause of saline water intrusion is excessive extraction of water from coastal aquifers. Other causes include changes in sea level due to dredging and other human activities. Over pumping reduces the hydraulic head of the aquifer, thus slowing or stopping the southward flow of fresh water, which allows salt water to move further inland [4]. Excessive extraction of groundwater induces an upcoming whereby deeper saline waters from an underground salt water wedge drain towards a pumping well. A reduction in the recharge rate of an aquifer due to less precipitation and an increase in sea level often leads to changes in the saline water/fresh water dynamics.

A detailed hydrogeophysical study is therefore necessary to understand the saline water/fresh water dynamics in the area, and also to determine the depth of freshwater aquifers and the saline water/fresh water interphases. This is in order to provide high-quality portable water for a variety of uses in the area. The study looked at the salinity situation of the subsurface coastal aquifers in the Niger Delta. Detailed mapping of saline water/fresh water boundaries was done based on the resistivity values of the formation. It is believed that his map will be a valuable guide to water professionals in their efforts to provide good quality water for various uses in the area.

This study was done in parts of the Niger Delta. The area encompasses four Local Government Areas in coastal Rivers State – Andoni, Obio/Akpor, Bonny, and Onne, Nigeria. The Niger Delta, which is the second largest delta in the world, covers an area of 75,000km$^2$ and is located between latitudes $4^0 3^{'}$ and $5^0$20'N and longitudes $3^0$ and $9^0$E with a coastal line of about 450km [3].

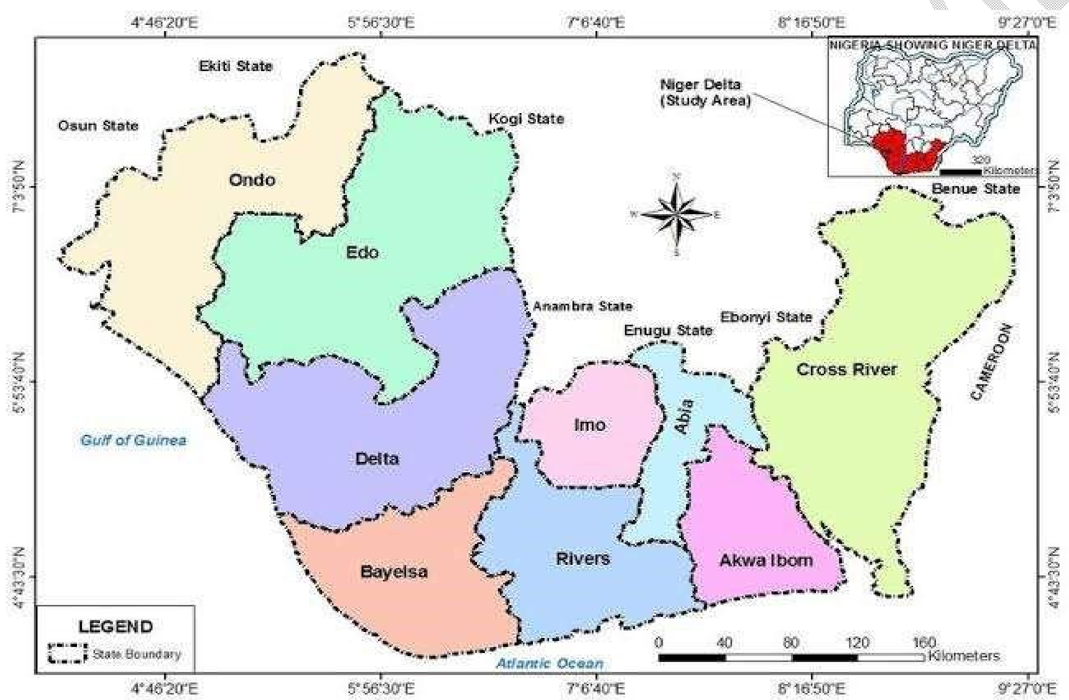


Figure 1: Location Map

## 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 [18].

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 [16][3]. 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 [2].

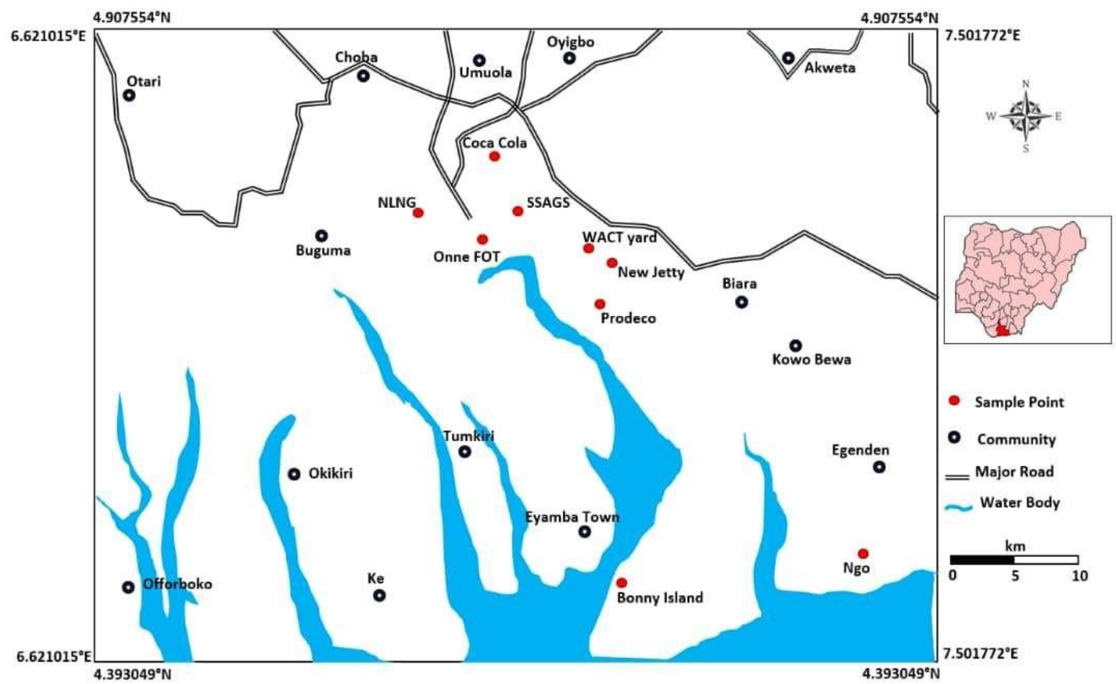


Figure 2 Sample Location Map

**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. The intercalations of sand and clay gave rise to multiple aquifer systems in the Niger Delta [8][1] Etu-Efeotor [9] identified and delineated three main aquifer zones (upper, middle, and lower zones), while Ngah (1990) demarcated four zones in the Niger Delta.

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 [16][7] 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 [12] [4].

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.

**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 Figure 2). 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 units 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 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.

Table 1: Summary of Studied Boreholes in the Niger Delta

| S/N | BH No | LOCATION | DEPTH (m) | DEPTH LOGGED (m) | COORDINA | |
|---|---|---|---|---|---|---|
| | | | | | 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 | $4.76997^{o}$ | $7.06438^{o}$ |

**Result 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 Figures 3 to 6. 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 (Figure 3 to 6). This is in line with other studies in the Niger Delta [13]; [10]; [2]. Following the method of Jimoh et al. [10], 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 (Figure 4). Furthermore, where there is no thick continuous sand layer, clayey sands and/or sandy clay are the primary water-bearing units (Figure 3).

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

| S/N | Location | Borehole Depth (cm) | Types of Logs | Depth Range of Surface aquifer (1□g) | Saline/Fresh Water Interface (1□g) | 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 – |



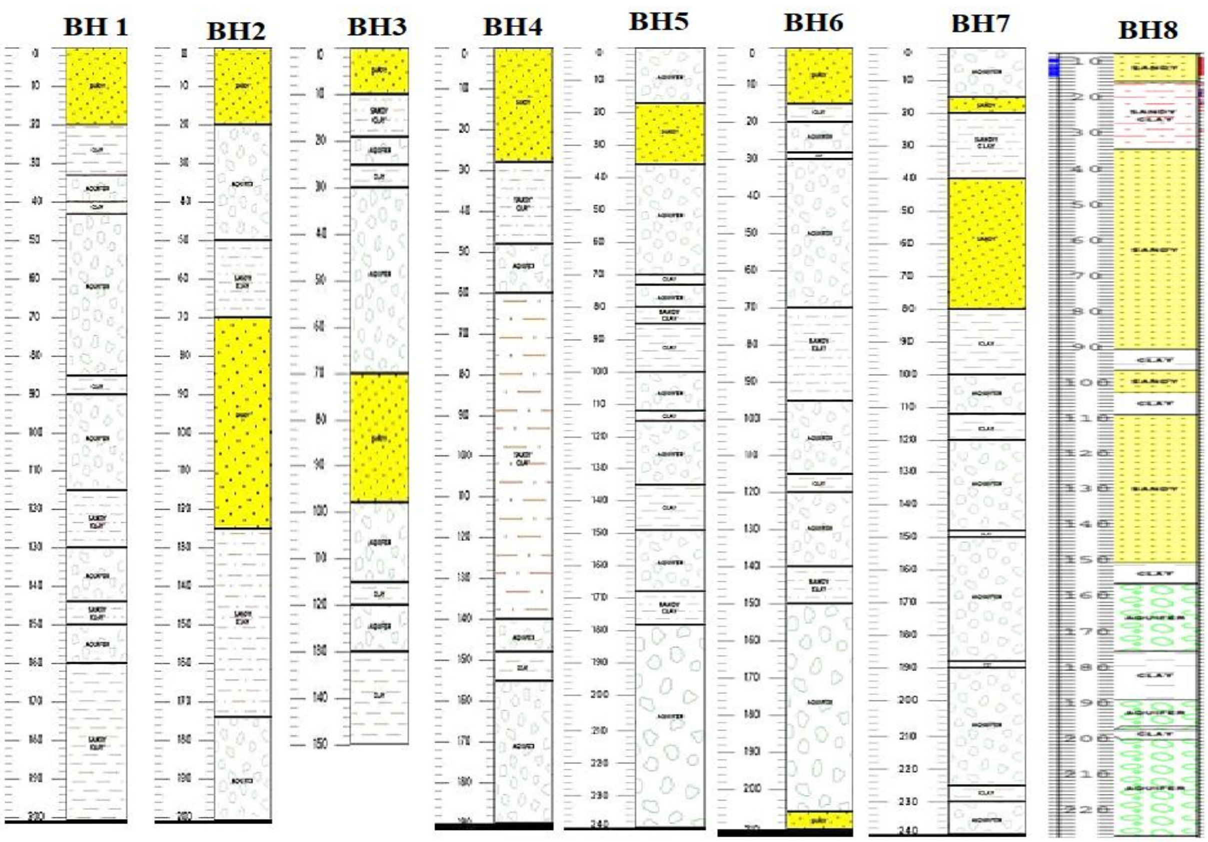


Figure 3. Summary of Stratigraphic Logs

**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 Figure 4. The freshwater-bearing structures are the sand units, with intermittent clay units at various points.

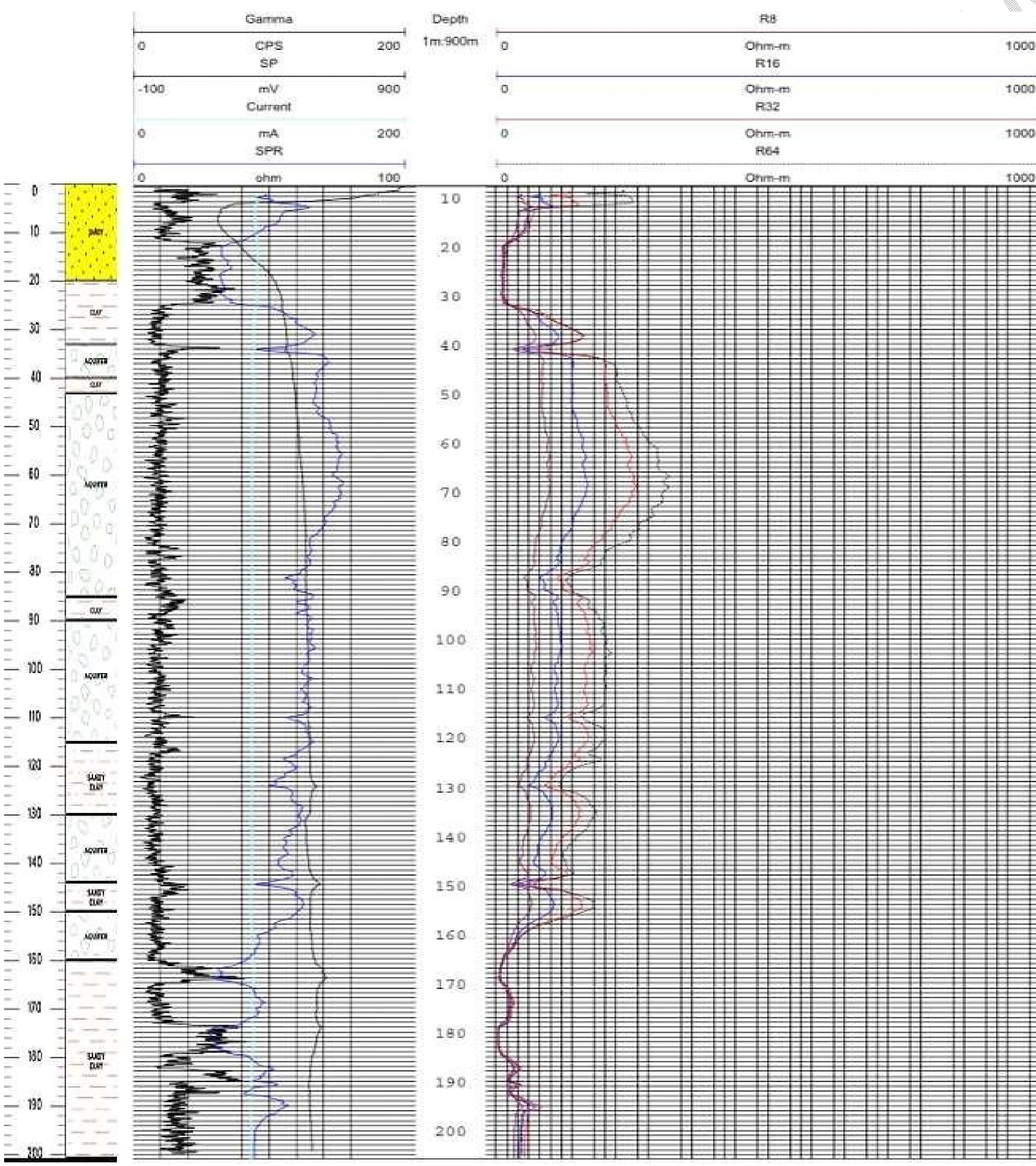


**Figure 4. : Geophysical Log of a Borehole at Ngo, Andoni LGA**

**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 Figure 5. 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.

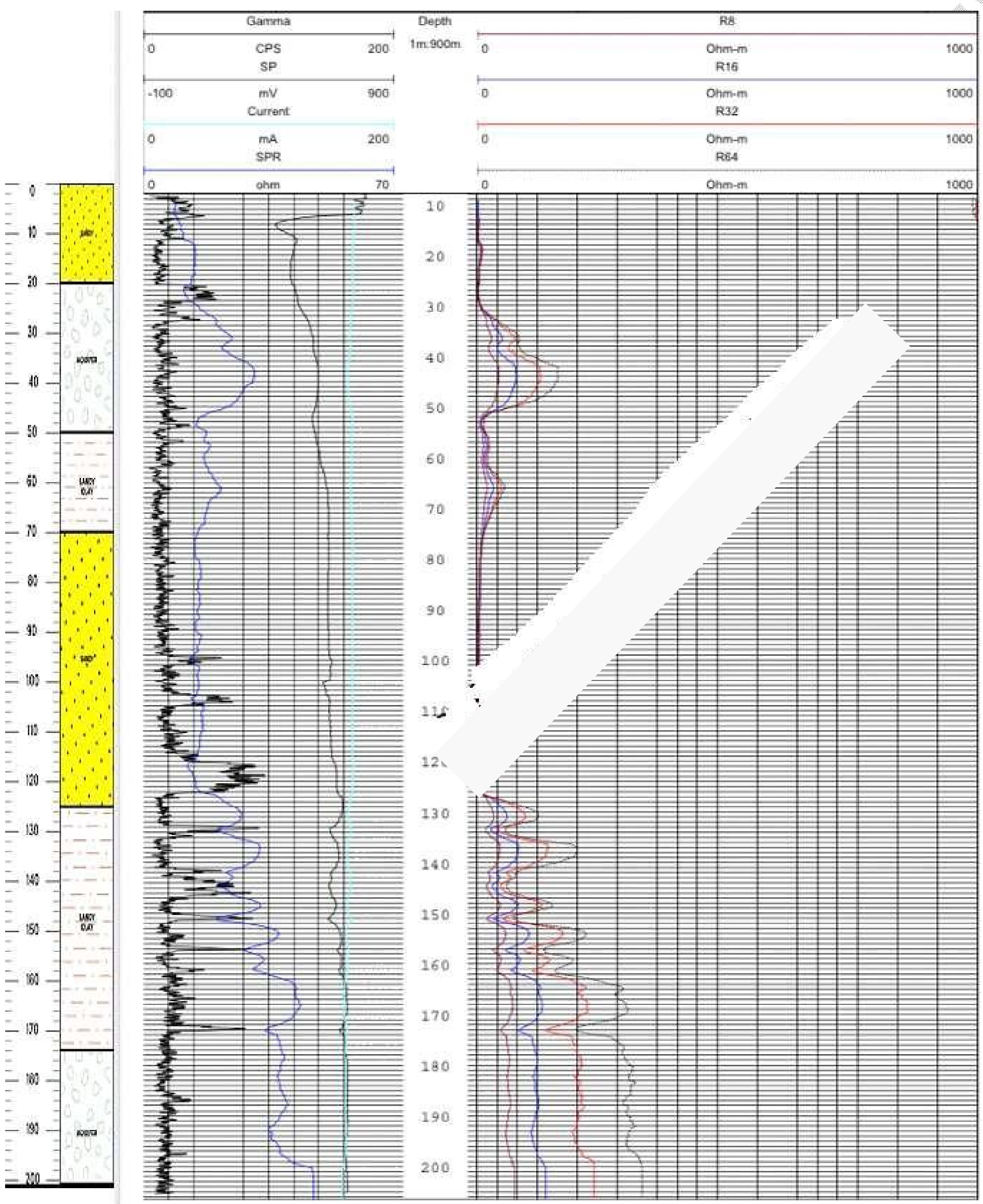


Figure 5: Geophysical Log of a Borehole in Wact Yard FOT Onne

**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 Figure 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 Figure 6. The fresh water-bearing structure is the sand units with intermittent clay at different points.

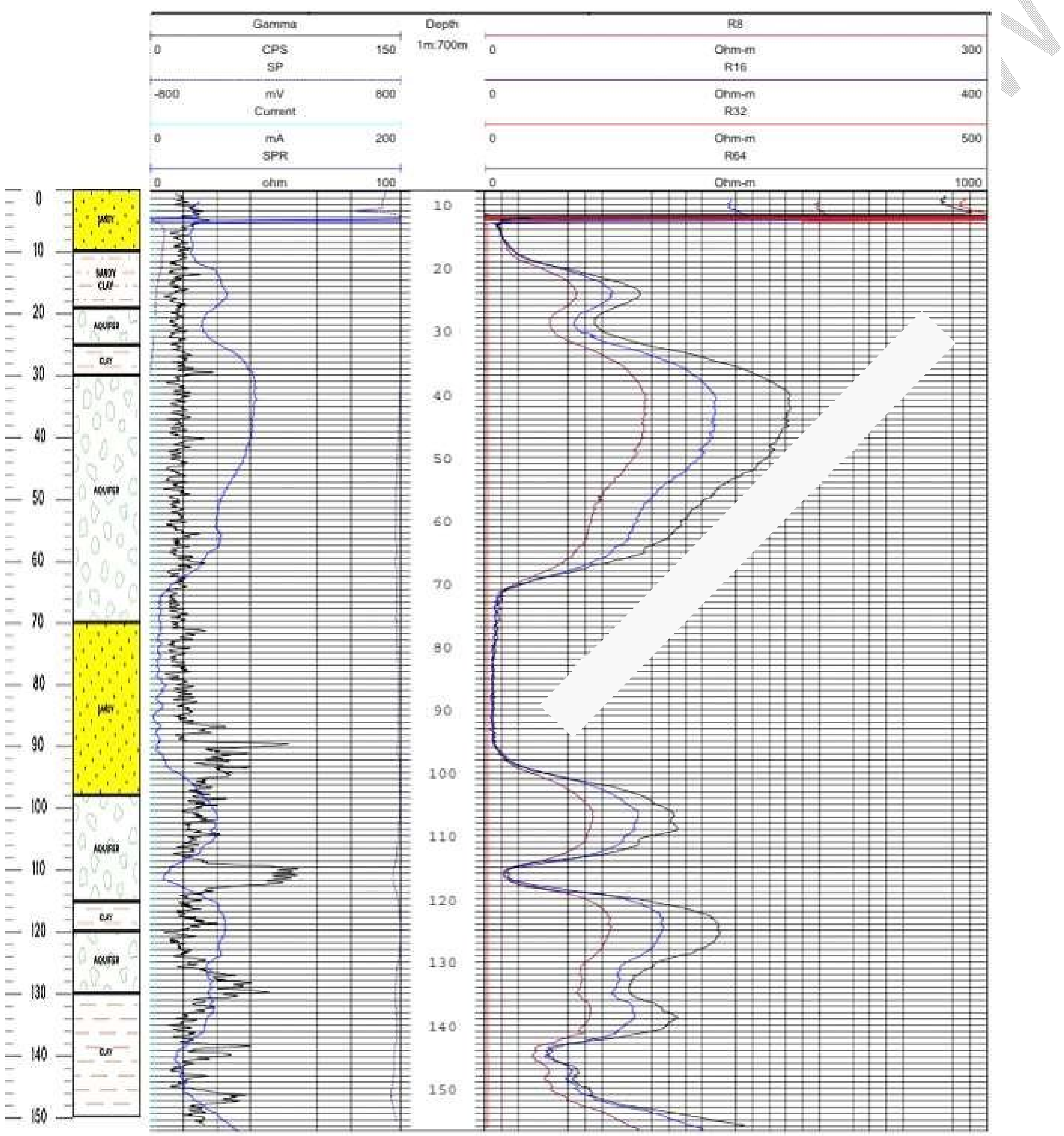


Figure 6: Geophysical Log of a Borehole at Onne Flt/Prodeco

**Borehole 7 (BH7)**

The resistivity values between 15 and 19 ohms and from 40 to about 80 m are very low (between O and 10 ohms). This indicates that the region corresponds to saline water-bearing layers. 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 (Figure 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 Figure 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.

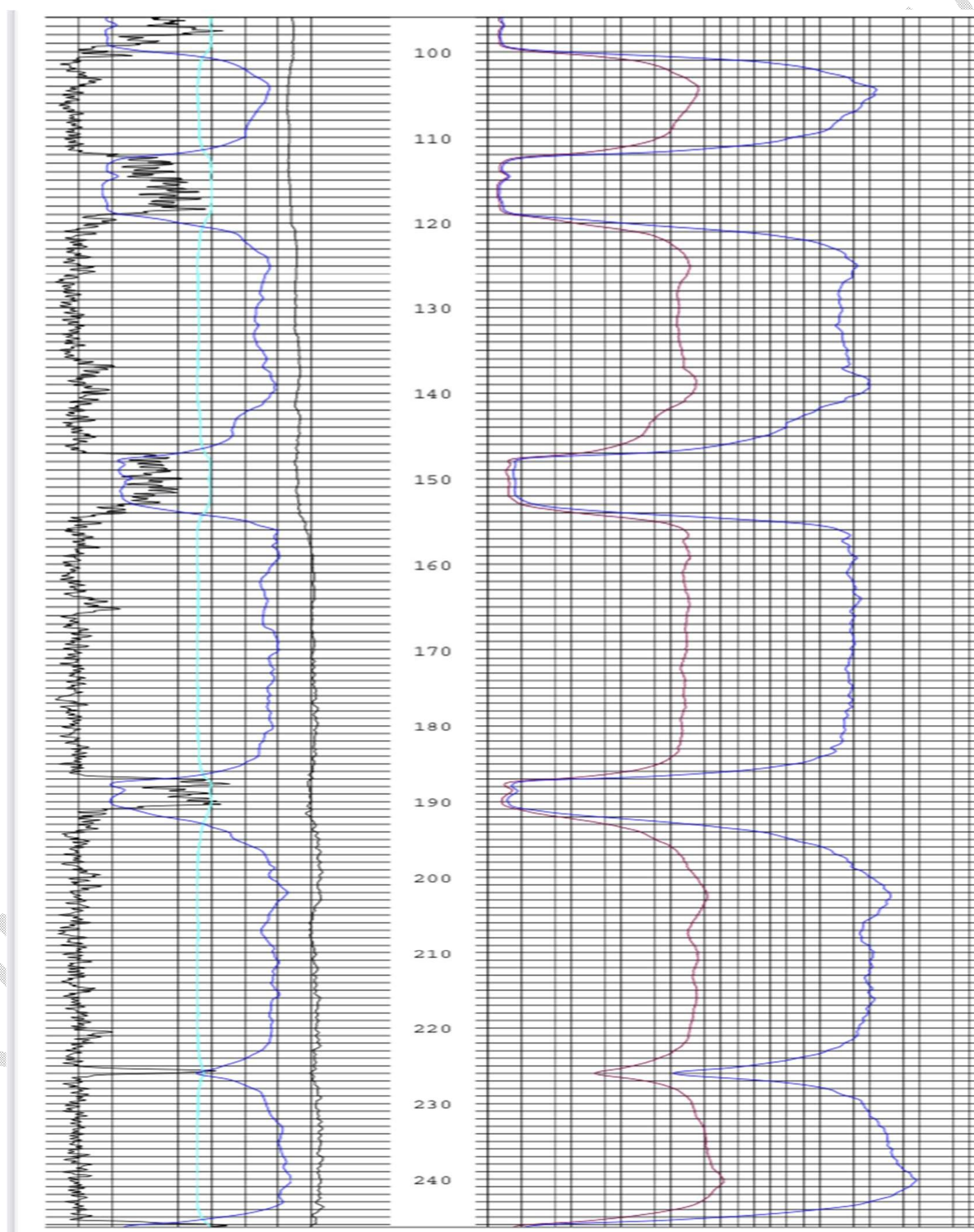


Figure 7: Geophysical Log of a Borehole at IMT/OSB

## 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 [11]. The combination of geographical and stratigraphic logs identified multiple aquifers for fresh water and about two transitions (there may be more as deeper). The fresh water zone is the high-resistance, unconfined surface aquifer, which is shallow and at varying depth ranges (from about 0 to 50m). The surface unconfined shallow aquifer is missing in some areas This may be as a result of there being no suitable water-bearing aquifer. Aquifers recharge here by infiltration from direct precipitation because of high rainfall almost throughout the year. Ola et al. [15] cautioned against groundwater extraction from this shallow surface aquifer for domestic uses because of the potential risk of contamination through human activities and saltwater infiltration.

The second freshwater horizon is indicated between 90m and 250m depending on location, with an increase in resistivity values. Here the resistivity ranges above 100 ohms. However, these values are higher as one moves up, indicating a seaward movement of ground water because of hydraulic head differences [5] In between these two horizons of fresh water is a transition zone or an interface of saline/salt water – fresh water whose thickness is dependent on location. The resistivity values in this zone are between 50 ohms and 100 ohms. It is important to note that the interface between the fresh water and the saline/salt water interface is not shaped but gradual.

The absence of the shallow unconfined aquifer in one location may be attributed to changes in sea level, which can lead to change. The direction of groundwater flow in the coastal aquifer [6].

The presence of salt water above some fresh water horizons has been attributed by Buckey et al. [6] and [5] to the influence of variations in sea level caused by storms and tides, which change the direction of ground water flow and move saline sea water into fresh water aquifers.

One should note that excessive extraction of fresh water from coastal aquifers can offset the geodynamic equilibrium existing between the fresh water and saline water boundary. This could push the salt/saline water inward. When this happens, the borehole that was previously pumping fresh water will begin to pump salt/saline water.

## Conclusion

Using geographical and lithostratigraphic logs, the subsurface stratigraphy of the study area was delineated. Also, the various aquifers and their depths have been 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.

## Recommendation

Based on the above studies, the following recommendations are given:

(i) The result of the above study should be considered in any ground water development programme in the area. Boreholes should be designed and groundwater extracted accordingly in order to sustain the project.

(ii) A detailed hydrological study is recommended to determine the coastal aquifer characteristics of the area and to evaluate the hydrodynamic setting of the salt/fresh water interactions in the area.

(iii) Urgent government intervention is required to stop the indiscriminate drilling of groundwater boreholes and also to effectively manage the delicate water resources of the coastal areas of the Niger Delta.

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