Application of Geophysical Well Logging in Investigation of Salt–Water Intrusion in Parts of Lagos State, Southwestern Nigeria

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Abstract
The salineation of freshwater aquifer units with the view of assessing groundwater quality in parts of Lagos State areas has been investigated in this study. The objectives task was achieved via exploring the potential of borehole geophysical method. The obtained suites of geophysical well logs covering the west – east and south – northeast directions were subjected to lithostratigraphic correlation analysis using the Petrel software. Based on the analysed results, five aquifer units characterized the study area with thickness ranging from > 5 m to 205 m were delineated. Further analysis established that saline water aquifer, brackish water sand, fresh water sand with resistivity values in the range of 0 – 60 ohm-m, 60 – 80 ohm-m and > 80 ohm-m, respectively at the depths of 10 – 165 m were delineated using the resistivity well log tool along the lithostratigraphic sequence. It was evidenced from the analysis that saline water often occurred greatly at depth of 10 – 160 m and the depth at which fresh water can occur in the area is greater than 200 m along the east – west and 0 – 200 m in the southwest – northeast sections. This study concludes that borehole geophysical wireline logs can be effectively relied upon in the delineation of aquifer units and assessment of groundwater quality in the investigated area.
Keywords: Geophysical, Well Log Analysis, Aquifer, Salt-water Intrusion, Lagos State.

1. Introduction

Intense pressure on the shallow coastal aquifers (Paleocene – Recent) has been driven by the population explosion of about 5.5 million people and rapid industrial development experienced in Lagos and the adjoining States. To satisfy current and future demand for portable water due to inadequate public water supply by the Lagos State Water Corporation, a new source of water for domestic, drinking and industrial use is needed. This alternative supply is readily available in the fresh water aquifers, either at shallow or deep depth. Lagos State is a coastal belt bordering the Atlantic Ocean. It is traversed by the Lagos Lagoon, through which saline water is probably intruding the hinterland aquifers, apart from the direct incursion from the sea to pollute the fresh water aquifers and thereby degrading the groundwater quality. It is suspected that the current eustatic sea level rise aided by the present climatic change could have exerted a push back pressure on the fresh water occurrence along the coastline. Further, the pressure induced by pumping of groundwater from boreholes in the area may have also contributed a great deal to the sea incursion and eventual saline water contamination of fresh water aquifers along the coastal area of the State. Recent studies carried out in the area have further confirmed the occurrences of the saline water contamination (Adeoti *et al*., 2010; and Oladapo *et al*., 2014). As such, it is becoming increasingly difficult to locate fresh water aquifer for groundwater development in the area adjoining the coast of Lagos State. In evaluating the groundwater potential of Lagos State, it is important to have a clear picture of the subsurface geologic sequence and thickness as well as the continuity and consistency of occurrence of groundwater aquifers in the area. The mapping of saline water contamination involving surface geophysical methods and borehole logging tools has been investigated by several researchers in several areas (Oteri, 1984; Williams *et al*., 1993; Temples and Waddell, 1996; Robert and Thomas, 2010; Phongpiyah and Helmut, 2012; and Oladapo *et al*., 2014). But then, the use of borehole geophysical method is relatively limited in Lagos State in comparison to the former method. Besides, the borehole logging tool being placed very close to the lithologic units has a huge attributes of better sensitivity to both lithology and the fluid content than the surface geophysical measuring equipments which is more remotely located to the measured geologic formation. However, the previous authors who have used borehole log data for groundwater investigation in the study area have failed to apply new interpretation software tools in their log data interpretation and analysis. As such, this study intends to employ advance PETREL software interpretation tool, a tested and efficient tool in the oil industry will be adapted for interpreting of borehole logs in the field of hydrology with the view of greatly enhancing groundwater resources management accuracy. The suitability of the PETREL software in this aforementioned field ranging from its accuracy as well as its consistency in result output have been documented (Adewoye *et al*., 2013 and Eniolayimika *et al*., 2014). Hence, this work is aimed at delineating saline-water intruded sands in the study area via exploring the potential of borehole geophysical logging tool.

2. Site Description

The study area (Lagos State) is located along the coastal region in southwestern Nigeria. It is situated between longitudes 2^o 42^l E and 4^o 22^l E (west of Badagry – east of Ode-Omi) and latitudes 6^0 22^l N along the Bight of Benin Coastline and 6^0 41^lN (Fig. 1). The average topographic elevation in the area is about 21.7 m above mean sea level (Iloeje, 1980). It is located in the coastal area within the tropical rain forest belt of southwestern Nigeria, which enjoys two climatic seasons. The wet season starts from around March and ends in October while the dry season starts around November and ends in March. The average annual precipitation is 2250mm – 2600mm. The humidity is high (about 80%) while the average temperature is about 21 ˚C (Ofodile, 2002). Due to poor drainage system, the area is susceptible to flooding during heavy rain falls and occasional ocean incursion from the Atlantic Ocean.

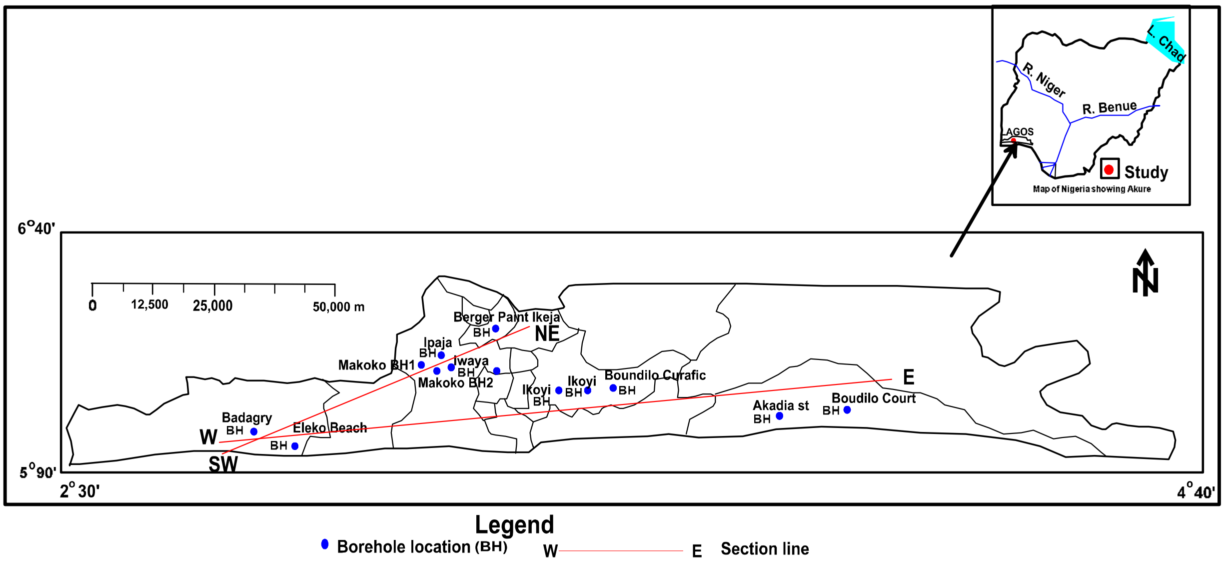

Fig. 1: Location and Data Acquisition Map of the Study Area.

3. Geology and Hydrogeology

Lagos State lies within the Dahomey Basin (Fig. 2). The Dahomey Basin was formed following the break-up of the African and South American Plates Burke *et al*., 1971. The Dahomey Basin is partially separated from the Niger Delta and the Eastern Nigeria sedimentary basin by the Okitipupa Ridge. The basin extends from the eastern part of Ghana through Togo and Benin Republic to the western margin of the Niger Delta. Previous workers including (Jones and Hockey, 1964; Adegoke, 1969; and Ogbe, 1972). The authors concluded that the study area is underlain by a sequence of sedimentary rocks of Benin Basin, Southwestern Nigeria. Abeokuta group constitute the basal formation in the area. This is overlain by stratigraphic sequence consisting of the Ewekoro Formation, Akinbo Formation, Oshosun Formation, Ilaro Formation and Benin Formation (Jones and Hockey, 1964). The exposed rock unit in the study area is the Coastal Plain Sand. It is made up of poorly sorted sands with lenses of clays.

In area underlain by sedimentary rocks, the alternate layers of sand, silts, gravel, sandstone and fractured limestone deposits constitutes the major aquifer unit. The groundwater in the study area is primarily recharged through surface precipitation (rainfall), streams, and rivers and via lateral groundwater flow and salt water intrusion from the Atlantic Ocean. The bore holes drilled by government, industrial and private individuals provide the main source of portable water supply in the study area.

The work of (Omatsola and Adegoke, 1981; and Oteri, 1977 and 1986) on the hydrogeology of Lagos State as reported in (Adeoti *et al*., 2002) showed that the sands of Abeokuta Group (Cretaceous), Coastal plain sands (Pleistocene – Pliocene) and recent sediments constitute the aquifer units in Lagos area. Ofodile, 2002 also reported that the Ilaro and Benin Formations, and the coastal plain alluvial which underlie the investigated area had been found to constitute the major aquifer units within the study area. He also reported that the water table in the area occurs at a depth range of 20 – 25 m within the Benin Formation.

4. Methodology

Geophysical well logging or wireline logging method involves lowering of sensing devices into a drilled hole and record some physical parameters which can be interpreted in terms of the characteristics (physical property) of the

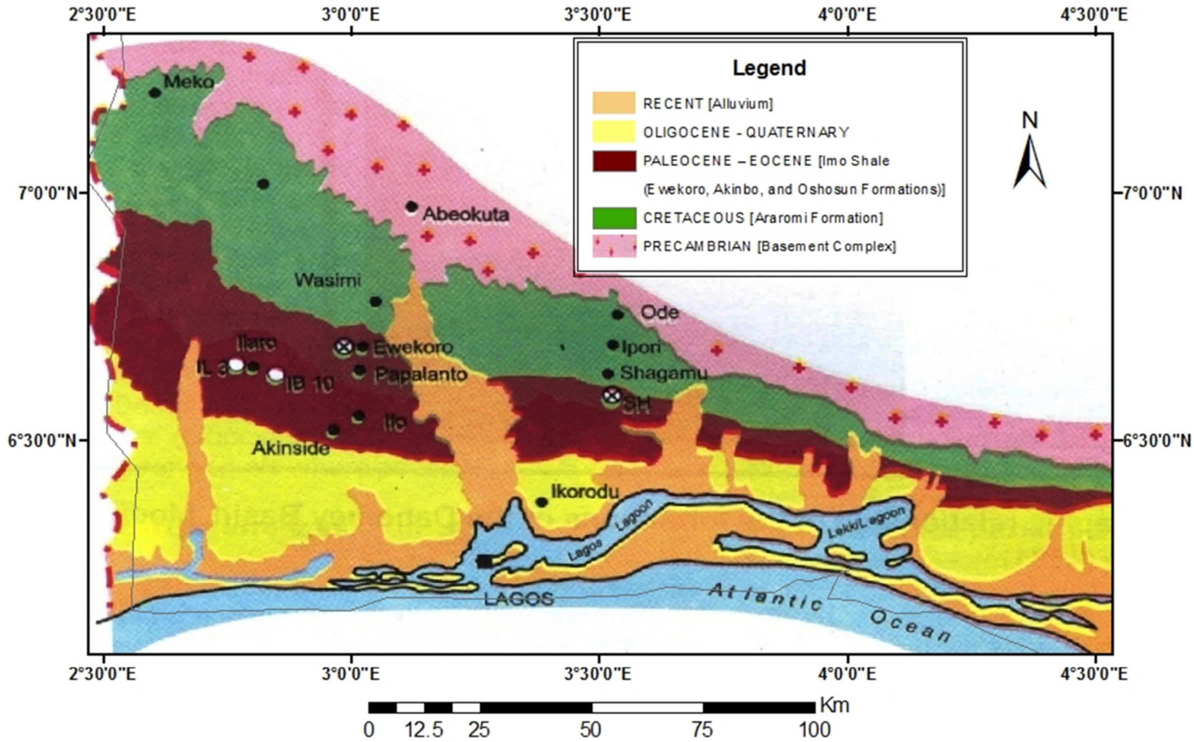

Fig 2: Geological Map of Southwestern Nigeria Showing the Study Area (Modified after Billman, 1976).

lithologic unit penetrated by the well. These include fluid chemistry and lithologic contacts. Thirteen (13) wire line logs used for the study were obtained from Groundwater and Geophysical Services (GGS) Lagos. The measurements were made using the Delta Epsilon Logger equipment. The wells were spread across the coastal part of Lagos State from Badagry in the southwest to Leki area in the southeast, and from Badagry in the southwestern part to Berger in Ikorodu area in the northwestern part of Lagos State (Fig. 1). Two lines of section along the E – W and SW – NE directions were drawn across the study area (Fig. 1). The borehole logs run in the investigated area include Gamma Ray (GR) logs and Electrical Resistivity (ER) logs. Typical logs obtained in the investigated area are presented in (Fig. 3). Gamma ray logs measure natural radioactivity in formations, based on this, it can be used to identify lithologies and correlate between formations across zones. Due to concentration of radioactive material in shale/clay, shale/clay formation has high gamma ray readings. Shale free sandstone/sands and carbonates display low gamma ray readings. The interpretation of the gamma ray log was based on the determination of the Gamma Ray Index (I_{GR}) of geologic formations Schlumberger (1974), defined in Equation (1) as:

$$I_{GR} = \frac{GR_{Log} - GR_{\min}}{GR_{\max} - GR_{\min}} \quad (1)$$

where GR_{max} = gamma ray maximum (shale zone)
GR_{min} = gamma ray minimum (clean sand)
GR_{log} = gamma ray log (shaly sand)

The long Normal resistivity log recoded measures deep resistivity of formations. The logarithmic scale values increase from left to right (i.e. 10 – 1000 ohm-m). The long Normal logs are used to determine water bearing zones and the type of fluid contained in the formation. The gamma ray logs are recorded in track 1 while the resistivity log contained in track 2. In this study the GR logs were used as lithologic tool and for correlation of lithology across the investigated area while the ER logs were interpreted in terms of the formation fluid content. The depth penetrated by the borehole logs range from about 110 to 240 m in the investigated area. The interpretation of the well logs was carried out with the aid of PETREL software, 2009.

The GR and electrical resistivity well logs data used for the analysis was loaded into the PETREL seismic interpretation software environment. The well header and the well logs were loaded simultaneously and the result was viewed using the well section window. Lithology logs (GR) and resistivity logs were displayed on the window to enable a one-time viewing and correlation of the identified lithologic interval of interest. Gamma ray logs were used to map the different lithologies while resistivity logs were used as formation fluid indicator. Correlation of lithologic units was done by linking the same sand, clayey sand, sandy clay, and clay bodies from well to well using the tops by mapping the top and base of the formation to view their lateral extent and geometry. The aquifer units were delineated by linking the sand bodies from well to well along the east west and north eastern directions within the investigated area. The interpretation result was used to assess saline-water intrusion into the coastal aquifers within the investigated area.

5. Results and Discussion

5.1 Delineation of Subsurface Geologic Sequence

The interpretation of the gamma ray (GR) logs using the Gamma Ray Index (I_{GR}) values from the study area were used to characterize the subsurface lithologic units into sand, clayey sand, sandy clay and clay layers and hence to delineate the aquifer units, while the electrical resistivity (ER) logs were used to assess the groundwater quality in the aquifers. The results obtained from the interpretation of the 13 borehole water well logs (Figs. 4 and 5) were used to generate the lithostratigraphic sections along the west – east and southwest – northeast directions across the study area. Generally, the lithologic units identified in the

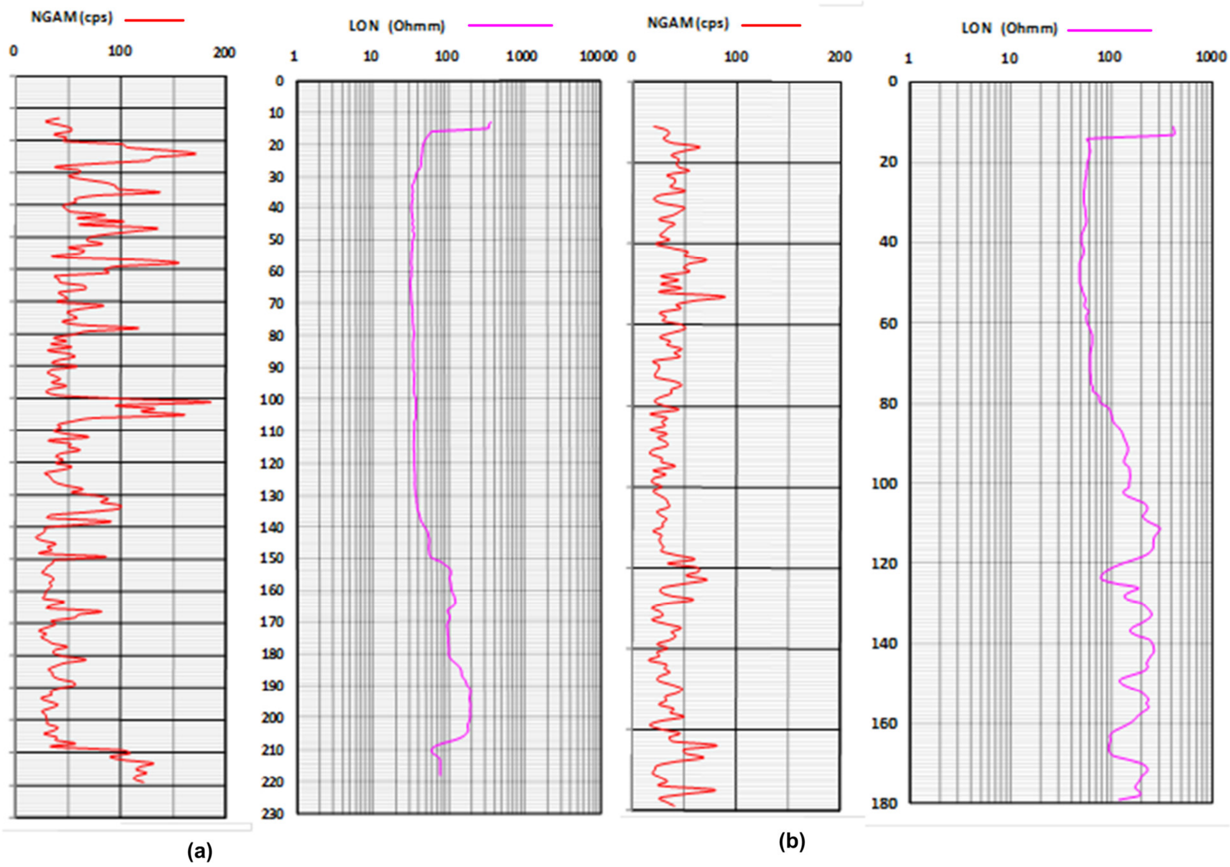

Fig. 3: Typical Gamma ray and Electrical resistivity Logs from (a) Victoria Island and (b) Ikoyi Area of Lagos State.

wells are cyclothems of sand, clayey sand, sandy clay and clay which give rise to the multiple nature of aquifer system observed in the investigated area (Figs. 4 and 5). Natural Gamma radioactivity measurements values from wells in the study area generally range from 0 to 200 American Petroleum Institute (API) (Fig. 3). The gamma ray measurement reference line index (I_{GR}) value in the rage of 0 – 60 API was interpreted to be (sand formation); 60 – 90 API (sandy shale/sandy clay formation); 90 – 120 API (shaley sand/clayey sand formation); and 120 - > 150 API (shale/clay formation). This was used to classify the geologic formations in to lithologic units (sand, sandy clay, clayey sand and clay) (Figs. 4 and 5). The sand formation was identified as the main aquifer unit in the study area.

5.2 Delineation of Aquifer Units

Based on this, four (4) major aquifer units were delineated along the west-east section while two (2) major aquifer units were delineated in the southwest – northeast section across the study area (Figs. 4 and 5). The units are labeled AQF1, AQF2, AQF3, AQF4, and AQF5. The aquifers are mainly composed of sand deposit. The range of thickness of the aquifer units in the west – east section are AQF1 (10 – 25 m), AQF2 (7.5 – 25 m), AQF3 (12.5 –37.5 m), AQF4 (17.5 – 104 m) and AQF5 (> 5 – 65 m) (Fig. 4). Similarly, the range of thickness of the southwest – northeast aquifer units are AQF1 (6 – 10 m), AQF2 (2.5 – 40 m), AQF3 (7.5 – 37.5 m) and AQF4 (20 – > 62.5 m) thick (Fig. 5). The sequence of alternating clay (I_{GR} of 120 - > 150 API) and sand layers result in a multi-story aquifers some of which are confined aquifers, such as

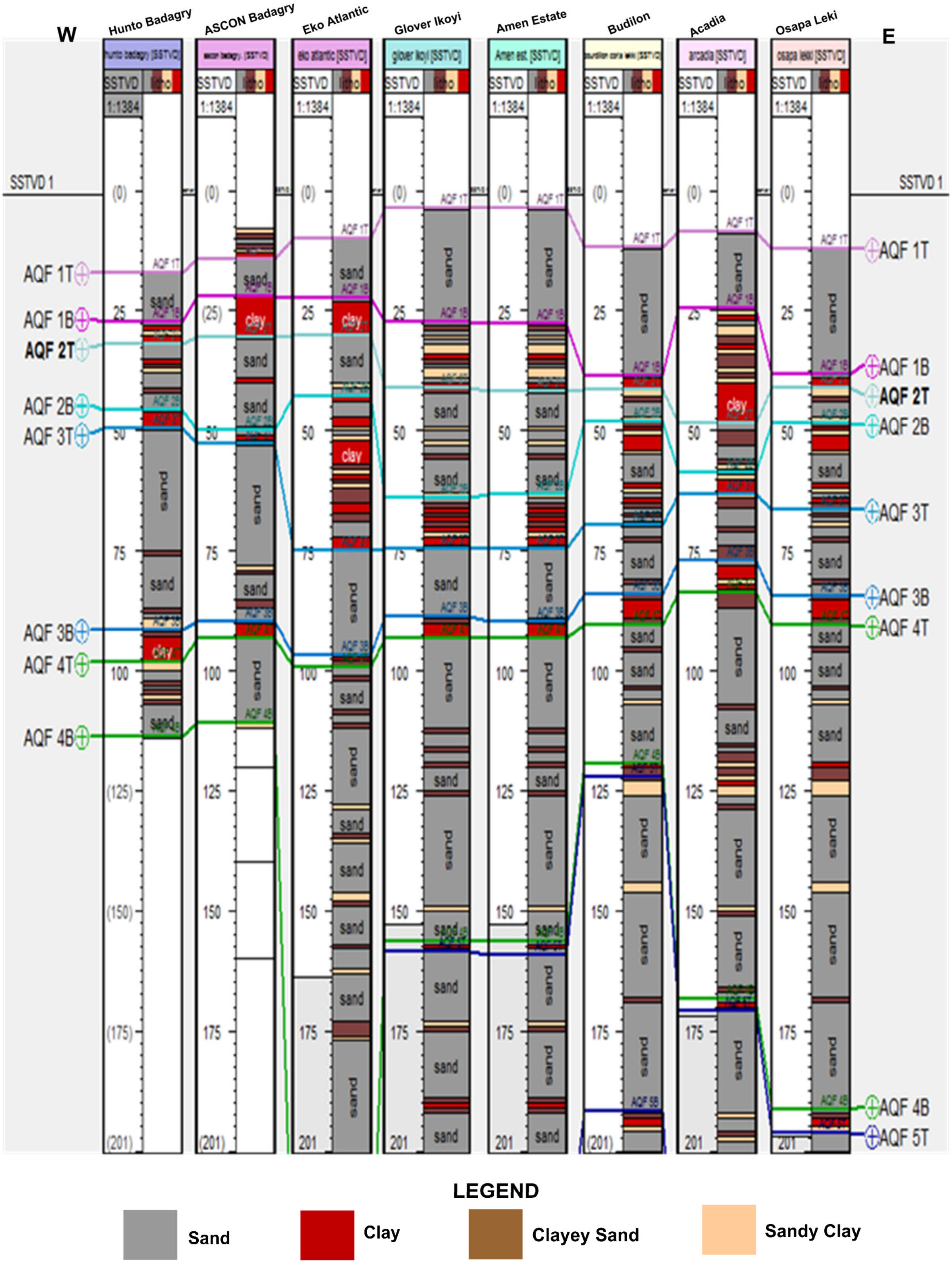

Fig. 4: Lithologic Correlation Panel of Well Logs along the West – East Direction in the Study Area.

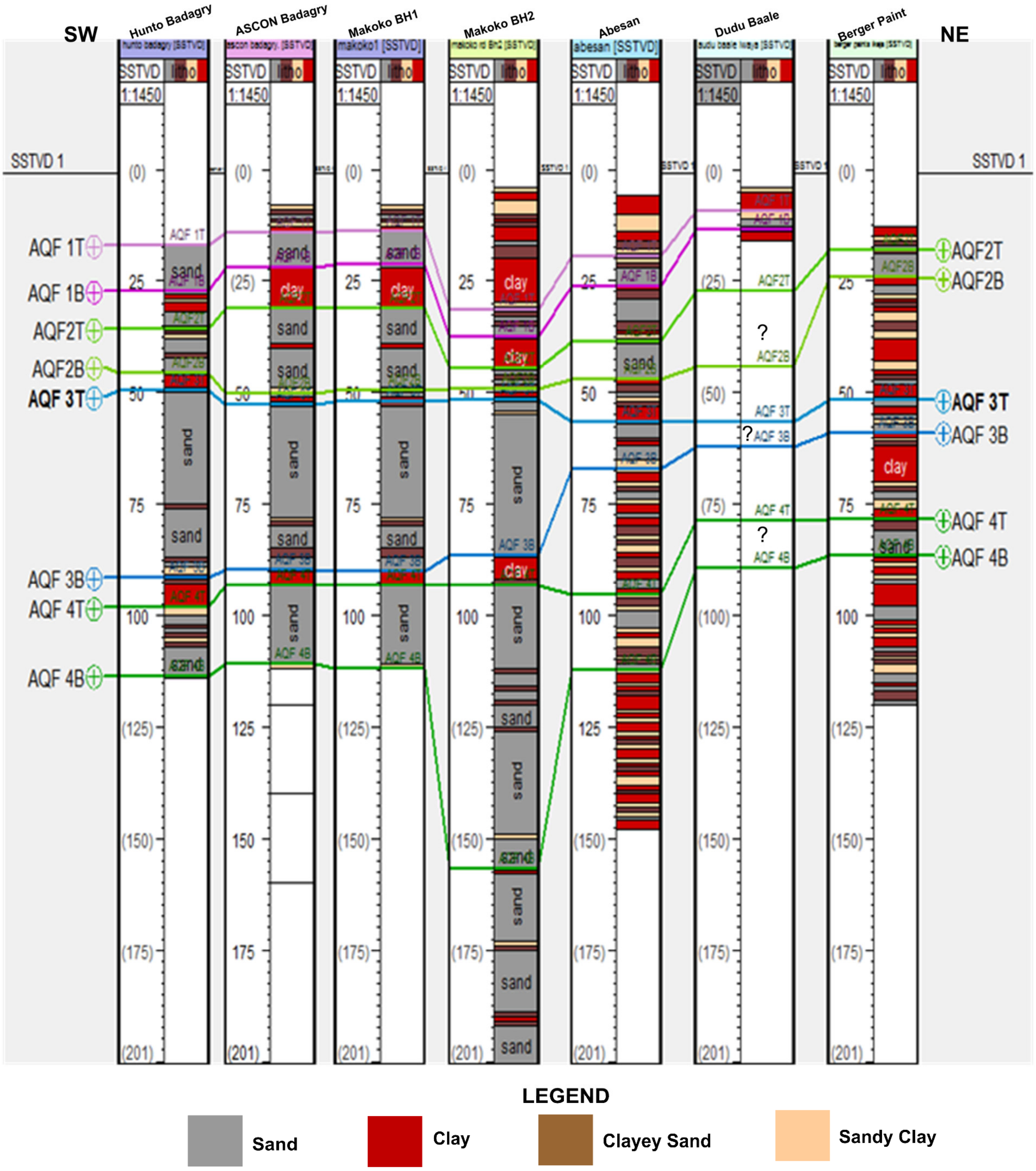

Fig. 5: Lithologic Correlation Panel of Well Logs along the Southwest – Northeast Direction across the Study Area.

AQF2, AQF3, AQF4, and AQF5 (Fig. 4); and AQF2, AQF3 and AQF4 (Fig. 5) while aquifer (AQF1) in (Figs. 4 and 5) are considered as an unconfined.

5.3 Assessment of Saline-water Intrusion

The GR log is an indicator of lithology, with clay/shale having the higher radiation index (I_{GR}) values of 120 - > 150 API while sand layers are characterized with lower radiation index (I_{GR}) values of 0 – 60 API. Saline water aquifers are delineated in seven out of the thirteen wells logged, six were identified in the W – E section (Fig. 6) and one in the SW – NE section (Fig. 7) in the investigated area with the aid of the electrical resistivity (ER) logs. The electrical resistivity well log measurement value which range from 0 – 60 ohm-m was interpreted as (saline water sand); 60 – 80 ohm-m (brackish water sand); and 80 – > 150 ohm-m (fresh water sand). Aquifers in filled by saline water occur within a depth range of 10 – 165 m in the study area. There is occurrence of brackish water interface between the saline water and the fresh water within the aquifer at a depth range of 124 – 130 m. This is well defined in three of the well logs obtained around Ikoyi, forming a transition zone between the saline water and the fresh water zones. Fresh water occurs at a variable depth range of 10 – 120 m and 125 – 200 m respectively in the aquifers within the investigated area (Figs. 6 and 7).

The first Aquifer (AQF1) is generally observed to be partly filled with fresh water in wells that are saline water intruded. This is an indication that the (AQF1) along the coastal area from Victoria-Island through Ikoyi to Lekki area has probably been intruded by saline-water at shallow depth range of 10 – 25 m (Fig. 6). Aquifers AQF2 and AQF3 are completely saturated with saline water in the west – east section (Fig. 6) between Eko Atlantic in Ikoyi to Ossapa Lekki at a depth range of 30 – 80 m. Aquifer AQF4 is partly encroached by saline water in wells between Eko Atlantic and Ossapa Likki. The lower bottom of the saline-water intruded sands is defined within the aquifer at a depth range of 125 – 150 m. The lower part of aquifer AQF4, and the whole of AQF5 are observed to contain fresh water sands up to the bottom of the wells at a depth range of 125 – 200 m as shown in the W – E section (Fig. 7). Aquifers AQF1 – AQF4 in the SW – NE section are mainly characterized with fresh water sand while saline-water intrusion was only delineated at a depth range of 120 – 155 m in the well log drilled at Makoko BH2 as shown in (Fig. 7). This suggests an inland (northward) migration of the saline-water intrusion or contrarily, the source of the saline-water encountered in the well at Makoko BH2 is suspected to be a contribution from connate (fossil) water within the stipulated depth range. The west – east section shows that the aquifer units AQF1 thins out towards the western part due to continuous decrease in thickness of sand layer

between Eko-Atlantic in Victoria Island and Hunto-Badagry, Lagos as shown in the borehole log acquired in the area while the thickness increases from Glover-Ikoyi to Osapa-Leki area. The second and third aquifer units AQF2 and AQF3 with thickness range of 2.5 – 40 m, and 7.5 – 37.5 m respectively are considered to be thick in the western part around Hunto-Badagry and thin out towards the eastern part as noticeable at Eko-Atlantic area within the study area. Aquifers AQF4 and AQF5 with thickness range of 20 – 70 m and > 5 – 65 m respectively are considered to be reasonably thick in the west – east section across the investigated area. The southwest – northeast section show that the aquifer unit AQF1 – AQF4 generally thickens from the southwest in Hunto-Badagry area and thins out towards the northeastern part at Berger paint Ikeja area. This is an indication of a change in the deposition sequence that give rise to a decrease in sand deposit at shallow depth range of < 50 m from Maroko BH2 through Abesan and Dudu-Baale to Berger paint in Ikorodu area in the northern part of the investigated area. The observed richness in clay deposit suggests a more marine or quiet environment of deposition. The occurrence of clay layer which sandwiched the sand layer gives the aquifer a multi-story character which is identified as confined structure as observed in aquifers AQF2, AQF3, AQF4, and AQF5 (Fig. 4); and AQF2, AQF3 and AQF4 (Fig. 5) while aquifer (AQF1) in (Figs. 4 and 5) are considered as an unconfined aquifer.

5.4 Groundwater Prospect Evaluation

The correlation of the interpretation results of the well logs in the investigated area across the west - east and southwest – northeast sections (Figs. 4 and 5) was used to delineate fresh water aquifers (AQF1 – AQF5) and (AQF1 – AQF4) with expected high groundwater storage discharge capacity. The groundwater prospect within the investigated area is high along the west – east section due to the occurrence of reasonably thick sand layer with thickness rage of 10 – 25 m (AQF1); 7.5 – 25 m (AQF2); 12.5 –37.5 m (AQF3); 17.5 – 104 m (AQF4); and > 5 – 65 m (AQF5) (Fig. 5). The aquifer thickness obtained in the southwest – northeast section range from 6 – 10m (AQF1); 2.5 – 40m (AQF2); 7.5 – 37.5 m (AQF3); and 20 – > 62.5 m (AQF4) (Fig. 5). Abstraction boreholes in the area may need to be drilled beyond the first three aquifers units AQF1 – AQF3 because they are relatively thin. The litho sequence in boreholes drilled in Maroko, Abessan, Dudu-Bale Iwaya and Beger-paint in the northeastern part of the area (Figs. 1 and 5) show thick clay beds with thin sand inter-beds suggests that the sediment in this area is probably of little hydrogeological significance at a depth range of 50 – 150 m and hence an indication of poor groundwater prospect zone. Aquifers AQF3 – AQF4 located between Bunto-Badagry and Maroko area (Fig. 5) are relatively thick (17.5 – > 104 m) and constitute the major aquifer units along the southwest – northeast sections from which reasonable quantity of groundwater abstraction can take place (Fig. 5).

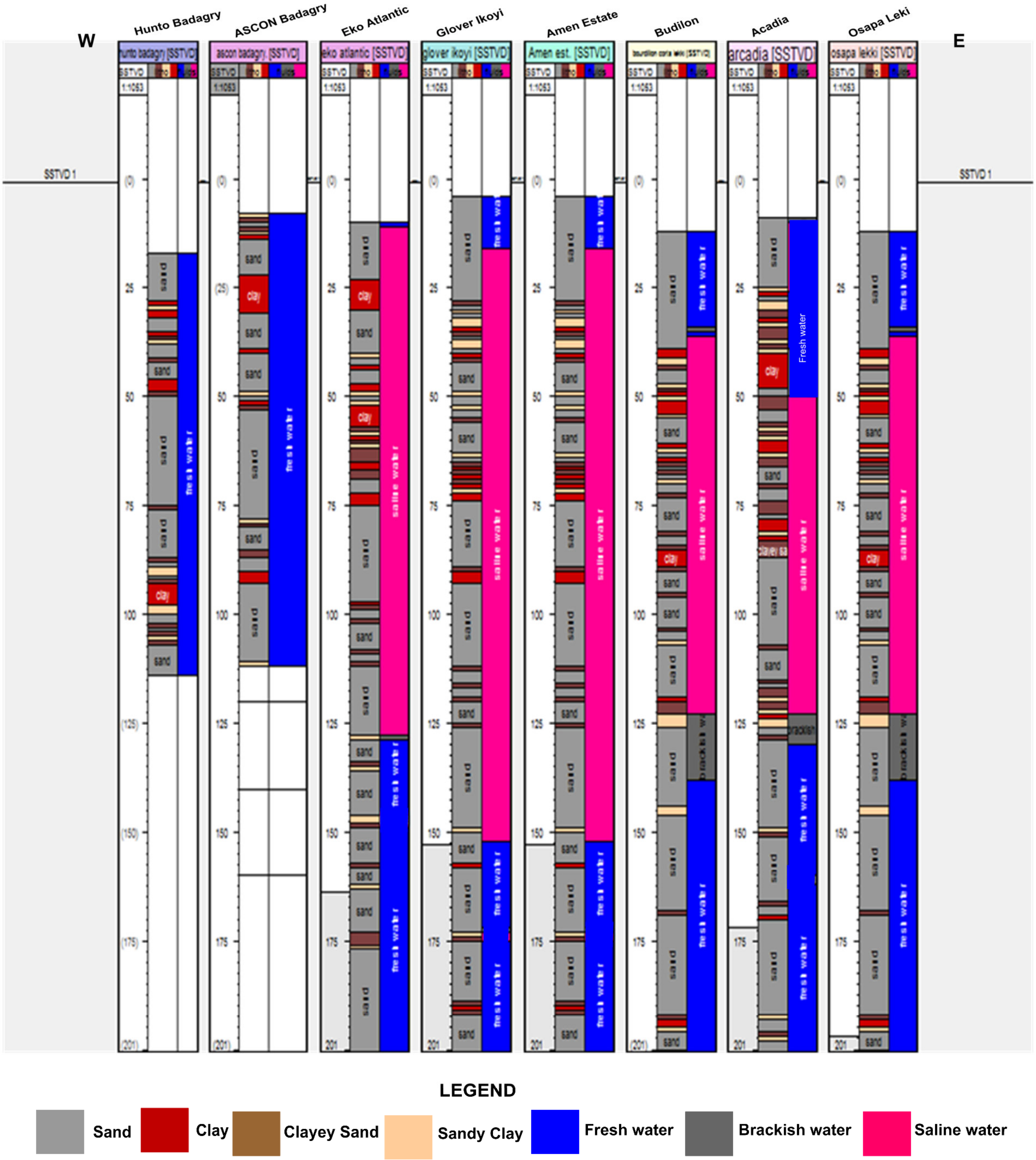

Fig. 6: Lithologic Log Showing Lithology and Fluid Content, Correlated along West to East Section in the Study Area.

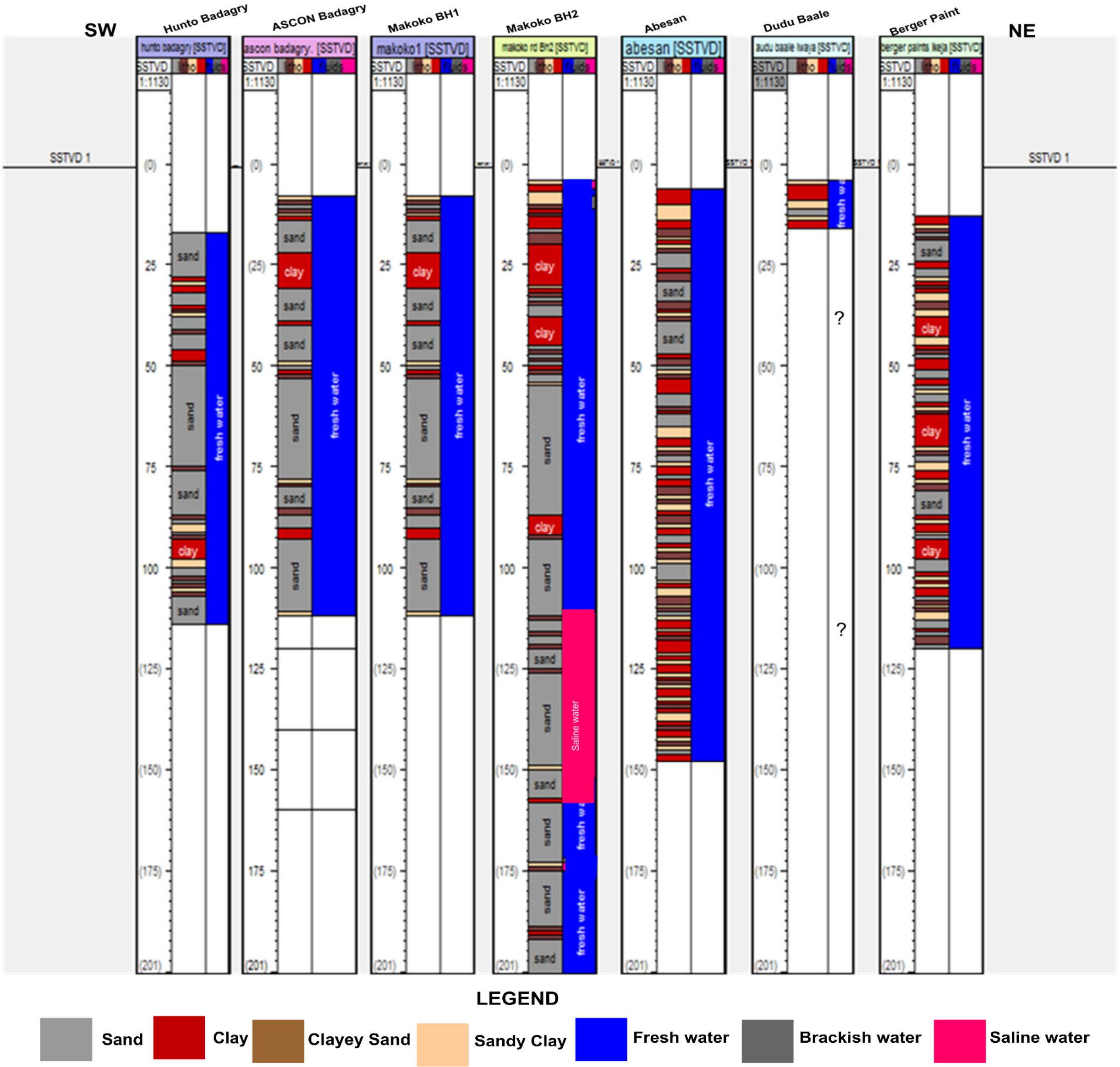

Fig. 7: Lithologic Log Showing Lithology and Fluid Content, Correlated along South West to North East in the Study Area.

6. Conclusion

Gamma ray (GR) and electrical resistivity (ER) wire line logs have been used to assess the aquifer units and groundwater quality in parts of Lagos State, southwestern Nigeria, underlain by Dahomey Basin. Thirteen (13) gamma ray (GR) and electrical resistivity (ER) wire line logs from the study area were used to delineate the aquifer units and the fluid content across the area. Gamma ray index (I_{GR}) range of 0 – 60 API was classified as (sand); 60 – 90 API (sandy clay); 90 – 120 API (clayey sand); and 120 - > 150 API (clay). The borehole lithostratigraphic sections delineated a maximum of five aquifer units denoted as AQF1, AQF2, AQF3, AQF4, and AQF5. The aquifer thickness ranges from 10 – 25 m (AQF1); 7.5 – 25 m (AQF2); 12.5 –37.5 m (AQF3); 17.5 – 104 m (AQF4); and > 5 – 65 m (AQF5) (Fig. 4). While the aquifer thickness in the southwest – northeast section range from 6 – 10 m (AQF1); 2.5 – 40 m (AQF2); 7.5 – 37.5 m (AQF3); and 20 – > 62.5 m (AQF4) (Fig. 5). Aquifers AQF2, AQF3, AQF4, and AQF5 in the west – east section (Fig. 4); and AQF2, AQF3 and AQF4 (Fig. 5) in the southwest – northeast sections are confined aquifers while aquifer AQF1 in both sections is unconfined.

Electrical resistivity log measurement value in the range of 0 – 60 ohm-m was characterized as (saline water sand); 60 – 80 ohm-m (brackish water sand); and 80 – > 150 ohm-m (fresh water sand). Saline water intruded aquifers were delineated using the resistivity logs at a depth range of 10 – 165 m in the study area. The transition zone from the saline water to the fresh water aquifer was delineated as zone of brackish water. This occurred in the aquifers at a depth range of 124 – 130 m. These zones are well defined in three of the well logs from Ikoyi

area. Fresh water occurs at a variable depth range of 10 – 120 m and 125 – 200 m respectively in aquifers in the west east and southwest – northeast sections within the area. This study shows that there is an evidence of saline water intrusion at a shallow depth range of 10 – 165 m along the coastal part of the area with a north-ward migration/lagoon intrusion as observed in Makoko BH2. This agrees with the work of (Adeoti *et al*., 2010).
Boreholes drilled for fresh water abstraction in the investigated area may need to penetrate deeper aquifers AQF4 and AQF5 at a variable depth range of 125 – 160 m with characteristic higher thickness of sand which varies from < 5 – 104 m. This study revealed a better groundwater prospect in the west – east section than the southwest – northeast section where the sediments show a progressive enrichment in clay material north wards in the area as shown in the boreholes drilled at Maroko, Abessan, Dudu-Bale Iwaya and Beger in the investigated area. This study concludes that borehole geophysical wire line logs can be effectively relied upon to delineate the aquifer units and to assess the groundwater quality within the investigated area.

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