NJBAS

Available online at http://www.ajol.info/index.php/njbas/index
Nigerian Journal of Basic and Applied Science (June, 2018), 26(1): 31-45
DOI: http://dx.doi.org/10.4314/njbas.v26i1.4

ISSN 0794-5698

Full Length Research Article

Application of Geophysical Borehole Logs For Aquifer Characterization in Coastal Environment of Lagos, Southwestern Nigeria

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ABSTRACT
In order to understand the hydrogeological structure and orientation of the study area, an attempt was made to do well correlation and aquifer characterization. A total of nine composite logs comprising of Resistivity and Gamma Ray logs were used for the study. Three correlation panels trending in different directions were prepared. Each panel consists of series of well logs arranged horizontally in accordance with the spatial distribution of the wells on the field. This assisted in carrying out litho-stratification delineation that was used to identify fluid types obtainable in the area. Two parameters (aquifer potential and vulnerability) were used to characterize the delineated aquifer in the area. The aquifer thickness was used to produce the aquifer potential map for the area. The GALDIT-Index (GI) score was computed for each borehole and this was used to evaluate the aquifer vulnerability The formation stratification sequence comprises predominantly of sand and clay with intercalations of both occurring as clayey sand and sandy clay. Three distinct fluid types were delineated and these were: saline water, brackish water and fresh water with bulk resistivity respectively ranging from 0 - 80Ωm, 80 – 120 Ωm and 120 – 620 Ωm. The depth to saline/fresh water interface range from 123 – 167m. The study shows that 5.7% of the study area is of low potential, 45% is of intermediate potential while 49.3% is of high potential. The GI scores obtained for the area vary between 2.67 and 5.5 suggesting that two vulnerability classes (moderate and low vulnerability) were obtainable. The study established that the groundwater system within the region is under pressure and boreholes in the area are vulnerable to saline water contamination if left without necessary monitoring.
Key words: *Aquifer Characterization, Aquifer Vulnerability, Aquifer Potential, Formation Fluids and Stratification Sequence*

INTRODUCTION
Water is an essential proponent of livelihood for all living organisms. Ever since human existence, considerable efforts have been put in the search of water in its most natural form void of all possible forms of contamination and pollution. Due to the pressure on easily contaminable surface sources of water such as rainwater, springs, snow, sleet, hail etc. there has been a necessary and rapid evolvement to subsurface or underground sources otherwise known as groundwater due to its quality, economic viability and abundance. Viable groundwater accumulation can be found in Aquifers. One notable hindrance to the effective accumulation of groundwater in its cleanest and unpolluted form is its contamination by saline water intrusion, particularly within the coastal regions.

Saline water intrusion migrating from neighbouring large water bodies is an inevitable problem of coastal freshwater aquifers associated with the urban area (Hwang *et al.,* 2004). There is a persisting urgency to monitor and prevent the imminent feasible risk of saline water intrusion into coastal aquifers because once it occurs, it is extremely difficult to reverse its contaminating effects and generally disrupts the effectual management of the groundwater system on the long term. Unfortunately, less than 2% of seawater intrusion into the freshwater aquifers is capable of diminishing the water's potability (Custodio, 1987). In Lagos state (particularly the island areas), one common problem of groundwater exploitation is the salinity occurrence which leads to contamination of viable groundwater aquifers within the area (Adepelumi *et al.,* 2008; Adepelumi *et al.,* 2009). The problem imposed by saline water intrusion in Lagos coastal aquifers is driven by an imbalance of the hydraulic gradient that exists between the freshwater and seawater components within the coastal aquifers (Goldman and Kafri, 2004). This is partly due to the large-scale groundwater abstraction occasioned by rapid urbanization (Pareek *et al*., 2006); it can also be as a result of its proximity to the Atlantic Ocean (Oladapo et al., 2014). Due to the metropolitan nature of the study area couple with the Government's inability to provide sufficient usable water for the people of the area, the general population is faced with problem of obtaining vast amounts of water in its potable form thereby resulting to the uncontrolled abstraction of groundwater from the subsurface through borehole drilling. Consequentially, many boreholes fail and are abandoned. Alternative boreholes having deeper depth of penetration are drilled within a small locality and usually at a very high cost. Groundwater as an alternative water source is therefore heavily relied on within the study area where surface water is seriously polluted. This continued reliance on groundwater has consequentially resulted in the decline, both in quantity and quality, of this natural resource and this has subsequently led to imbalance in the hydraulic gradient.

Well correlation and aquifer characterization provide an avenue for understanding the hydrogeological structure and orientation of an area. In this study, a composite log comprises of gamma ray and resistivity logs would be used to do correlation and characterization of the aquifer in the study area. The objectives of the study are to:

i. Identify fluid types obtainable in the area and their depths of occurrence
ii. Evaluate the aquifer potential of the area and
iii. Assess the vulnerability of the aquifer in the study area.

Materials Used, Study Area Description, Geology and Hydrogeology

The coordinates of the borehole logs utilised for this study vary between longitudes 3°28'58"E and 3°32'01"E and latitudes 6°25'45"N and 6°27'34"N (Table 1). The spatial extent of the borehole logs across the study area is shown below in Figure1. The study area falls within the southwestern Nigeria portion of the Dahomey Basin. Five geomorphology sub-units were recognized in the coastal landscape. These are the: abandoned beach ridge complex; coastal creeks lagoons; swamp flats; forested river flood plain; and active barrier beach complex.

Table 1: Coordinates of the Borehole Logs utilised for the Study

S/N	Long	Lat
BH1	3°29'20.46"E	6°26'21.59"N
BH2	3°30'49.50"E	6°25'45.00"N
BH3	3°31'08.09"E	6°26'37.06"N
BH4	3°32'01.00"E	6°27'34.00"N
BH5	3°30'34.57"E	6°27'17.23"N
BH6	3°30'38.60"E	6°26'55.70"N
BH7	3°28'58.00"E	6°26'56.80"N
BH8	3°30'26.90"E	6°26'33.30"N
BH9	3°29'5.31"E	6°26'42.22"N

Lagos is underlain by the Dahomey Basin. The rocks of the Dahomey Basin are mainly sands and shales with some limestone which thickens towards the west and the coast as well as down dips to the coast. The stratigraphic description of sediments in the basin has been provided by various authors (Okosun, 1990; Omatsola and Adegoke, 1981). Five lithostratigraphic formations covering the Cretaceous to Tertiary ages have been described. The formations from the oldest to the youngest include Abeokuta Group (Cretaceous), Ewekoro Formation (Paleocene), Akinbo Formation (Late Paleocene - Early Eocene), Oshosun Formation (Eocene) and Ilaro Formation (Eocene). The Abeokuta Group presents an unconformity with the basement complex. The geological map of Lagos state covering the study area is shown in Figure 2.

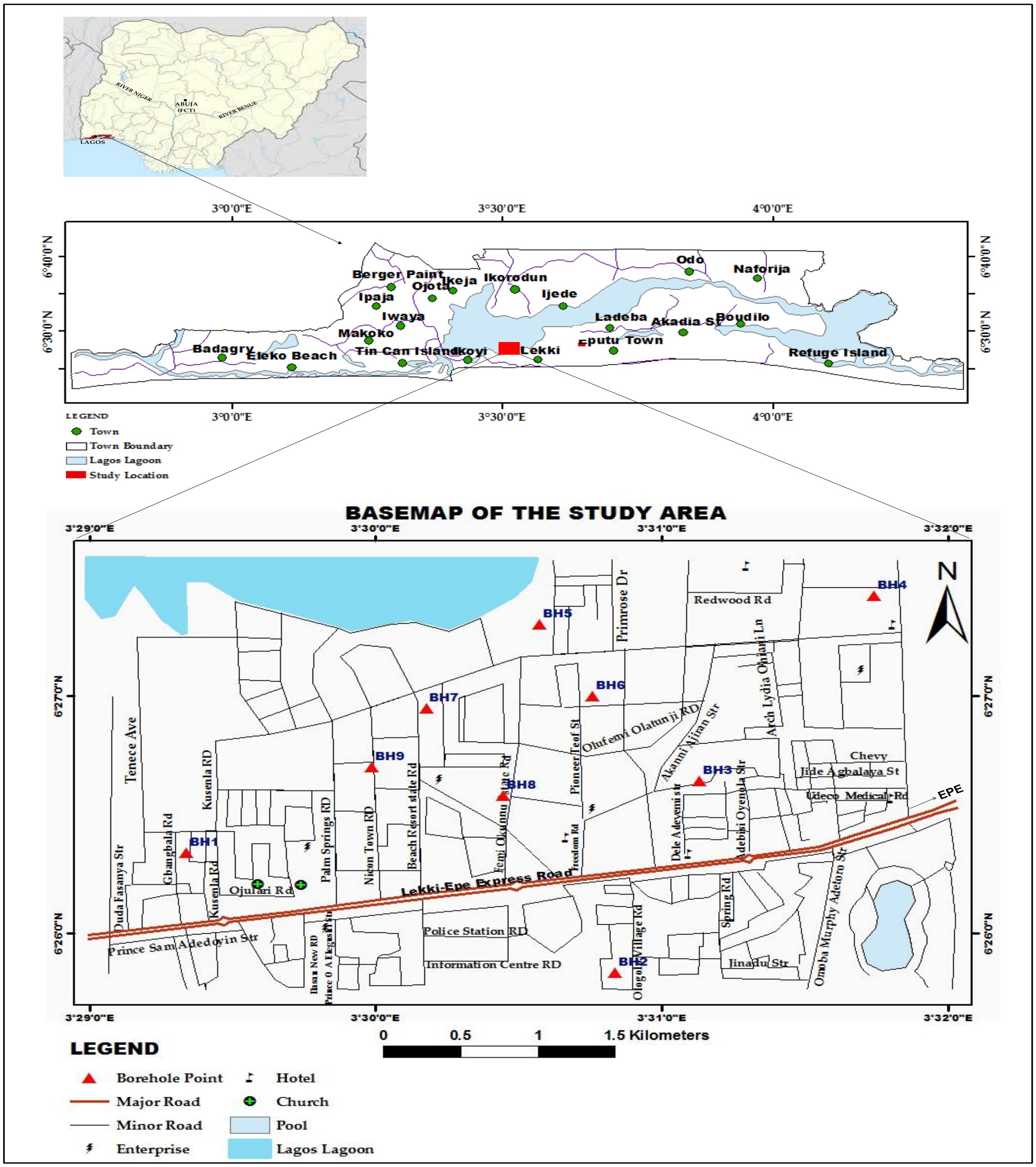

Figure1*:* Map of the study area showing the Spatial Distribution of Borehole Locations

The aquifers in Lagos State can be subdivided into four, with the first representing the recent sediments and the second and third aquifers being the Coastal Plain aquifer. The fourth aquifer represents the Abeokuta formation. Sands and gravels constitute the materials in the aquifer of recent sediments, coastal plain sand and Abeokuta formation. Limestone forms the aquifer material in the Ewekoro formation. In the northern part of the State, the Abeokuta formation is made up of very thick sands the majority of which consists of fairly coarse to very coarse-grained clean quartz.

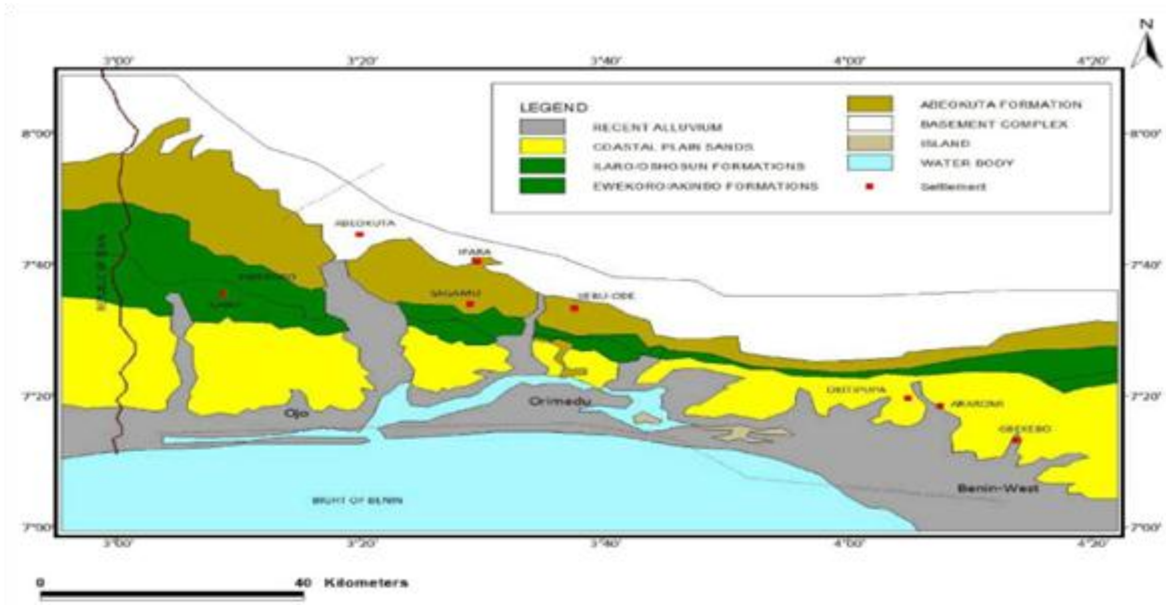

Figure 2: Geological map of Lagos, Nigeria (after Oladapo, 2014)

Over 95% of all boreholes in Lagos State obtain their water from the coastal plain sand. There are a lot of lateral variations in lithology and water quality in this aquifer. The aquifer thickens from its outcrop area in the north to the coast in the south and the sand percentage in the formation changes from north to south (see stratigraphy of Dahomey Basin below). Salt-water occurs in this aquifer with the second aquifer being freshwater bearing in the northern and central parts of the State but salt water bearing in the southern coastal belt.

As the salt water in the upper coastal plain sand aquifers overlies fresh water in the lower coastal plains sands aquifer, there is always a clay layer that separates the salt water above from the fresh water below. The transition from salt water to fresh water is not abrupt; there is an interface of intermediate salinities known as saline/fresh water interface.

The freshwater interval at Akodo in the lower coastal plain sand aquifer is sandwiched between salt water above and below. While a clay layer separates the salt water from the fresh water above the lower coastal plain sand aquifer, an interface exists between freshwater and saline water in the lower coastal plain sand aquifer. The transition from the fresh water to saline water at the base is gradual.

A total of nine composite logs comprising of Resistivity and Gamma Ray logs were used for the study. The spatial distribution of these logs had already been shown in Figure 1. The Gamma Ray Logs were used for litho-stratification delineation while the Resistivity Logs were utilised for fluid types characterization. Typical example of composite log used for the study is shown in Figure 4 .

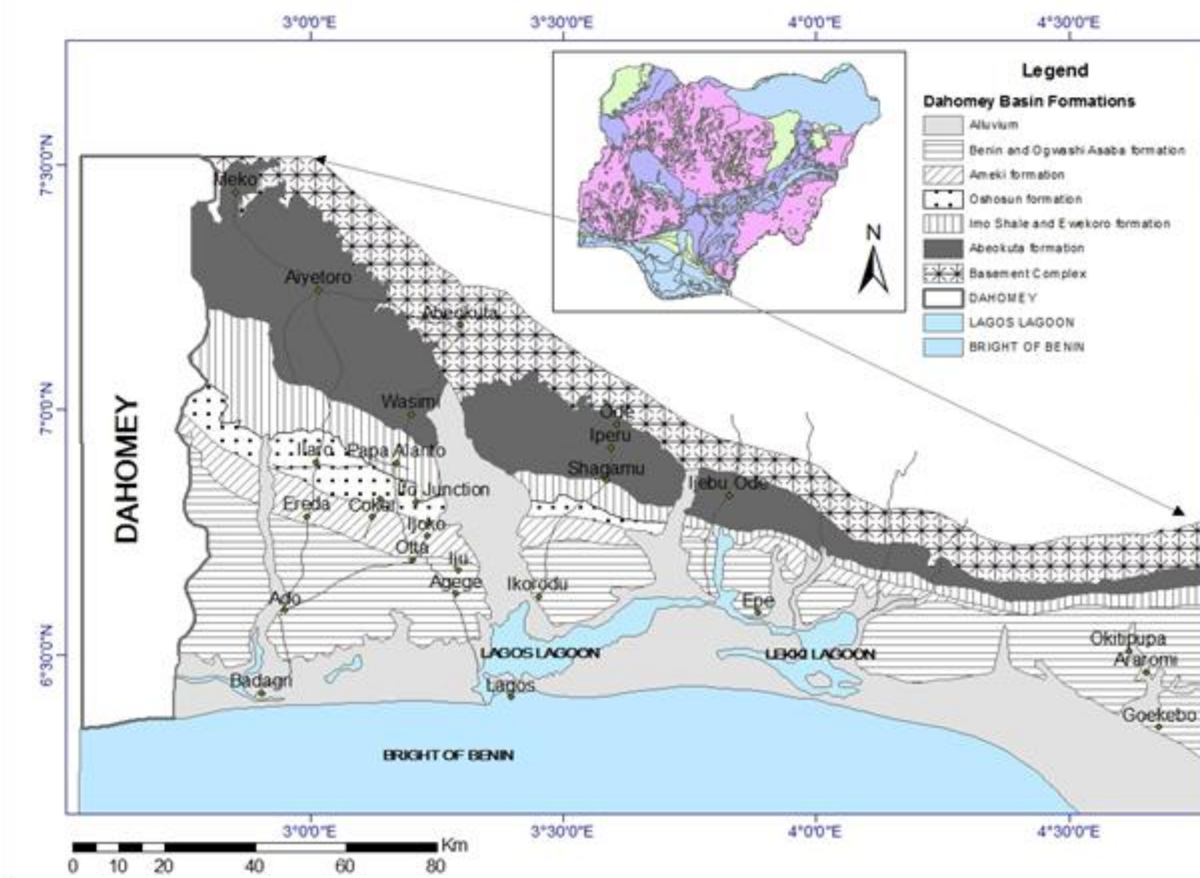

Figure 3: Stratigraphy of Dahomey Basin (After NGSA, 1973)

METHODOLOGY

AQUIFER CORRELATION

The first stage was a visual correlation of well logs; this was accomplished by preparing a correlation panel consisting of series of well logs arranged horizontally in accordance with the spatial distribution of the wells on the field. Three correlation panels labeled COR 1, COR 2 and COR 3 trending in different directions as shown in Figure 5 was prepared. Series of logs in each correlation panel were digitized with a view to carrying out litho-stratification delineation across the wells in the panel. In addition to this, saline/freshwater interface delineation, lithology/formation and fluid nature characterization were also carried out. Finally, areas of interest exhibiting substantial level of similarity were picked and connected as similar layers.

Figure 6 shows the correlation panel 1 (**COR 1).** It trends in the SW-NE direction and consists of four borehole logs. Resistivity logs were used for fluids delineation. Low resistivity values of between 20 to 80Ωm were classified as saline water zones. These zones were occupied in intercalations of sand and clay and are also of varying depth across the boreholes making up this correlation panel as seen in Figure 6. Similarly, resistivity values of 120Ωm and above were classified as fresh water aquifer (FW AQF1-FW AQF4). The interface between the saline water and fresh water aquifer is the brackish water zone and this was delineated as saline/fresh water interface as shown on the figure. The same procedure was repeated for correlation panels 2 and 3 (COR2 and COR3).

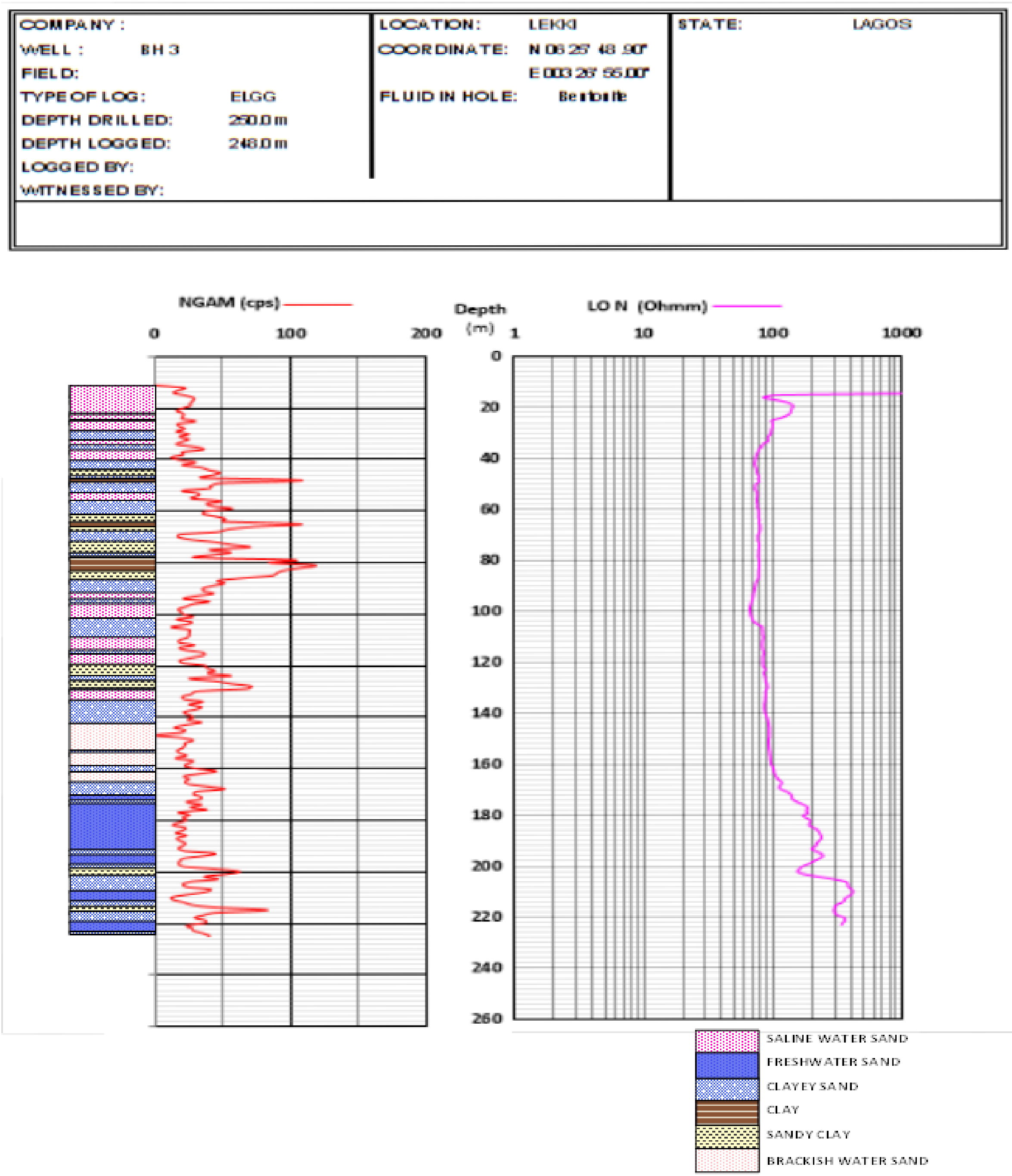

Figure 4: Typical Composite Log from the Area of Study

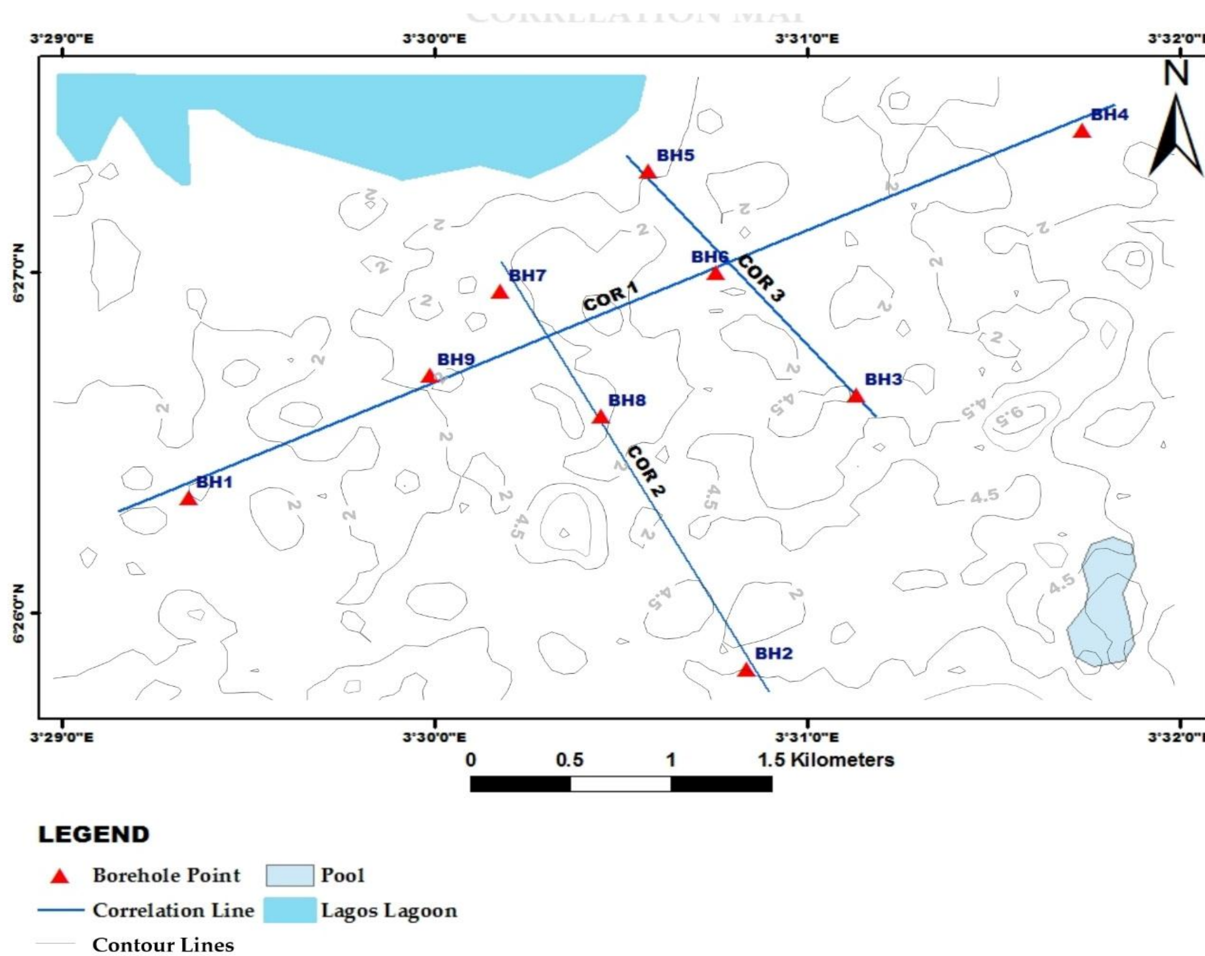

Figure 5: Correlation panel map

AQUIFER CHARACTERIZATION

Aquifer potential and aquifer vulnerability were the two parameters used to characterize the delineated aquifers based on their respective yields and their vulnerability/exposure to contamination. In sedimentary environments, aquifer potential is directly proportional to the thickness of the freshwater sand lithology. This is because, unlike in the basement complex terrain, aquifer parameters (i.e.porosity and permeability) in sedimentary terrain are largely homogeneous, isotropic and unlocalized; consequently, the potential of aquifer (sand lithology) in sedimentary environments is largely dependent on its thickness. Consequently, aquifer thicknesses obtained from each borehole was used to produce the aquifer potential map of the study area.

The approach of Chachadi, 2005 was adopted in evaluating the aquifer vulnerability of the area. In this approach, the estimation of coastal aquifer vulnerability to saline water intrusion was codified in the acronym called "GALDIT" formula. Each parameter of the acronym is defined as follows:

G: Aquifer Type (Obtained by visualization of the log's geosection and is controlled by the thickness of clay layers enclosing the aquifers).
A: Aquifer Hydraulic Conductivity (Obtained from the log using a mathematical formula (Fatoba et al, 2014): K (in m/s) = 10^{-5} X 97.5^{-1} x $\rho^{1.195}$; K (in m/day) **=** 60 x 60 x 24 x [K in (m/s)]. Where ρ is the average resistivity obtained from the log

L: Depth to freshwater (Obtained from the Litho-stratigraphic simulated subsurface section through obtaining the vertical depth to freshwater as portrayed by the log.)

D: Distance from shore (Obtained from Google Earth through a linear distance measurement tool used laterally across the study area from the borehole point with known coordinate to the closest ambient seawater).

I: Impact of saline water (Obtained from the log using the measurement of the average resistivity of the saline water intruded area and inversing it to determine its conductivity. The conductivity is a measure of the amount of free mobile ions present in the fluid and this was used as an alternative to bicarbonate-chloride ratio to determine the concentration or impact of saline water).

T: Thickness of aquifer (Obtained from the Litho-stratigraphic simulated subsurface section via direct visualization and estimation of the various aquifer thicknesses across borehole logs).

The first step in evaluating the aquifer vulnerability of the area is to obtain the values of each of the “GALDIT” parameter for all the boreholes used for the study.

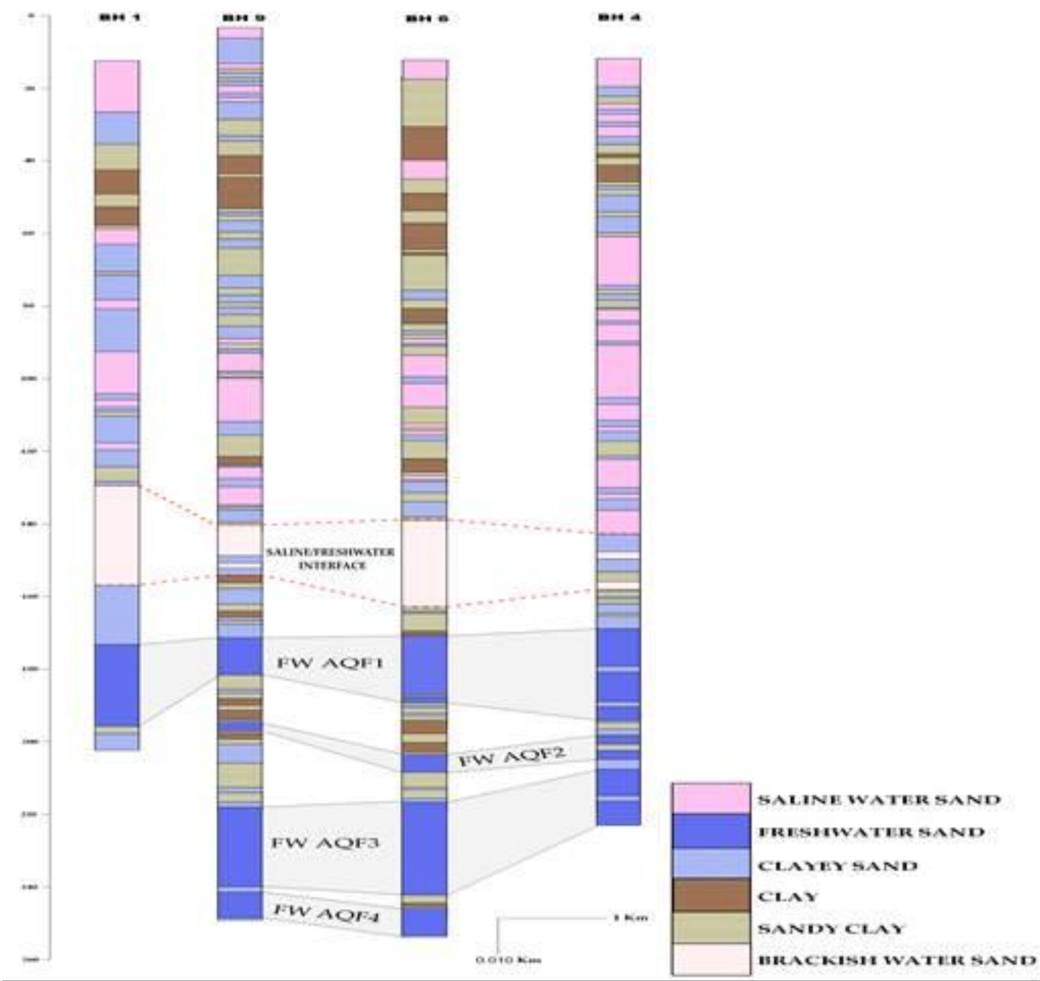

Figure 6: Correlated geosections for COR 1

In the second step, weight was assigned to each GALDIT parameter from 1 – 4 with 1 being equivalent to low weight while 4 is equivalent to high weight. Thereafter, each parameter was classified into four and subsequently rated. The ratings ranging from 2.5 – 10.0 where 2.5 is equivalent to low and 10.0 equivalents to high influence on vulnerability were adopted for the study (Table 2).

In order to establish the consistency of the weights assigned to each GALDIT parameter as shown in Table 2 above, the technique of the Analytic Hierarchy Process (AHP) was used to determine the consistency ratio of the assigned weights. For the consistency and hence usability of the weights, the consistency ratio must lie within the acceptable limit of less than or equal to ten percent (≤10%) (Saaty, 1980, 1990 and 1994). The procedure for determining the consistency ratio had been discussed in Adiat *et al*.; 2012, Adiat *et al*.; 2013, Akinlalu *et al*.; 2017 and Adiat *et al*.; 2018.

In the third step, the GALDIT Index is then obtained by computing the individual indicator scores and summing them using the following expression:

Galdit index (GI) $=\sum_{i=1}^{6}\{((W_i)R_i\}/\sum_{i=1}^{6}W_i$ (1)

Where *Wi* is the weight of the *ith* indicator and *Ri* is the importance rating of the *ith* indicator.

Thus, the user can use hydrogeologic and geological information from the area of interest and choose variables to reflect specific conditions within that area. The corresponding importance ratings of the chosen variables can be used to compute the indicator score. This system allows the user to determine a numerical value for any hydro-geographical setting by using this additive model. The "maximum GALDIT-Index" is obtained by substituting the values of the weight and the maximum importance ratings of the indicators presented in Table 2 as shown below:

Max = $\{(1)*R_1+(3)*R_2+(4)*R_3+(4)*R_4+(1)*R_5+(2)*R_6\}/\sum_{i=1}^{6}W_i$ (2)

= $\{(1)*10+(3)*10+(4)*10+(4)*10+(1)*10+(2)*10\}/15 = 10$ (3)

Similarly,

The "minimum GALDIT-Index" is obtained by substituting the minimum importance ratings of the indicators as shown below:

Min = $\{(1)*R_1+(3)*R_2+(4)*R_3+(4)*R_4+(1)*R_5+(2)*R_6\}/\sum_{i=1}^{6}W_i$ (4)

= $\{(1)*2.5+(3)*2.5+(4)*2.5+(4)*2.5+(1)*2.5+(2)*2.5\}/15 = 2.5$ (5)

Therefore, the minimum and maximum GALDIT-Index varies between 2.5 to 10. The vulnerability of the area to seawater intrusion is assessed based on the magnitude of the GALDIT Index.

In the last step, the GALDIT-Index computed for each borehole (presented as a Table) would be used to evaluate the aquifer vulnerability of the study area. Consequently, it will be possible to classify the area into various categories/classifications of seawater intrusion vulnerability. Three classes of vulnerability proposed by Chachadi, 2005 (adopted for this study) is shown in Table 3.

Table 2: The assigned weights and ratings for each parameter (Modified after Chachadi, 2005)

S/N	Factors	Weights	Indicator Variables: Class	Indicator Variables: Range	Ratings
1	**Groundwater Occurrence (Aquifer Type): G**	**1**	Confined Aquifer		10
			Unconfined Aquifer		7.5
			Leaky Confined Aquifer		5
			Bounded Aquifer		2.5
2	**Aquifer Hydraulic Conductivity: A**	**3**	High	> 40	10
			Medium	10 – 40	7.5
			Low	5 – 10	5
			Very Low	< 5	2.5
3	**Depth to Freshwater zone: L**	**4**	High	> 170	2.5
			Medium	150 – 170	5
			Low	130 – 150	7.5
			Very Low	< 130	10
4	**Distance from Shore: D**	**4**	Very Small	< 500	10
			Small	500 - 750	7.5
			Medium	750 - 1000	5
			Far	>1000	2.5
5	**Impact of Saline water: I**	**1**	High	> 2	10
			Medium	1.5 – 2.0	7.5
			Low	1.0 – 1.5	5
			Very Low	< 1	2.5
6	**Thickness of Aquifer: T**	**2**	High	> 40	10
			Medium	30 - 40	7.5
			Small	20 – 30	5
			Very Small	<20	2.5

Table 3: GALDIT Vulnerability classes (After Chachadi, 2005)

S/N	GALDIT-Index Range	VULNERABILITY CLASSES
1	≥ 7.5	Highly Vulnerability
2	5 to 7.5	Moderate Vulnerability
3	< 5	Low Vulnerability

RESULTS AND DISCUSSIONS

AQUIFER CORRELATION

Summary of saline water depth, thickness of brackish water zone, delineated fresh water aquifers and their corresponding thicknesses in Table 4. It is obvious from the Table that there is varying degree of saline water intrusion in the area; this is evident by the variation in the saline water depth as well as the brackish water thickness obtained in the area. Similarly, substantial fresh water aquifers of varying thicknesses also characterized the entire area.

Table 4: Interpretation Summary of Borehole Logs Within COR 1, COR 2 and COR 3

BH	Elevation	Saline Water Depth (m)	Thickness of Brackish Water Zone (m)	Thickness of Delineated Freshwater Aquifers (m)
		COR 1		
BH1	3	0-126.5	27.5	22
BH9	6	0-140.5	12.5	10.5, 2.5, 20.5 & 7.0
BH6	3	0-136.5	27.5	18.0, 5.0 & 8.0
BH4	3	0-138.5	21.5	24.5, 2.5 & 12.0
		COR 2		
BH2	4	0-123.5	38	22.5, 27.5 & 7.5
BH8	2	0-144	23	4.0, 2.5 & 4.5
BH7	1	0-152	12	10.0, 9.5, 5.0 & 4.0
		COR 3		
BH3	4	0-143	23	2.0, 23.5, 4.0 & 4.0
BH6	3	0-136.5	27.5	18.0, 5.0, 25.0 & 8.0
BH5	2	0-152	12	9.0, 3.0 & 6.5

AQUIFER POTENTIAL

The Aquifer thickness obtained from each of the borehole is shown as the last column of Table 5 below. This was used to produce the aquifer potential map shown in Figure 7. Quantitative interpretation of the study area indicates that 5.7% of the study area is of low potential, 45% is of intermediate potential while 49.3% is of high potential.

Table 5: Obtained values of the GALDIT Parameters determined for each well

S/N	G ALDIT	PARAMETERS				
	G	A (m/Day)	L (m)	D (m)	I (s/m)	T (m)
BH 1	Unconfined Aquifer	7	170	1730	0.019	22
BH 2	Leaky Aquifer	9.5	168.5	936	0.021	57.5
BH 3	Leaky Aquifer	7.8	171	1869	0.012	33.5
BH 4	Unconfined Aquifer	6.4	163.5	2087	0.011	39
BH 5	Unconfined Aquifer	1.9	169	267	0.016	18.5
BH 6	Leaky Aquifer	9	167.5	890	0.021	56
BH 7	Leaky Aquifer	6.2	171	650	0.036	28.5
BH 8	Leaky Aquifer	2.1	175	1342	0.02	11
BH 9	Unconfined Aquifer	7.5	171.5	1054	0.02	41

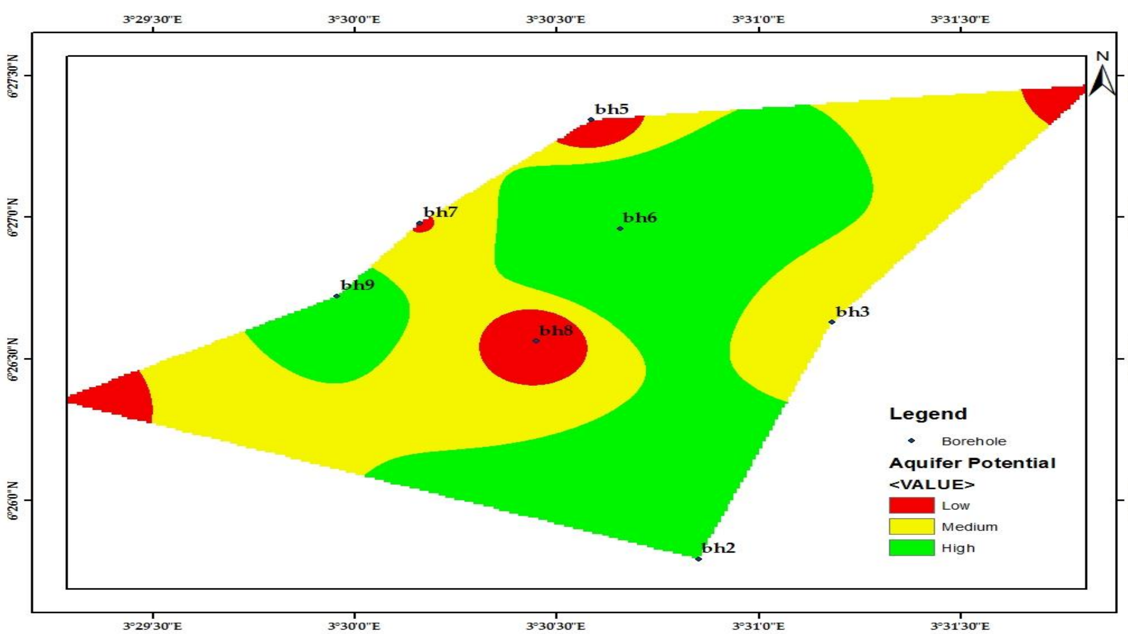

Figure 7: Aquifer potential map/Thickness map

Table 6: GALDIT Index Score obtained for each Well

BH S/N	Cordinates		G (W=1)		A (W=3)		L (W=4)		D (W=4)		SI (W=1)		T (W=2)		GI
	easting	northing	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	∑W*R/∑W
1	3°29’20.46”E	6°26’21.59”N	7.5	7.5	5	15	5	20	2.5	10	2.5	2.5	5	10	4.33 (LV)
2	3°30’49.50”E	6°25’45.00”N	5	5	5	15	5	20	5	20	2.5	2.5	10	20	5.50 (MV)
3	3°31’08.09”E	6°26’37.06”N	5	5	5	15	2.5	10	2.5	10	2.5	2.5	8	15	3.83(LV)
4	3°32’01.00”E	6°27’34.00”N	7.5	7.5	5	15	5	20	2.5	10	2.5	2.5	5	10	4.33 (LV)
5	3°30’34.57”E	6°27’17.23”N	7.5	7.5	2.5	7.5	5	20	10	40	2.5	2.5	3	5	5.50(MV)
6	3°30’38.60”E	6°26’55.70”N	5	5	5	15	5	20	5	20	2.5	2.5	10	20	5.50(MV)
7	3°28’58.00”E	6°26’56.80”N	5	5	5	15	2.5	10	7.5	30	2.5	2.5	5	10	4.83(LV)
8	3°30’26.90”E	6°26’33.30”N	5	5	2.5	7.5	2.5	10	2.5	10	2.5	2.5	3	5	2.67 (LV)
9	3°29’5.31”E	6°26’42.22”N	7.5	7.5	5	15	2.5	10	2.5	10	2.5	2.5	10	20	4.33 (LV)

AQUIFER VULNERABILITY

A summary of all the derived GALDIT parameters derived for all the boreholes is shown in Table 5. Assignent of weight and appropriate rating to the results presented in Table 5 were used to obtain the GALIDIT INDEX (GI) score for each borehole in the study area. This is presented in Table 6. The results shown in Table 6 reveal that the GI scores for the area vary between 2.67 and 5.5. This suggests that two vulnerability classes are obtainable in the study area and these are moderate vulnerability (MV) and low vulnerability (LV) classes (Table 3). A further quantitative analysis of the results shows that six of the nine borehole representing about 66.67% of the study area is oderately vulnerable while three boreholes representing 33.33% of the study area is of low vulnerability. This indicates that the groundwater system within the region is under pressure and boreholes in the area are vulnerable to saline water contamination if left without necessary monitoring.

CONCLUSION

In order to understand the hydrogeological structure and orientation of the study area, well correlation and aquifer characterization were carried using a total of nine composite logs comprising of Resistivity and Gamma Ray logs. Three correlation panels trending in different directions prepared assisted in carrying out litho-stratification delineation that was used to identify fluid types obtainable in the area. Two parameters (aquifer potential and vulnerability) were used to characterize the delineated aquifer in the area. While the aquifer thickness was used to produce the aquifer potential map for the area, the approach of Chachadi, 2005 was adopted in evaluating the aquifer vulnerability. The formation stratification sequence comprises predominantly of sand and clay with intercalations of both occurring as clayey sand and sandy clay. Three distinct fluid types were delineated and these were: saline water, brackish water and fresh water. The bulk resistivity (formation and fluid resistivity) of these fluids respectively ranged from 0 - 80Ωm, 80 – 120 Ωm and 120 – 620 Ωm. Salinity occurrence was observed throughout the entire the study area with depth of occurrence ranging between 14 – 152m. The depth to saline/fresh water interface range from 123 – 167m. Two aquifer types (unconfined and leaky confined aquifers) were observed in the study area. The depths to the delineated aquifers ranged from 163 – 249m with the aquifer thickness ranging from 10 to 56m. The quantitative interpretation of the aquifer potential map developed shows that 5.7% of the study area is of low potential, 45% is of intermediate potential while 49.3% is of high potential. The GI scores obtained for the area vary between 2.67 and 5.5. This suggests that two vulnerability classes are obtainable in the study area and these are moderate and low vulnerability classes. A further quantitative analysis of the results show that about 66.67% of the study area is moderately vulnerable while 33.33% of the study area is of low vulnerability. This indicates that the groundwater system within the region is under pressure and boreholes in the area are vulnerable to saline water contamination if left without necessary monitoring.

ACKNOWLEDGEMENT

The author expresses his profound gratitude to Mr Ibekwe, C.C. for his assistance during data acquisition and data processing phases of this work.

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