

Coastal aquifer vulnerability evaluation of Bonny Island, Niger Delta, Nigeria

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Abstract— The objective of the study is to evaluate the hydraulic characteristics of the aquifer confining layer (aquitard) in Bonny Island in view of the possibility of surface pollution due its large reserve of crude oil and natural gas and companies with industrial plants. The investigation involved boring of six boreholes to a depth of 30metres using dismountable percussion rig. The field data were obtained from six hours pumping test conducted on the boreholes at a constant discharge rate of 32.5m³/hr. (780m³/day). The De Glee method for steady state drawdown in an aquifer with leakage from a confining layer (aquitard) was adopted for the analysis of data and determination of hydraulic characteristics of the aquifer and confining layer. The permeability values of the confining layer vary between 9.55x 10⁻⁴ m/day and 1.33 x 10⁻² m/day with an average value of 5.61 x 10⁻³ m/day while the permeability values for the aquifer vary between 4.83 x10⁻² m/day and 103 m/day. The transmissivity values of the confining layers vary between 9.55 x 10⁻⁴ m²/day and 2.13 x 10⁻¹m²/day with an average value of 5.39 x 10⁻² m²/day and between 8.21 x 10⁻¹m²/day and 4.22m²/day for the aquiferous zone. The values for the aquiferous zone are high, suggestive of a highly transmissible aquifer in the area. However, the average transmissivity value of the confining layer in borehole No3 is relatively high, indicating the possibility of occurrence of leakage especially when there is influence of gravitational and capillary forces on the moisture movement of the underlying soil through the pore spaces. The leakage factor values vary between 1.00m and 15.0m for confining layer. The hydraulic resistance values for confining layers vary between 9.39 x 10² day and 3.32 x 10³day. Although, the permeability and transmissivity of the confining layers are low, the capacity of the layer to transmit water through leakage is sufficiently high especially within the location of borehole No3.

Key words: aquifer, borehole, vulnerability, aquitard, permeability, transmissivity, hydraulic resistance, confining layer

1 INTRODUCTION

The rapid growth of population, urbanization, industrialization and increasing awareness of the need for adequate water supply by Government, communities, public and private institutions have contributed to the enormous demand for potable water supply in the country. Urban pressure due to the reclamation of part of Bonny Island and infrastructural development has caused many industries and individuals to move to the area. For sustainable water supply, emphasis has been placed on the exploitation of the groundwater resources rather than the traditional dependence on surface water either from rainfall or from streams. The results of various researchers (Yisa et al, 2012; Ordinioha, 2011; Ibiyemi, 2001; Adah and Abok, 2013; Ochuko and Origho, 2013; Olasumbo, 2001; Kola-Olusanya, 2003) have revealed that water resources (surface and groundwater) in many parts of the country, especially the southern parts, are more than adequate to meet any demand and only need development and proper management.

However, Bonny Island is within the coast of Atlantic Ocean with no rivers or stream as surface water. Thus, groundwater is the only safe source of water supply for drinking and for all daily needs. However, in spite of these efforts, most part of the Niger Delta, including Bonny Island suffers from groundwater pollution due to its large reserve of crude oil and natural gas and companies with industrial plants. Water seeping near industrial plants can become heavily contaminated with industrial solvents or chemical residues related to manufacturing or processing activities. Percolation of these contaminants poses a

serious threat to the preservation of groundwater quality (Amangabara and Ejenna, 2012). Hence, boreholes can be contaminated biologically and chemically by substances entering the boreholes from the surface. The protection of water quality of the boreholes therefore depends on the engineering and hydraulic characteristics of the aquifer confining layer.

The objective of the study therefore is to evaluate the engineering and hydraulic characteristics of the aquifer confining layer (aquitard) in view of the possibility of surface pollution. The study therefore assumes great significance in the context of the confining layer protecting the under-groundwater against surface pollution.

General description of the study area

Bonny Island is located within latitudes 4^o 20' N and 4^o 35' N and longitudes 7^o 5' E and 7^o 20' E (Fig. 1). It has a tropical climate with two distinct seasons, wet (April-October) and dry (November-March). The mean annual rainfall exceeds 3500mm. About 85% of the mean annual rainfall occurs in the wet season, thereby causing widespread occurrence of floods. In the area, the water levels rise to the ground surface and inundate the area.

The intricate network of rivers and their discharge patterns result in the formation of several morphological units: Dry flat land and plain; Sombreiro warri deltaic plain; freshwater backswamps; saltwater or mangrove swamp and active/abandoned coastal beaches (Fig. 2). Bonny Island lies within the active/abandoned coastal beaches.

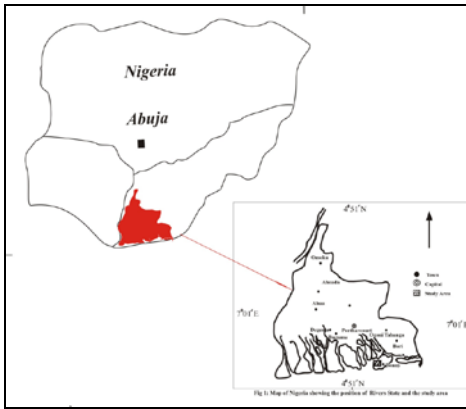


Fig. 1: Map of Rivers State showing the study area

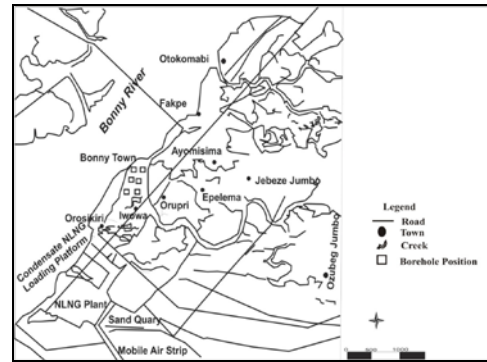


Fig. 3: Map of part of Bonny Island showing the study area and Relative Positions of the Boreholes

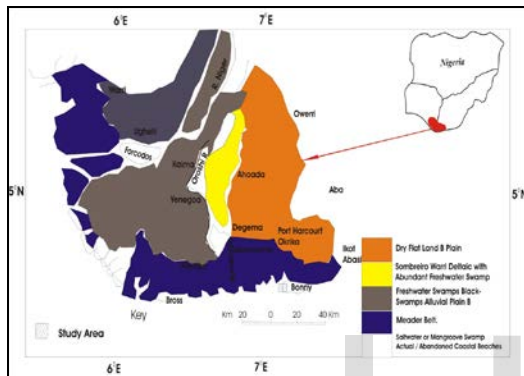


Fig. 2: Location of study area within the geomorphic units of the Niger Delta (Modified after Akpokodje, 1987).

The geology of Niger Delta has been discussed by various authors (Short and Stauble, 1967; Murat, 1970; Merki, 1970, etc). The Niger Delta was formed during the last depositional cycle of the Southern Nigerian basin which commenced in the Paleocene. The general geology of the area consists of Quaternary deposits overlying the Tertiary sandy and clayey deltaic deposits. The Niger Delta has three main subsurface lithostratigraphic units namely, Benin, Agbada and Akata Formations (Short and Stauble, 1967).

2 METHOD OF STUDY

Six boreholes (BH) (Fig. 3) were drilled with dismantable percussion rig. The pumping test was conducted on the boreholes to determine the potential for groundwater resources of the study area. The pumping test was conducted at a constant discharge rate of 32.5m³/hr (780m³/day) and the pumping water levels were measured using dip-meter at the test well and boreholes at a distance of 8m,12m, 20m, 25m, 30m and 38m respectively. Initially, the readings in the production well and observation wells were at every one minute for the first 10 minutes followed by every 2 minutes for the next 10 minutes. Thereafter, readings were taken at every 5 minutes, 10 minutes and 30 minutes. Uninterrupted readings were achieved for 10 hours of pumping. At the termination of pumping test, measurement of well recovery or recharging commenced immediately.

3 ANALYSIS OF DATA

De Glee's method (1951) for a steady state drawdown in an aquifer with leakage from an aquitard (confining layer) proportional to the hydraulic gradient across the aquitard was adopted for the determination of the hydraulic characteristics of the aquitard and aquifer. The field data was derived from the six hours pumping test conducted on the boreholes using a constant discharge method. De Glee derived the following formula:

$$S_m = \frac{Q}{2\pi KD} K_0 \left(\frac{r}{L} \right) \dots \dots \dots (1)$$

$$KD = \frac{Q}{2\pi S_m} K_0 \left(\frac{r}{L} \right) \dots \dots \dots (2)$$

where S_m = steady state drawdown (m) in a borehole at a distance (r) in m from the pumped borehole

Q = discharge of the borehole in m³/d

$$L = \sqrt{K D c} \dots \dots \dots (3)$$

$$C = \frac{D'}{K'} \dots \dots \dots (4)$$

where

C = hydraulic resistance in day

D' = thickness of aquitard (confining layer)

K' = hydraulic conductivity of the aquitard for vertical flow (m/day)

$K_0 \left(\frac{r}{L} \right)$ = modified Bessel function of the second kind and zero order (Hankel function)

A De Glee type curve was prepared by plotting values of $K_0 \left(\frac{r}{L} \right)$ versus values $\frac{r}{L}$ values on a log-log paper. The field data of the drawdown in each borehole was plotted against the corresponding values of r on log-log paper of the same scale with the type curve (Fig. 4). The plots of drawdown versus the corresponding distances (r) was fitted with the De Glee's type curve and an arbitrary point A on the overlapping portion of the sheets (a point where $K_0 \left(\frac{r}{L} \right) = 1$ and $\frac{r}{L} = 1$) was selected (Fig.5).

The transmissivity (KD) was calculated by substituting the known value of Q and the values of S_m and $K_o \frac{r^2}{L}$ on point A in equations (1) and (2). The hydraulic resistance, c was calculated by substituting the value of KD and the values of r and r/L into equation 3, expressed as:

$$C = \frac{L^2}{D} = \frac{1}{r/L^2} \times \frac{r^2}{KD} \dots\dots\dots (5)$$

where r/L = Hankel function

r = distance between the borehole and the pumped well.

The leakage coefficient was determined from the relationship below:

$$\text{Leakage Coefficient} = \frac{K'}{D'} \dots\dots\dots (6)$$

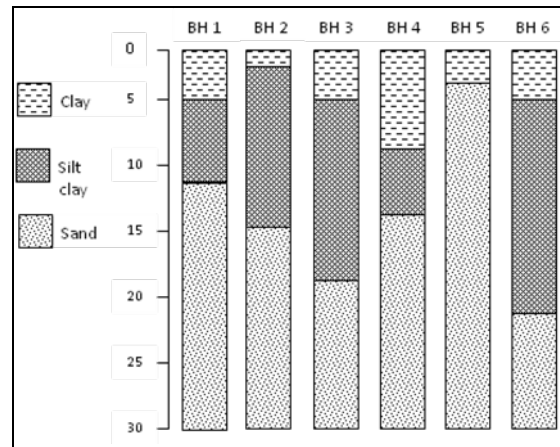


Fig. 6: Lithostratigraphical section of the boreholes in the study area

4 RESULTS AND DISCUSSIONS

Fig. 6 shows a litho-stratigraphical section of the boreholes as derived from the drilling data. In broad terms, each of these boreholes could be rationalized as underlain by at least three primary soil zones. The primary soil zones include an organic clayey layer of about 0-5m thickness, which is soft and grayish brown in color. The dark gray coloration is mostly ascribed to its rich organic content. Beneath the clay is a layer of soft grayish silty clay with variable thickness of about 7-11m, which may extend to the depth of 20m. Underlying the silty clay is a relatively clean, medium to coarse-grained, uniformly-graded sand deposit (aquiferous zone) of about 10-26m thick, which is the water bearing formation. In the clay sandy soils, the infiltration rate is likely to increase because of the sandy nature of the soil. Generally, active clays have high water holding capacity and are also characterized by low permeability and low resistance to shear.

Hydraulic characteristics

When the borehole fully penetrates the aquifer and is screened over a total thickness as shown in Figure 6, the piezometric surface of the aquifer coincides with the water-table (Kruseman and de Ridder, 1991). When the borehole is pumped, the hydraulic head in the aquifer will drop, thereby creating a hydraulic gradient not only in the aquifer itself, but also in the confining layer. The flow induced by the pumping is assumed to be vertical in the aquitard and horizontal in the aquifer (Neuman and Witherspoon, 1969). The water that the pumped aquifer contributes to the borehole discharge comes from storage within the aquifer.

The water that the pumped aquifer contributes to the borehole discharge comes from storage within the aquifer. The water contributed by the aquitard comes from storage within the aquitard and leakage through it. After a certain time, the borehole discharge comes into equilibrium with the leakage through the aquitard (confining layer) and a steady-state flow

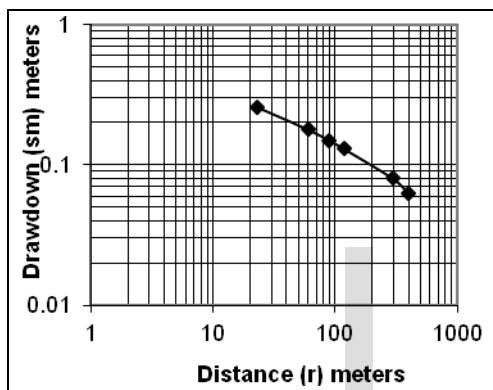


Fig. 4: Plot of drawdown against distance of the borehole from the production borehole in the study area

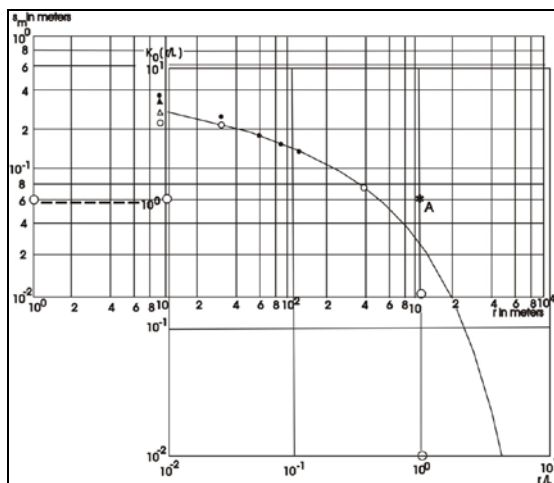


Fig. 5: Typical analysis of data from pumping test of the boreholes with the De Glee method

is attained. In this condition, the aquitard serves merely as a water-transmitting medium.

The summary of the hydraulic characteristics and the average values of the results are presented in Tables 1 and 2. The permeability values of the confining layer vary between 9.55×10^{-4} m/day and 1.33×10^{-2} m/day with an average value of 5.61×10^{-3} m/day while the permeability values for the aquifer vary between 4.83×10^{-2} m/day and 103 m/day. When the result is compared with the ELE International classification (Table 3), the confining layer has poor drainage characteristics and low

to very low permeability while the aquifer has good drainage characteristics and medium to high permeability. The low permeability values of the confining layer could be attributed to the clayey nature of the soil. The average permeability values of the confining layer in BH 1, 2, 4, and 5 are relatively lower than that of BH 3. This variation in the permeability values of BH 3 indicate that the confining layer in the borehole is ineffective in controlling surface pollutions. In this case, surface pollutant could move into the aquifer through the surrounding boreholes.

Table 1: Summary of hydraulic characteristics of the subsoil of the Bonny Island

BH No	Depth range(m)	Soil type (USCS)	Thickness (m)	Coefficient of Permeability (K) (m/day)	Transmissivity (T) (m ² /day)	Hydraulic resistance(c) (day)	Leakage Coefficient	Leakage factor(L) (m)
1	0-4	Clay	4	1.34×10^{-3}	5.36×10^{-3}	2.99×10^2	3.35×10^{-2}	4.00
	5-12	Silty clay	7	2.11×10^{-2}	1.48×10^{-2}	3.32×10^2	3.01×10^{-2}	7.00
	13-30	Sand	17	4.83×10^{-2}	8.21×10^{-1}	3.51×10^2	2.84×10^{-1}	16.97
2	0-2	Clay	2	2.13×10^{-3}	4.37×10^{-3}	9.39×10^2	1.07×10^{-3}	2.00
	3-14	Silty clay	11	2.52×10^{-2}	2.77×10^{-2}	4.37×10^2	2.29×10^{-1}	11.00
	15-30	Sand	15	3.08	46.22	4.87	2.05×10^{-1}	15.00
3	0-1	Clay	1	9.55×10^{-4}	9.55×10^{-4}	1.05×10^3	9.55×10^{-4}	1.00
	2-5	Silty sand	3	3.89×10^{-1}	1.17	7.71	1.30×10^{-1}	3.00
	6-18	Silty clay	12	3.2×10^{-2}	3.84×10^{-1}	3.75×10^2	2.64×10^{-2}	12.00
	19-30	Silty Clayey sand	11	1.26	13.89	8.73	1.15×10^{-1}	11.00
4	0-8	Silty clay	8	3.47×10^{-1}	2.78×10^{-2}	2.3×10^2	4.34×10^{-1}	8.00
	9-13	Silty clayey sand	4	4.53	18.11	8.8×10^{-1}	1.13	4.00
	14-30	Silty clay	16	1.33×10^{-2}	2.13×10^{-1}	1.2×10^2	8.31×10^{-2}	16.00
5	0-3	Clay	3	1.55×10^{-2}	4.65×10^{-2}	1.9×10^2	5.17×10^{-1}	3.00
	4-30	Sand	26	103	2.68×10^2	2.5×10^{-1}	3.96	26.00
6	0-4	Clay	4	2.56×10^{-3}	1.02×10^{-2}	1.56×10^2	6.4×10^{-1}	4.00
	5-20	Silty clay	15	4.73×10^{-2}	7.10×10^{-2}	3.17×10^2	3.15×10^{-1}	15.00
	21-30	Silty clayey Sand	9	3.73×10^{-2}	3.4×10^{-1}	2.41×10^2	4.14×10^{-2}	9.00

Note: USCS = Unified Soil Classification System

The transmissivity values of the confining layers vary between 9.55×10^{-4} m²/day and 2.13×10^{-1} m²/day with an average value of 5.39×10^{-2} and between 8.21×10^{-1} m²/day and 4.22 m²/day for the aquiferous zone. The values for the aquiferous zone are high, suggestive of a highly transmissible aquifer in the area. However, the average transmissivity value of the confining layer in BH 3 is relatively high, indicating the possibility of occurrence of leakage especially when there is influence of gravitational and capillary forces on the moisture movement of the underlying soil through the pore spaces. In this case, the hydraulic conductivity depends on the moisture content and the soil fabric.

The leakage factor which is the measure for spatial distribution of leakage through an aquitard into the aquifer and vice versa (Kruseman and de Ridder, 1991) vary between 1.00m and 15.0m (Table 1) for confining layer and between 3.0m and 26.0m for the aquifer. The result of the leakage factor (Table 2) shows that the average values of the confining layer for BH 4 and 6 are high. This high leakage factor indicates that the rate of leakage from the confining layer into the aquifer is low for BH 4 and 6. Similarly, the leakage factors for BH 1, 2, 3 and 5 are low which suggest that the leakage into the aquifer is high.

Table 2: Average values of the hydraulic characteristics of the aquifer confining layer (clay and silty clay) in the study area

BH	Coeff. of perm. (k) m/day	Transmissivity (T) m/day	Hydraulic resistance (c) day	Leakage coefficient	Leak factor (L) m
1	1.73×10^{-3}	1.0×10^{-2}	3.16×10^2	3.18×10^{-4}	5.5
2	2.33×10^{-3}	1.6×10^{-2}	2.65×10^2	6.47×10^{-4}	6.5
3	1.6×10^{-2}	1.92×10^{-1}	7.11×10^2	1.81×10^{-2}	6.5
4	8.39×10^{-3}	6.02×10^{-2}	1.75×10^2	6.33×10^{-4}	12.0
5	1.55×10^{-3}	4.64×10^{-3}	1.9×10^2	5.17×10^{-4}	2.97
6	3.65×10^{-3}	4.06×10^{-2}	2.37×10^2	4.78×10^{-4}	9.0

Table 3: Drainage characteristics and permeability classification based on ELE International (2005)

Drainage Characteristics	Perm. Classification
Coeff of permeability, K (m/sec)	Coeff of permeability, K (m/sec)
K, 10^{-1} - 10^0 Good	K, 10^{-1} - 10^{-3} High
10^{-4} - 10^{-6} Poor	10^{-3} - 10^{-5} Medium
10^{-6} - 10^{-12} Practically Impervious	10^{-5} - 10^{-7} Low
	10^{-7} - 10^{-9} Very low
	10^{-9} - 10^{-12} Practically Impermeable

The leakage coefficient which is defined as the measure of the amount of leakage through the confining layer ranges between 9.55×10^{-4} and 1.065×10^{-3} for the confining layer. The hydraulic resistance which characterizes the resistance of the aquitard (confining layer) to vertical flow into the aquifer (Kruseman and de Ridder, 1991) varies between 9.39×10^2 day and 3.32×10^3 day, for confining layer and between 8.8×10^{-1} day and 3.51×10^2 day for the aquiferous zone. The average value of hydraulic resistance of the confining layer in BH 3 is relatively lower than BH 1, 2, 4, 5 and 6. This indicates that the confining layer of BH 3 has a high rate of leakage into the aquifer. The permeability and hydraulic resistance values suggest that after rainfall, the voids of the confining layers are likely to be filled with water which would affect the cyclic recharge of other adjoining aquifer. In all the boreholes, the organic clay has an expected low permeability values, varying between 9.55×10^{-4} m/day and 1.34×10^{-3} m/day and also low transmissivity values varying between 9.55×10^{-4} m/day and 1.02 m/day. However, the leakage factors of the organic clay are also low varying between 1.0m and 4.0m. Although, the organic clay has low permeability and transmissivity values, the low values of the leakage factor indicate that the rate of leakage through the clay is high in all the boreholes. The hydraulic resistance of the organic clay (Table 1) in BH 2, 3 and 6 are relatively low. The values suggest that the organic clay has the least resistance to vertical flow in these boreholes. Similarly, the leakage factor of the organic clay in BH 2, 3 and 6 are also low, suggesting high rate of leakage into the underlying stratum. However, the underlying silty clays in BH 2 and 6 have relatively high hydraulic resistance (4.37×10^3 days and 3.17×10^3 days respectively) and leakage factor (11.0m and 15.0m respectively). The under-

lying silty clay in these locations would not allow the movement of pollutants into the aquifer.

In BH 3, the organic clay is underlain by silty sand which is water bearing formation. Consequently, the location of BH 3 is vulnerable to pollution. Moreover, the average values of the hydraulic characteristics as shown in Table 2 also reveals the low hydraulic resistance value (7.11×10^2 days) and low to moderate leakage factor (6.5m) of the confining layer of the BH 3, which indicate least resistance to vertical flow and high rate of leakage of the confining layer in BH 3 location.

5 CONCLUSION

The hydraulic characteristics of the confining layer and the aquifer are related to flow of water into the aquifer. The results of the investigation have revealed that the general drainage of the area is controlled by the nature of the aquifer confining layer which comprises of upper clayey and silty clay soil. Although, the permeability and transmissivity of the confining layers are low, the capacity of the layer to transmit water through leakage is sufficiently high especially within the location of BH 3. The analyses and evaluation of the field data show that the hydraulic resistance and leakage factor of organic clay in BH 2, 3 and 6 are low. This indicates that the organic clay in these locations have high rate of leakage into the underlying stratum.

However, the underlying silty clays in these locations except BH 3 have high resistance to vertical flow of water and low rate of leakage into the aquifer. Consequently, proper attention should be given to Bonny Island in the management of industrial effluent and oil spillage in view of the hydraulic characteristics of the confining layer of the aquifer. The investigation reveals that the area is vulnerable to pollution especially in BH 3 location.

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