Updates on Aquifer Attributes of the Benin Formation within Eastern Niger Delta, Nigeria using Pumping Test and Hydraulic Parameters

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Abstract

Evaluation of aquifer hydraulic properties is a prerequisite in the characterization and management of the groundwater resources. It also provides vital information necessary for establishing and categorizing groundwater potentials of the area. Hydrogeological investigations shows that the aquifer in the area is largely unconfined sands with intercalations of gravel and clay. Results of boreholes logs and sieve analysis confirm the dominance of sandy/gravelly horizons in the area. Pumping test results show that the transmissivity ranged between 152.0 m^2/day and 2835.0 m^2/day with an average value of 1026.0 m^2/day while storativity ranged between $9.5x10^{-6}$ to $1.5x10^{-4}$ with a mean value of $5.8x10^{-5}$. The specific capacity varied between 828.0 m^3/day and 15314.0 m^3/day with a mean value of 6258.0 m^3/day. Well discharge ranged between 1624.0 m^3/day and 7216.0 m^3/day with an average value of 3218.0 m^3/day while hydraulic conductivity varied between 3.2 m/day and 478.4 m/day with a mean value of 98.6 m/day. These results obtained were further interpreted by comparing them with the works of Hazen, Gheorge, Krasny, Bouwer, Cooper and Jacob carried out on similar geological formation. These findings clearly established that the aquifer in the area has adequate groundwater potentials to meet the ever-growing water demands for the area. However, in terms of pollution, the aquifer system in the area is highly vulnerable and should be protected as much as possible.

Keywords: Aquifer System, Hydraulic Properties, Eastern Niger Delta, Nigeria

1. Introduction

The increase in groundwater demand for various human activities has placed great importance on water science and management practice world-wide. To meet the ever-increasing water demand in the Eastern Niger Delta region, groundwater is being extensively used to supplement the surface water thereby subjecting it to over-exploitation for domestic, agricultural and industrial uses (Amadi *et al.*, 2016). Eastern Niger Delta is the operational base of major oil producing and servicing companies in Nigeria. The presence of these companies has led to industrialization and urbanization in the area, with a corresponding increase in groundwater abstraction.

The Niger Delta area covers about 20,000 km² within wetlands of 70,000 km² formed primarily by sediment deposition and the floodplain make up 7.5% of Nigeria's total land mass (Nwankwoala, 2005). It is home to over 20 million people and 40 different ethnic groups, this It is the largest wetland and maintains the third-largest drainage basin in Africa (Akpokodje, 2001). The Niger Delta is among the world's largest petroleum provinces and its importance lies on its hydrocarbon resources. It is the 6th largest oil producer and 12th giant hydrocarbon province in the world (Nwankwoala et al., 2017; Nwakife et al., 2018; Igbomor and Amadi, 2019).

Pumping test is a field experiment in which a well is pumped at a controlled rate and water-level response (drawdown) is measured in one or more surrounding observation wells and optionally in the pumped well (control well). The data obtained from pumping tests are used to estimate the hydraulic properties of aquifers, evaluate well performance and identify aquifer boundaries. Aquifer test and aquifer performance test (APT) are alternate designations for a pumping test.

The objectives of a pumping test, as in any aquifer test, is to estimate hydraulic properties of an aquifer system in an area. The pumped aquifer was used to determine transmissivity, hydraulic conductivity (horizontal and vertical) and storativity (storage coefficient). In layered systems, pumping tests are also employed to estimate the properties of aquitards (vertical hydraulic conductivity and specific storage). Pumping tests can identify and locate recharge and no-flow boundaries that may limit the lateral extent of aquifers (Amadi, 2007; Amadi, 2014).

Hydraulic conductivity is a measure of a material's capacity to transmit water. It is defined as a constant of proportionality relating the specific discharge of a porous medium under a unit hydraulic gradient. The higher the hydraulic conductivity and the larger the hydraulic gradient, the greater the rate of groundwater flow through an aquifer. Hydraulic conductivity reflects the characteristics of both the water and the geology. The hydraulic conductivity, which is a function of water viscosity and density, is also a function of water temperature. However, due to the small range of temperature variation observed in groundwater systems, the temperature dependence of hydraulic conductivity is often neglected. Transmissivity is the rate of flow under a unit hydraulic gradient through a unit width of aquifer of given saturated thickness. The transmissivity of an aquifer is related to its hydraulic conductivity as follows:

$T = Kb$ ……………….. Equation 1,

where T is transmissivity, K is the hydraulic conductivity and b is aquifer thickness.

2. Study Area Description

The study area lies within the eastern Niger Delta region of Nigeria between latitude 4°40^{I}N to 5°40^{I}N and longitude 6°50^{I}E to 7°50^{I}E (Figure 1). It covers parts of Port-Harcourt, Aba and Owerri. The prevalent climatic condition in the area comprises of the rainy (March to October) and dry (November to February) seasons characterized by high temperatures, low pressure and high relative humidity throughout the year. The region sustains a wide variety of crops, economic trees and a variety of freshwater fish than any ecosystem in West Africa.

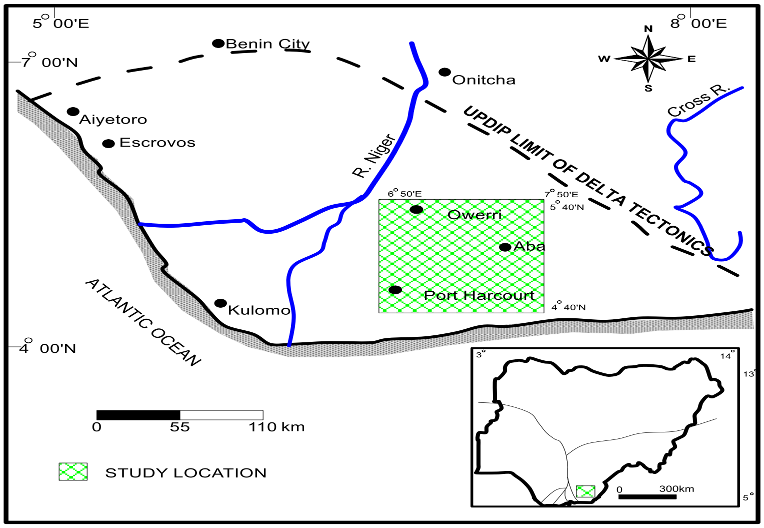

Figure 1: Niger Delta map showing the study area (Amadi, 2014)

3. Geology of the Eastern Niger Delta

The study area (Port-Harcourt, Aba, Owerri and environs) is underlain by Pliocene-Pleistocene Benin Formation (Figure 2). The type locality of the formation is in Port-Harcourt, Aba and Owerri where the formation overlies the older Ogwashi-Asaba Formation (Ezeigbo and Aneke, 1993). The formation made up of loose, poorly sorted extensive sands underlying recent Quaternary sedimentary deposits of southern Nigeria. It consists mainly of sands, sandstone and gravel with clays occurring in lenses as evident in burrowed pits, river channels and boreholes in the area (Onyeagocha, 1980). The Benin Formation is composed mostly of high resistant fresh water bearing continental sand and gravel with clay intercalations (Amadi, 2014), and the environment of deposition is partly lagoonal and fluvio–lacustrine/deltaic (Ofoegbu, 1998). The formation comes in contact with the Ogwahi–Asaba Formation in the northern part and with Alluvium in the southern part and thickens southwards into the Atlantic Ocean (Figure 2).

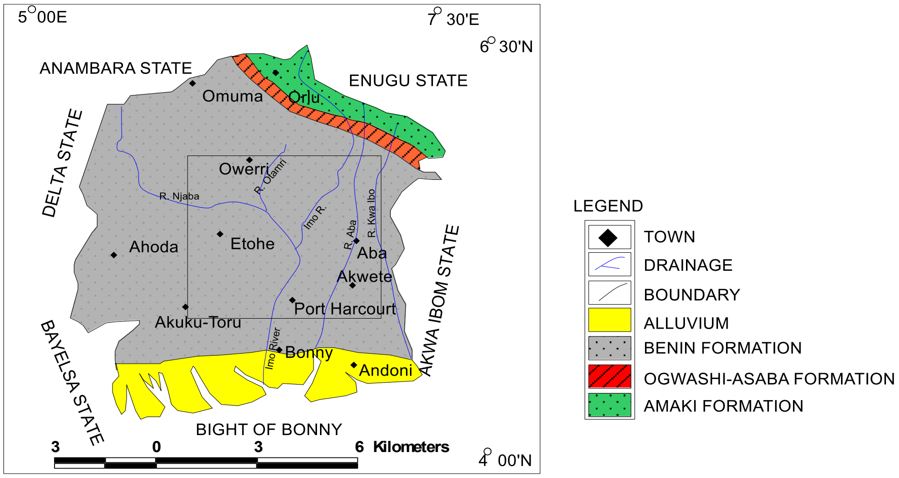

Figure 2: Geological Map of parts of Eastern Niger Delta showing the Study Area (Amadi, 2014)

4. Materials and Methods

4.1 Hydraulic Conductivity

The hydraulic conductivity of the aquifer was calculated from the grain size distribution curve using the Hazen's method (1911). The method is applied to sandy formation at exactly the effective grain size (d_{10}), which is the size corresponding to the 10% line on the grain size distribution curve. The Hazen's formula is given as:

$$K = c[d_{10}]^2 \ldots\ldots\ldots\ldots\ldots \text{Equation 2.}$$

Where:

K = hydraulic conductivity (cm/sec)
d_{10} = the effective grain size (cm)
C = a coefficient of fine to coarse grained sand and poorly sorted = 100

Transmissivity

The method used to determine the transmissivity of the aquifer was the Cooper and Jacob's method (1946). The Cooper and Jacob's method was used because:

- The aquifer is unconfined,
- The aquifer has a very large area extent,
- The aquifer is homogenous and of approximately uniform thickness,
- Prior to pumping, the water table was horizontal over the area influenced by the pumping test
- The aquifer is pumped at a constant rate,
- The borehole penetrates the aquifer and thus receives water from the saturated zone.

The Cooper and Jacob's method (1946) is a modification of Thesis method (1935) and given as:

$$T = \frac{2.3Q}{4\pi\Delta S} \quad \text{……………………} \quad \text{Equation 3.}$$

Where:

T = transmissivity (m^2/day)
Q = Pumping rate (m^3/day)
Δs = Slope

The values of Q was determined in the field as pumping was in progress while the values of Δs was determined from the slope along drawdown graph in the semi-log graph.

4.2 Storativity

Modified Cooper-Jacob's method (1946) was used to determine the aquifer storativity in the area. The equation is given as and the results obtained are discussed in chapter four:

$$S = \frac{2.25KTt_o}{r^2} \quad \text{…………………………} \quad \text{Equation 4}$$

where: r = radius of the well (mm)
t = time (Sec)
KD = hydraulic conductivity X aquifer thickness
T = Transmissivity (m^2/day)
S = Storativity (dimensionless)

5. Results and Discussion

5.1 Geological Mapping

The geological mapping carried out lead to the construction of the geological map of parts of Eastern Niger Delta (Figure 2). The mapping exercise revealed that the area is underlain by thick sandy horizons belonging to the Benin Formation of Miocene to Recent age. The formation is composed of friable sands with intercalations of clay of varying depths and this was ascertained through drilling borehole in the area. Recharge into the unconfined aquifer is through direct infiltration of precipitation (Offodile, 2002; Olasehinde and Amadi, 2009).

5.2 Borehole-logs

Borehole drilling in the study area is not difficult but care must be taken to make the drilling mud thick in order to cement the boreholes walls and prevent collapse of the walls, because of the loose and friable nature of the sandy formation, carving is common experience. The boreholes were logged at an interval of 3 m and it led to the production of lithogs. Borehole at Owerri (northern part of the study area) is terminated at 60 m (Figure 3) while the Port-Harcourt borehole (southern part of the study area), which shows both the casing tally and strata log stopped at 84 m (Figure 4). The borehole-logs show clear and concise lithostratigraphy of the subsurface geology is made up of fine to coarse grained sand with clay intercalations of variable thickness.

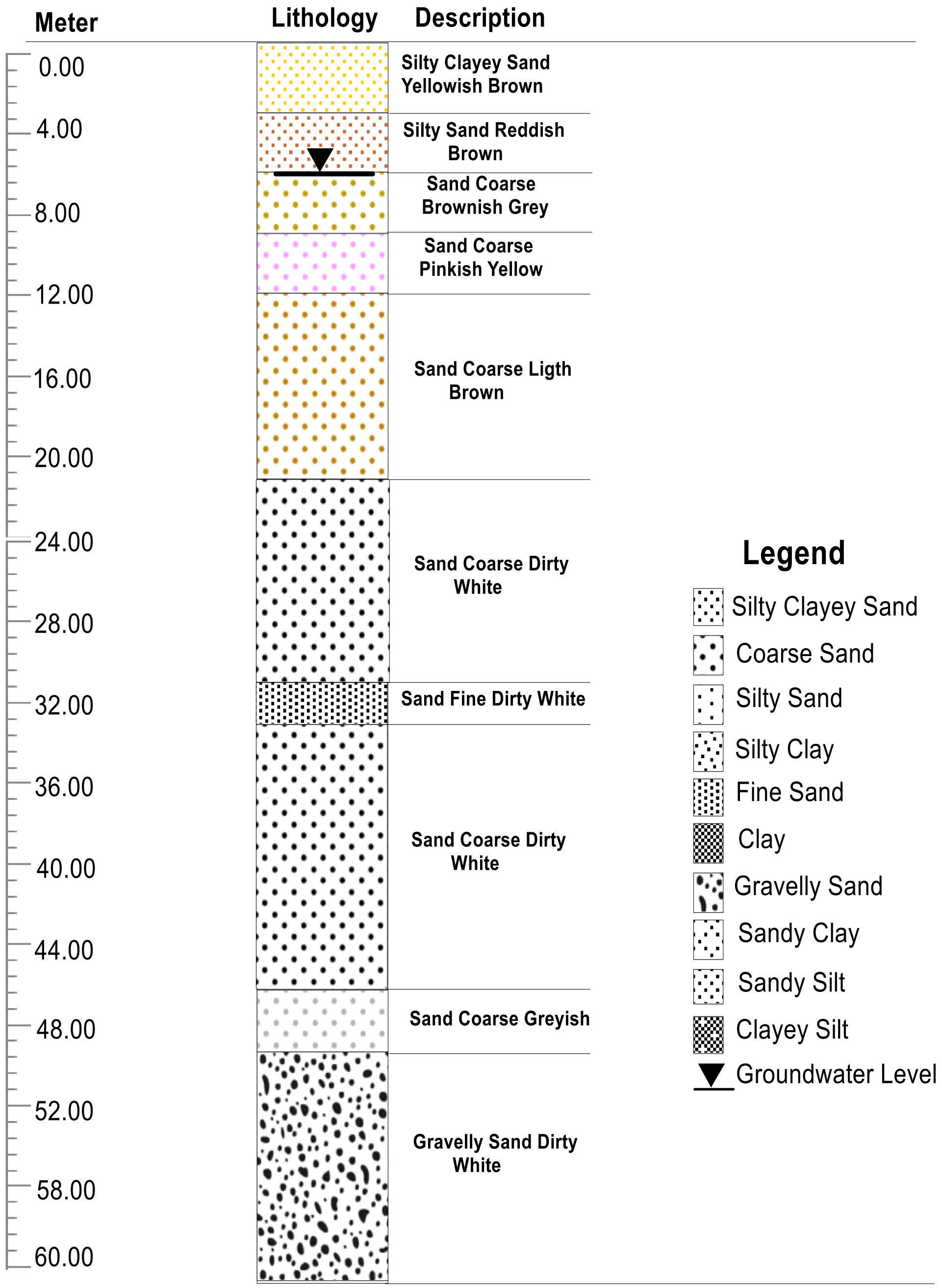

Figure 3: Borehole-Log from Owerri Area (Amadi, 2014)

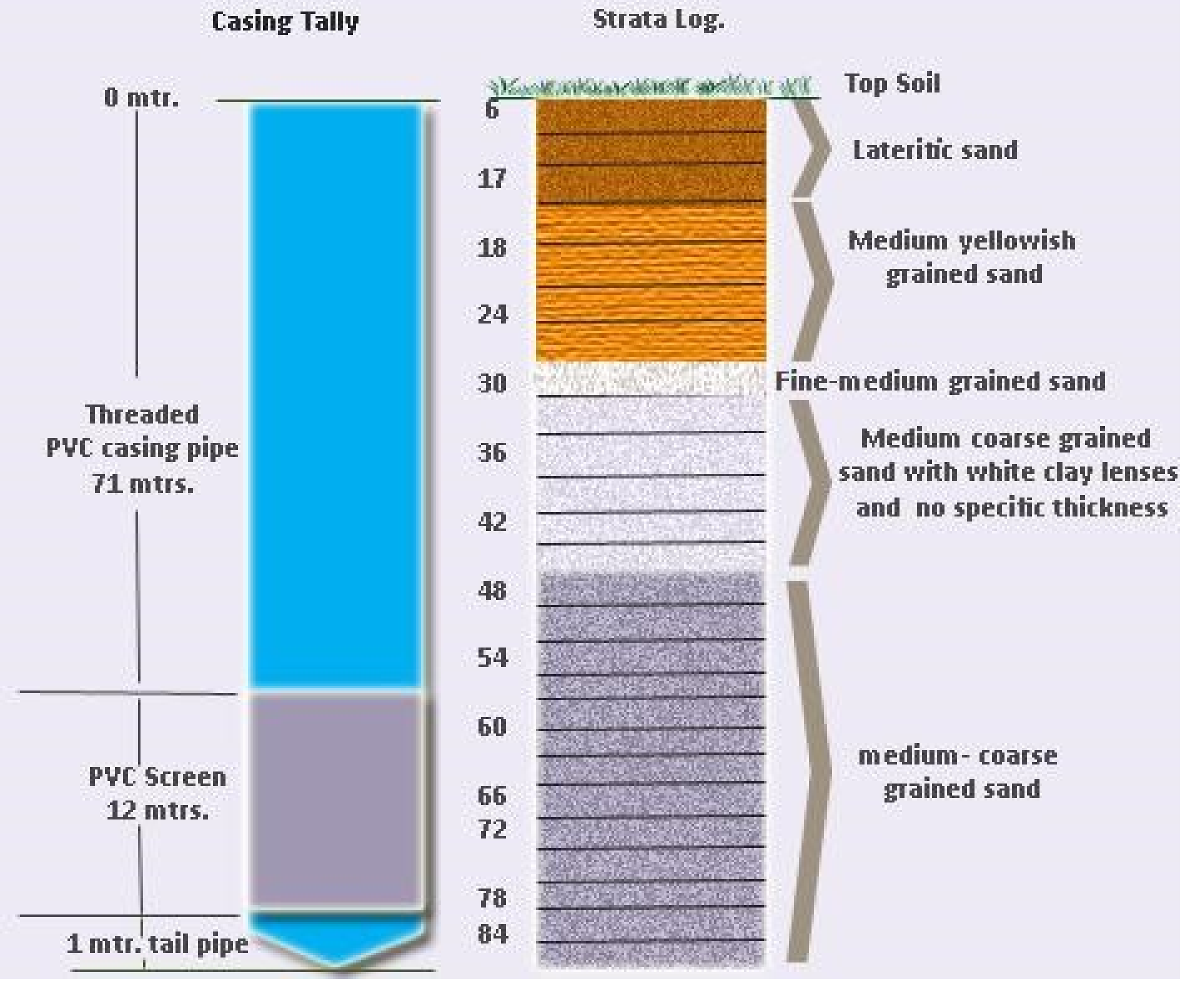

Figure 4: Port-Harcourt Borehole-log and the Casing Tally (Amadi, 2014)

5.3 Sieve Analysis

In order to determine the textural characteristics of the underlying formations, which invariably influence the rate of infiltration of rainfall, borehole samples were collected and subjected to sieve analysis. The particle size distribution curve (Figure 5) obtained from the sieve analysis shows that the subsurface lithologies are mainly sand, followed by fine gravel. This is conformity with the results of the geological mapping and boreholes logging. The sieve analysis of the borehole cuttings led to the choice of screen slot used in order to avoid siltation which could damage the borehole. A typical borehole completion set-up is shown in figure 6.

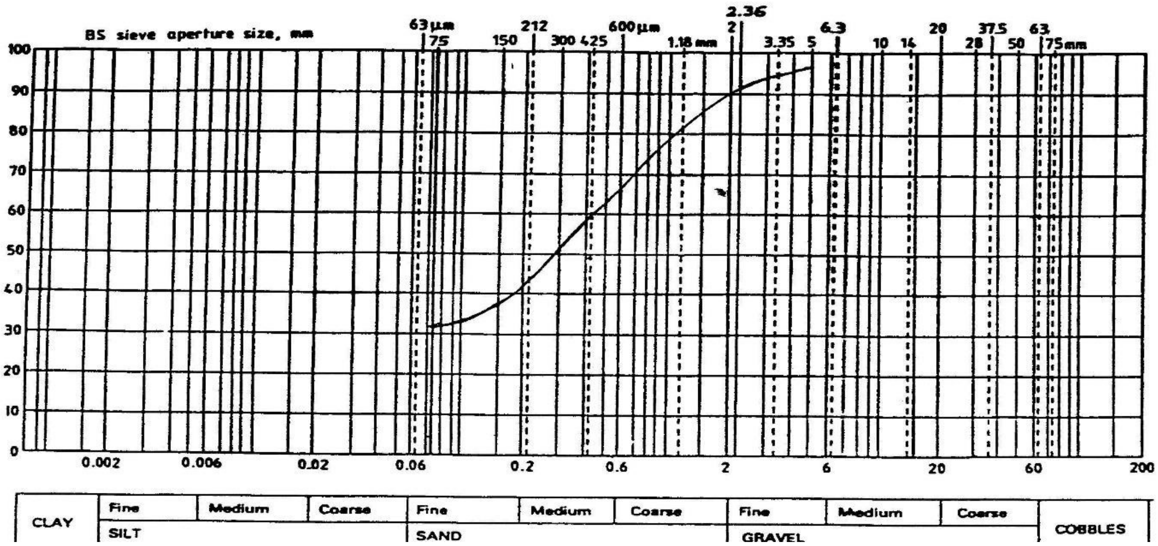

Figure 5: Particle Size Distribution Curves for the Study Area (Amadi, 2014)

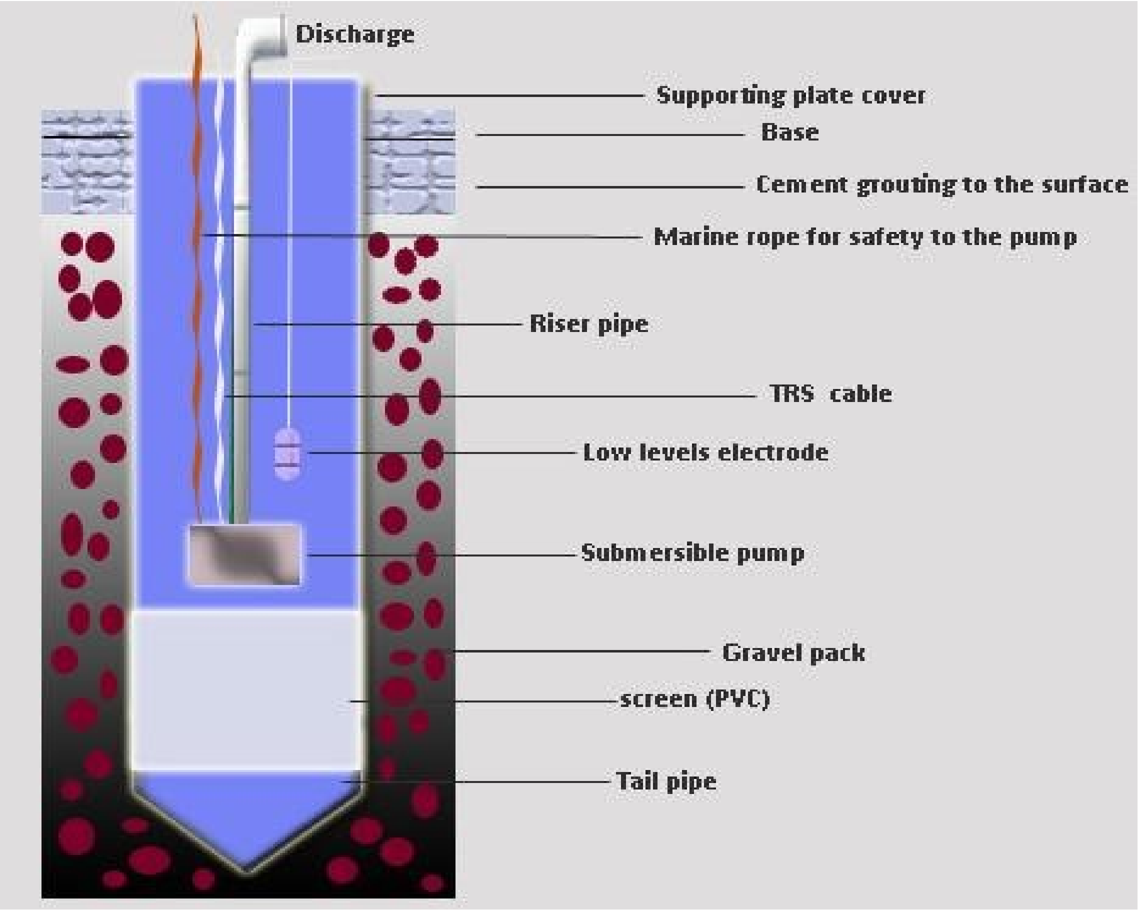

Figure 6: A typical Borehole Completion Set-up for the Study Area (Amadi, 2014)

5.4 Permeability Test

The results of the coefficient of permeability determined from Constant Head Permeameter test values ranged from 4.14 x 10^{-5} cms^{-1} to 9.4 x $10^{-5}$$cms^{-1}$ with a mean value of 6.8 x 10^{-5} cms^{-1} (Table 1). This by implication means that soil horizon, through which water infiltrate the underlying aquifer is of relatively high permeability. Due to the high permeability of the soils and rocks, coupled with the shallow water table, Uma, (1989) gave the average linear groundwater flow in the area at about 400 m/yr, a confirmation of the porous and permeable nature of the sandy formation in the study area. This findings is also in agreement with the outcome of sieve analysis, borehole-logs and geological mapping of the area.

Table 1: Summary of Coefficient of Permeability Determined using Constant Head Permeameter

Parameters	Minimum	Maximum	Mean
Coefficient of Permeability(K) Cms^{-1}	9.4 x 10^{-5}	4.14 x 10^{-5}	6.8 x 10^{-5}
Elevation (m)	53.0	78.0	61.0
Depth (m)	1.2	3.6	2.4

5..5 Pumping Test

The statistical summary of the pumping test data is contained in Table 2. The pumping test results were used to determine the aquifer discharge (Q), static water level (SWL), transmissivity (T), hydraulic conductivity (K), Storativity (S) and specific capacity (SC) contained in Table 2. The values of Q were determined in the field as pumping was in progress while the values of Δs were determined from the slope of the drawdown and recovery in a semi-log graph. The aquifer transmissivity and storativity were calculated using Cooper-Jacob's equation.

Table 2: Statistical Summary of Pumping Test Data from Eastern Niger Delta

Parameters	Minimum	Maximum	Mean
Borehole depth (m)	46.0	310.0	124.0
Discharge (m^3/day)	1624.0	7216.0	3218.0
Static water level (m)	3.0	28.0	11.0
Transmissivity (m^2/day)	152.0	2835.0	1026.0
Hydraulic conductivity (m/day)	3.2	478.4	98.6
Storativity (dimensionless)	9.5x10^{-6}	1.5x10^{-4}	5.8x10^{-5}
Specific capacity (m^2/day/m)	828.0	15314.0	6258.0

5.6 Hydraulic Conductivity

The hydraulic conductivity of the aquifer was calculated using the Hazen's equation. The method is applied to sandy formation at exactly the effective grain size (d_{10}), which is the size corresponding to the 10% line on the grain size distribution curve. From the grain size distribution curves, over 92% fall within the fine to coarse sand and poorly sorted. The results of hydraulic conductivity values ranged between 3.2 m/day to 478.4 m/day and a mean value of 98.6 m/day (Table 2). The result of hydraulic conductivity indicates high permeability rates. This is one good characteristics of unconsolidated, unconfined sandy aquifer and it is in line with the findings obtained from the borehole logging.

5.7 Aquifer Transmissivity and Storativity

The transmissivity of the aquifer were computed using Cooper and Jacob's equation while the aquifer storativity in the area were determined using the modified Cooper and Jacob's equation. The values of the transmissivity ranged from 152.0 m^2/day to 2835.0 m^2/day with an average transmissivity value of 1026.0 m^2/day while the storativity ranged between $9.5x10^{-6}$ to $1.5x10^{-4}$ with a mean value of $5.8x10^{-5}$ (Table 2).

The transmissivity values (152.0 m^2/day to 2835.0 m^2/day) in Table 2, from the study area falls within the moderate to high transmitting potential according to George (1978) standard in Table 3 as well as high to very high transmissivity magnitude in line with Krasny classification scheme in Table 4. Smilarly, the hydraulic conductivity values (3.2 m/day to 478.4 m/day) in Table 2 also fail under coarse grained sand/gravel materials by Bouwer standard in Table 5. This implies that the results of sieve analysis showing an aquiferious system comprising of sand and gravel (Figure 5) was in order. The borehole logs (Figure 3) indicating sand and gravel region further elucidates the facts that the study area is prolific hydrogeologically. It also implies that contaminants can easily infiltrate into the groundwater system and transported from one place to another, thereby making it vulnerable to pollution (Amadi *et al*., 2014; Ameh *et al*., 2019).

The high values of permeability, hydraulic conductivity, discharge, specific capacity, transmissivity and storativity (Table 2), when compared with known standards such as Bouwer, (Table 3), Gheorge (Table 4) and Krasny (Table 5), indicate a high groundwater potential typical of an unconsolidated, unconfined, porous and permeable sandy formation. The consistency in these results further collaborate to the fact that the study area dominated by fine to coarse grained unconfined and unconsolidated sandy aquifers. The results of the pumping test data were also used to plot the graphs of drawdown versus recovery (Figure 7), specific yield versus yield (Figure 8), specific yield versus discharge (Figure 9), specific yield versus drawdown (10) and specific yield versus time (11).

Table 3: Gheorge Standards for Transmissivity (T)

Transmissivity Range	Transmitting Potentials
T > 500 m^2/day	High potential
T between 50 – 500 m^2/day	Moderate potential
T between 5 – 50 m^2/day	Low potential
T between 0.5 – 5 m^2/day	Very low potential
T < 0.5 m^2/day	Negligible potential

Table 4: Krasny's Transmissivity Standards

T (m2/day)	Designation of Transmissivity Magnitude	Groundwater supply potential
1000	Very high	Regional consumption
100	High	Local consumption
10	Intermediate	Community consumption
1	Low	Private consumption
0.1	Very low	Limited consumption
< 0.1	Imperceptible	Negligible consumption

Table 5: Bouwer Standard for Hydraulic Conductivity (K)

K-ranges	Materials
10^{-8} – 10^{-2} m/day	Deep clay beds
0.001 – 0.1 m/day	Clay, sand and gravel mixes (till)
0.01 – 0.2 m/day	Clay soils (surface)
0.1 – 1 m/day	Loamy soils (surface)
1 – 5 m/day	Fine grained sand
5 – 20 m/day	Medium grained sand
5 – 100 m/day	Sand and gravel mixes
20 – 100 m/day	Coarse grained sand
100 – 1000 m/day	Gravel

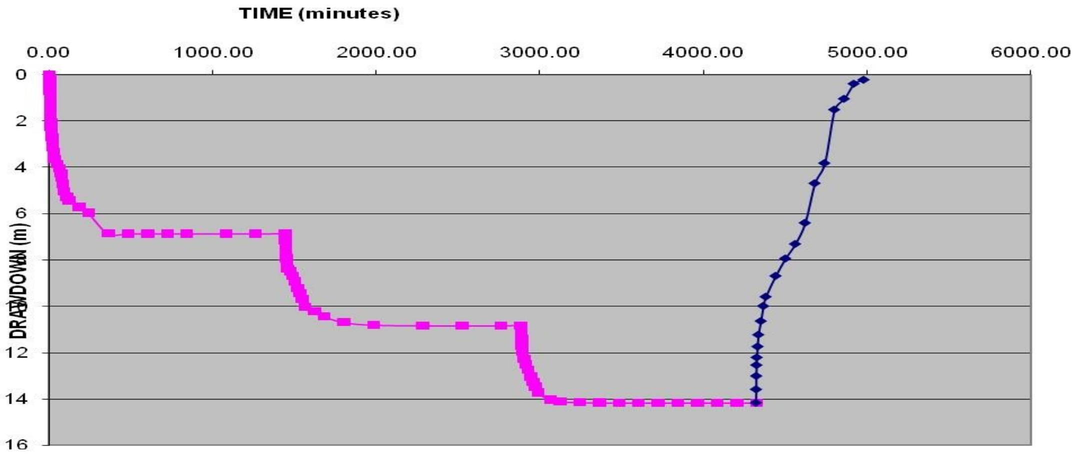

Figure 7: A Representative Drawdown & Recovery Graph from the study area

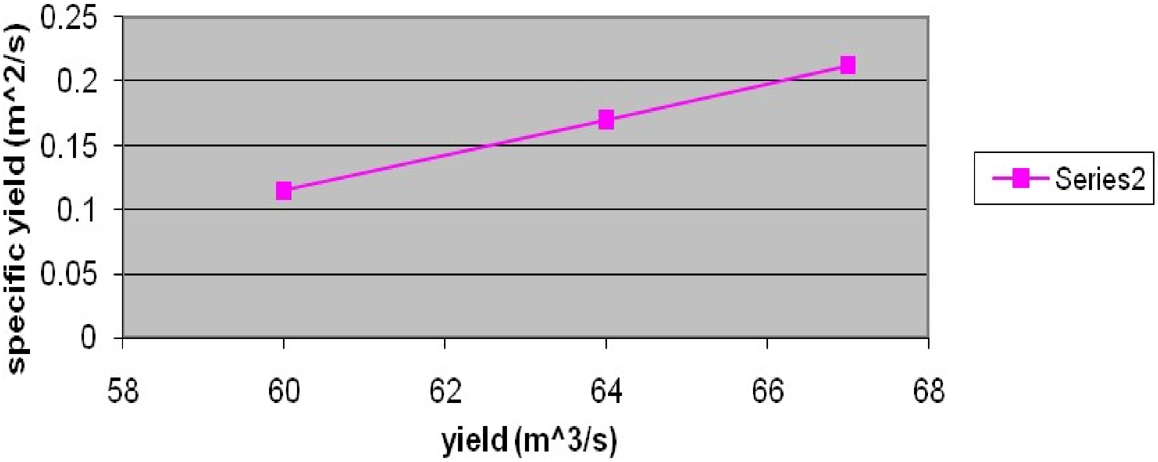

Figure 8: Graph of Specific yield versus yield

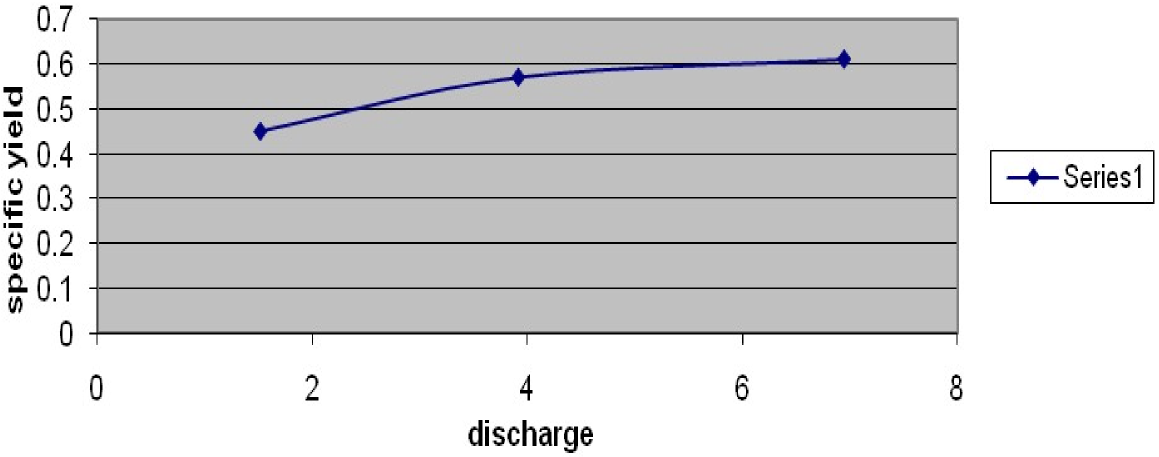

Figure 9: Graph of Specific yield versus discharge

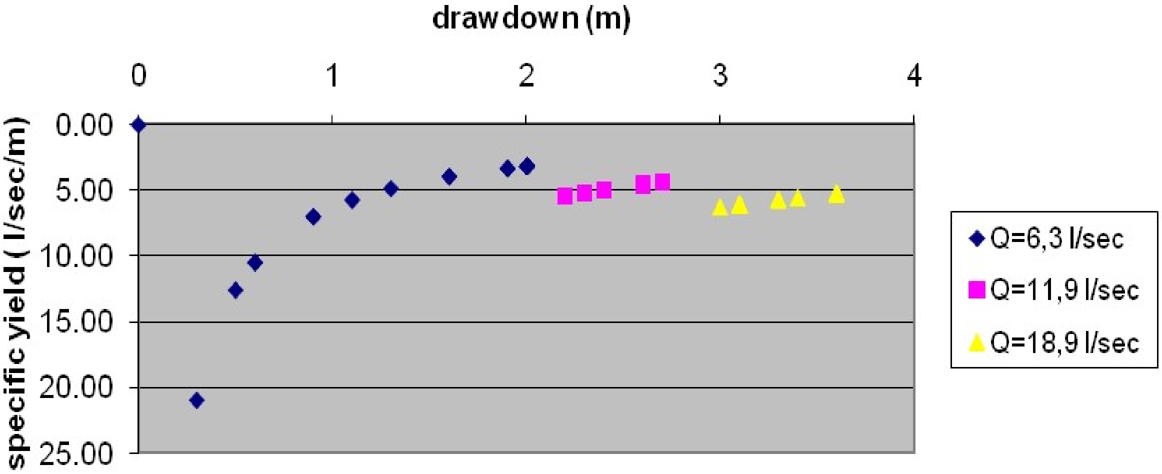

Figure 10: Graph of Specific yield versus drawdown

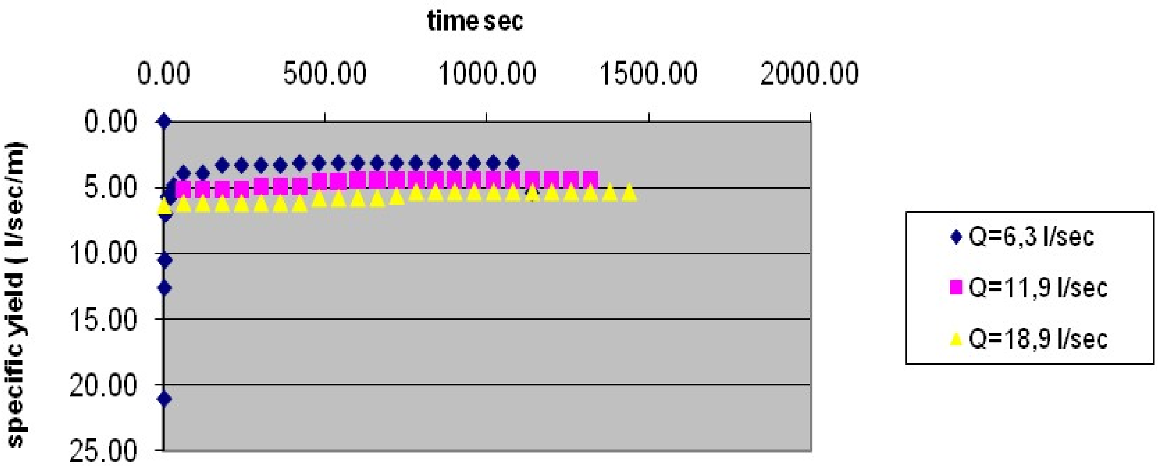

Figure 11: Graph of Specific yield versus time

6. Conclusion

Geologically, it has been established that the study area is underlain by the coastal plain sand belonging to the Benin Formation of the Niger Delta, Nigeria. The Benin Formation is characterized by high porosity and permeability. Hydrogeologically, the study area has high groundwater potential to sustain any form of commercial activities domiciled in the area. Results of the pumping test, permeability test, hydraulic conductivity, discharge, storage capacity, transmissivity and storativity points to the fact that the study area is highly prolific with good groundwater potentials. The wide range of values of the hydraulic properties and aquifers attributes (permeability, hydraulic conductivity, transmissivity, storativity, specific capacity and well discharge) confirm the fact that the aquifer system in the study area have very good transmitting abilities and yield potentials. This implies that the groundwater development potential of the area are very high quantitatively but may be poor qualitatively due to its vulnerability tendencies in terms of high porosity and permeability.

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