Evaluation of aquifer hydraulic parameters and groundwater protective capacity from shallow groundwater exploration in parts of Ejeme-Aniogor, western Niger Delta, Nigeria

Felix I. Chinyem[1*], Glory O. Ovwamuedo[1], Ernest O. Akudo[2], M.O. Ofomola[3], Victor, N. Nwugha[4], Roseline, T. Agbosa[5], Sikiru, A. Salami[6]

[1]Department of Geology, Delta State University, PMB 1, Abraka, Nigeria
[2] Department of Geology, Federal University, Lokoja, Nigeria
[3] Department of Physics, Delta State University, Abraka, Nigeria
[4] Department of Basic Sciences, Alvan Ikoku College of Education, Owerri, Nigeria
[5] Department of Science Laboratory Technology, Delta State University, Abraka, Nigeria
[6]Department of Geology, Faculty of Physical Sciences, University of Benin, Benin City, Nigeria
*Corresponding author: **fichinyem@gmail.com**; **fichinyem@delsu.edu.ng**

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Abstract: Aquifer hydraulic parameters (AHP) and groundwater protective capacity (GPC) assessments are crucial for groundwater sustainability studies. Therefore, this study aims to evaluate shallow groundwater exploration in Ejeme-Aniogor area of the western Niger Delta, using the vertical electrical sounding (VES), borehole logs as well as pumping test data, with the intent to assess AHP and GPC from shallow groundwater in the area. Fourteen (14) VES data, employing Schlumberger technique were acquired. The acquired VES data were interpreted using Win Resist software, for iteration, from where layer paameters were generated. Evaluation of layer parameters was subsequently done to derive the Dar-Zarrouk parameters, such as longitudinal conductance (S) and transverse resistance (R), which were applied in the evaluation of aquifer hydraulic conductivities (K) as well as transmissivities (T). The K and T values obtained from the pumping test data, were correlated with the computed values from the VES data, and the results gave a good relationship with the in-situ values obtained. The VES results revealed four to five geoelectric layers, with a dominance of four layers composed of lateritic topsoil/sand, fine sand, medium sand, medium-coarse sand, and coarse sand, respectively. The shallow groundwater-bearing aquifers, represented by the fourth and fifth layers, have resistivity values ranging from 1031.8 to 16122.6 Ωm, indicating the presence of a freshwater sandy/gravelly aquifer, located at depths of 20 to 90 m. The T values (1.860 to 29.328 m^2/day) and K values (0.045 to 0.597 m/day) from the VES results, suggest moderate to good groundwater prospects, with favorable porosity and permeability, as confirmed by the high values of R (36713.1 to 1168888.5 Ωm^2). The S values (0.003 to 0.48 Ω^{-1}) indicate poor GPC. Therefore, it is recommended that boreholes drilled in this area be properly and adequately gravel-packed to minimize the risk of contamination and pollution from surface sources. Besides, the high K and intermediate T revealed aquifer of great potential for groundwater exploration and exploitation. These findings suggest that the VES technique is a valuable tool for identifying prospective groundwater-bearing layers and could serve as a baseline for groundwater sustainability management policy in Nigeria.

Keywords: Vertical electrical sounding, Groundwater, Ejeme-Aniogor, Transmissivity, Niger Delta

Introduction

Fundamentally, the assessment of aquifer hydraulic parameters (AHP) as well as groundwater protective capacity (GPC) is crucial for groundwater studies (Chinyem, 2024). Assessment of AHP greatly contributes to the knowledge of groundwater occurrence and the effect of pumping exercise on the aquifer system in any given environment (Obasi et al., 2023). GPC assessment, on the other hand, assists in the understanding of the nature and hydrogeological characterization of the aquifer (Agada and Yakubu, 2022). Knowledge of AHP like transmissivity (T) and hydraulic conductivity (K) is vital for efficient groundwater development and management. Tijani et al. (2021) asserted that "exploitation of groundwater resources is a global challenge that has led to increased awareness of groundwater resources development and management". Akingboye (2022) posited that one of the attributes of a nation's sustainability development is its ability to provide potable water to its citizens. Thus, a scientific–oriented and pragmatic approach to groundwater resources management, becomes urgently needed.

Conventionally, assessment of AHP in any given environment is achieved through a pumping test, to obtain discrete information of the area (Lu et al., 2021; Ofomola et al., 2022a; Ofomola et al., 2022b). However, due to the cost and labor involved, pumping tests are rarely utilized in assessing AHP nowadays, hence a major limitation. Geophysical methods (e.g. vertical electrical sounding) on the other hand are non-invasive, cheaper alternatives (cost efficient), produce quality results, and rapid with high success rates (Akingboye, 2022). A good correlation is established between the AHP and the measured resistivity values through surface geophysical methods. Therefore, high–quality data is obtained through surface geophysical methods, and this provides the near-surface lithologic units, which are important in the selection of suitable points for groundwater development (Ekanem, 2020).

Assessment/evaluation of AHP and GPC has been conducted by several scholars (like Atakpo and Ayolabi, 2009; Asuma et al., 2018; Oseji et al., 2018; Anomohanran et al., 2020; Olajide et al., 2020; Oli et al., 2020; Youssef, 2020; Tijani et al., 2022; Agada and Yakubu, 2022; Akingboye, 2022; Akpah et al., 2022; Obasi et al., 2023; Chinyem, 2024) in different geological terrains. Atakpo and Ayolabi (2009) applied a geophysical method (vertical electrical sounding) to "evaluate the aquifer vulnerability and protective capacity in some oil-producing communities of western Niger Delta". Their findings showed a poor and unprotected GPC and remarked that the aquifer in virtually all the communities investigated, were vulnerable to hydrocarbon contamination,

should pollution occur. Similarly, Asuma et al. (2018) applied a Very-Low-Frequency Electromagnetic survey (VLF-EM) to assess the aquifer protective capacity (APC) in Burutu, Nigeria. The study revealed poorly protected (APC) aquifers, susceptible to contamination, and hence, underscored the efficacy of VLF-EM as a veritable tool for assessment of GPC when combined with other geophysical methods as well as borehole data. Oseji et al. (2018) also investigated the "aquifer protected capacity and groundwater capacity in some open dumpsites in Sapele, Delta State Nigeria". Their findings established an adequately protected aquifer of 0.7 – 0.9 mhos (VES 1 and 5), a moderately protected aquifer of 0.2 – 0.69 mhos (VES 4), and a poorly protected aquifer of 0.003 – 0.004 mhos (VES 8 and 9). However, their result indicated a good transmissivity, which implied a high rate of flow contaminant in groundwater, should there be any pollution/contaminant. Similarly, Anomohanran et al. (2020) utilized "geoelectric, geophysical well logging and pumping test techniques to determine the groundwater potential and aquifer hydraulic characteristics of Agbor, Nigeria". The authors established high-yielding aquifers that would be sustainable for domestic, agricultural, and domestic needs. Olajide et al. (2020) evaluated "the APC groundwater potential (GP) around Iju, Ondo State Nigeria". Their findings revealed a weak to poor APC (75%) and a low GP (70%) in the area studied. Oli et al. (2020) also assessed "the hydro geophysical and GPC of Ezza and Ikwo areas, Nigeria". Their study revealed a moderate APC, with a higher aquifer potential in the Ebonyi Formation. Similarly, Youssef applied "geoelectric analysis in Ain El-Soukhna area, west Gulf of Suez, Egypt to evaluate the aquifer characteristics". Their findings revealed a freshwater aquifer with some elements of sea intrusion in VES 2 and 6 respectively. The value of less than 0.56 m/day, as well as the T value of about 100 m^2/day, identified at VES 6, 10, and 11 respectively, implied lesser/intermediate groundwater potentiality. Furthermore, Tijani et al. (2021) estimated "the AHP and PC in southwestern (SW) Nigeria basement aquifer, using geophysical methods. Their study showed good groundwater-yielding materials, and poor-weak-moderate-good APC, that were evenly distributed. Agada and Yakubu (2022) equally employed the "electrical resistivity method (ERM) to evaluate the APC of Lambata area, Abuja, Nigeria". The study identified a fairly good APC, though not sufficient to prevent groundwater pollution/contamination. Akingboye (2022) also, applied "georesistivity and geostatistical methods to assess the geohydraulic characteristics and groundwater vulnerability of tropically weathered and fractured gneissic aquifers of Akungba-Akoko, SW Nigeria". The study identified an extremely high – moderate aquifer vulnerability index. Akpah et al. (2022) applied ''grainsize analysis to determine the hydraulic conductivity of Lokoja and Patti Formations, Ngeria''. Their findings revealed that ''Patti Formation has more porous, permeable and aquiferous sandstone of great potential for groundwater exploration and exploitation than Lokoja Formation''. Obasi et al. (2023) used electrical resistivity data as well as litholog from Idah area, Nigeria to estimate aquifer parameters. The study revealed a predominantly fracture–based aquifer, suitable for groundwater exploration/exploitation in the north-central region correspondingly. Chinyem (2024) applied similar methods to determine the AHP and GPC in Nsukwa clan, Nigeria. The study identified a moderate aquifer potential, with poor APC and recommended adequate aquifer protective strategies to be applied.
The study area is located in Ejeme – Aniogor area, western Niger Delta (WND), Nigeria. Due to its serenity, source of River Adofi, as well as rapid urbanization prospects, the area has become a choice habitation for tourists, locals, staff, and students of St Felix Catholic Seminary, Ejeme-Aniogor and Ejeme secondary school, Ejeme-Aniogor, respectively. Additionally, the location of the Tree Crop Unit (an agricultural unit of Delta State Ministry of Agriculture and Natural Resources) as well as several palm oil mills, dotted in the area has attracted several researchers, workers, and traders all over the country to the area. This has impacted groundwater availability and portability in the area. There is no functional public water provision, due to lack of political will. The people depend on the River Adofi (surface water) and groundwater from a few private boreholes for their domestic agricultural and industrial needs. There has been a reduction in the dependence on River Adofi by the inhabitants, due to groundwater accessibility, and this has improved the health status of the people, as the risk of waterborne diseases has drastically reduced. However, the thin overburden in the study area of the Niger Delta (ND), has made shallow aquifer susceptible to contamination.
In spite of several previous studies, AHP and GPC in the Ejeme-Aniogor area have not been evaluated. Chinyem (2017) mainly focused on "geoelectric investigation for groundwater prospect in Ejeme-Aniogor and environs, Aniocha South Local Government, Delta State, Nigeria". The findings revealed "a good groundwater prospect for development". The area has attracted many researchers in groundwater, aquatic, environmental, and agricultural sciences, but none of their findings have been published in the public domain. Therefore, it becomes imperative to expand on the existing knowledge of AHP and GPC, in the Ejeme-Aniogor area as this will be significant to holistically, alleviate the deficiency associated with information on parameters in the Ejeme-Aniogor area. The goal of this study, therefore, was to apply VES data and borehole data to assess the AHP and GPC in Ejeme-Aniogor for groundwater sustainability.

Location and geological setting of the study area.

The study area (Ejeme-Aniogor area) is part of sheet 299, southeast Agbor, Delta State, Nigeria. It falls within latitude 6º 00' to 6º 05' N and longitudes 6º 17' to 6º 24' E (Figure 1) in the northern part of western Niger Delta Basin (NDB) of Nigeria. Ejeme-Aniogor and its environs consist of semi-urban towns that are accessible by major and minor roads that were used during the fieldwork Topographic features in the area consists of hills, plains, and valleys that ranged between 55-102 m above sea level. The dendritic drainage pattern characterizes the area, with River Adofi and River Omu, draining the study area. In the area, the drainage pattern (dendritic) is being controlled by these topographic features. Chinyem (2017) noted that "the drainage system is denominated by River Adofi, which has its source at Ejeme-Aniogor and flows southwards towards Ossissa in Ndokwa-East local Government Area of Delta State before it empties its water into the River Niger". The typical rainforest climate of Nigeria characterizes the area, with two seasons: wet season (April-October) and dry season two (November-March), as well as a mean annual temperature range between 21-30 ℃ and mean rainfall of 2100 mm.
In terms of the geologic setting, the area falls within the NDB (Figure 2) characterized by three main lithostratigraphic units. These units have been discussed extensively by different scholars (Short and Stauble 1967; Murat 1972; Avbovbo 1978; Doust and Omatsola 1990; Akudo et al. 2024; Chinyem 2024). Tectonically, the origin of the NDB is traceable to the orogeny (regional tectonic episode) that led to the splitting of both African and South American continents. The NDB was formed due to the aulacogen (failed arm) of a triple junction, during the Jurassic period, resulting in the separation of the African, South Atlantic, and South American plates, respectively, and subsequent deposition of sediments. (sands and shales) during the Cretaceous period. The three units: Akata Formation (AkF), Agbada Formation (AgF), and Benin Formation (BF) consist of shales, sandstones and shale, and clay, silt, sand and gravel respectively. According to Doust and Omatsola (1990), "the AkF (Paleocene) constitute the chief

hydrocarbon-bearing formation, the AgF (Eocene) constitute the petroleum reservoir rocks, while the BF corresponds to the principal groundwater bearing formation". The hydrogeological characteristics of the subsurface of Ejeme -Aniogor area are similar to those of some neighboring towns in Nsukwa clan (Chinyem 2024) and some communities in NDB like Asaba (Chinyem 2013) and Abraka (Chinyem et al. 2023). Principally, groundwater recharge comes from rainfall, and the aquifer unit consists of coastal plain sand and clay/shale intercalations giving some level of protection to the sandy/gravelly aquifer.

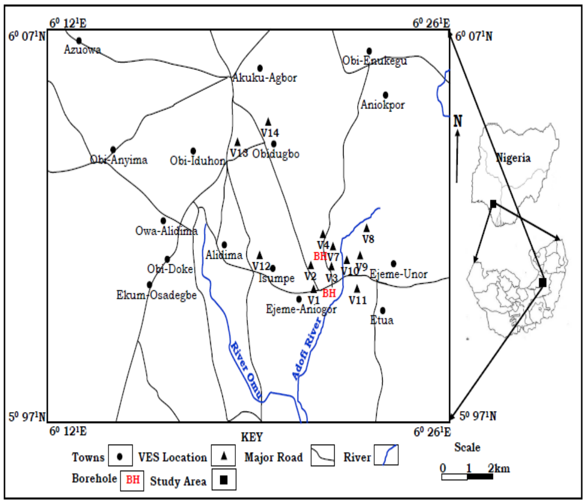


Figure 1: Location/accessibility map of the study area

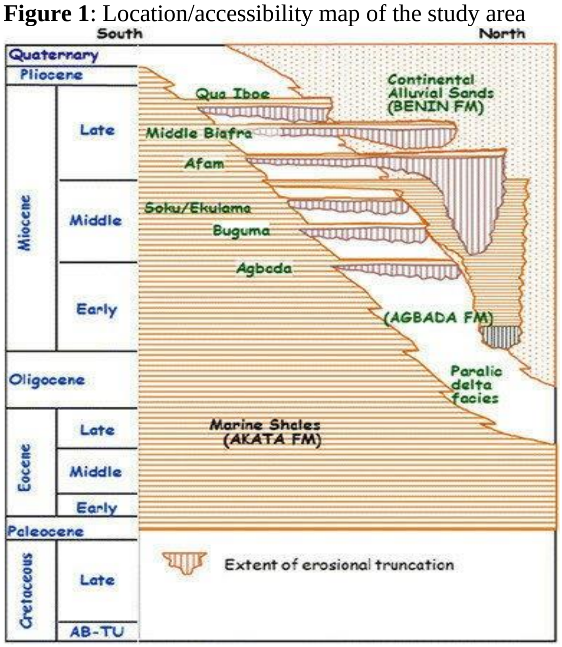


Figure 2: Stratigraphy of the Niger Delta (After Doust and Omatsola, 1990).

Materials and methods

Field operations

Fourteen (14) vertical electrical soundings (VES) were carried out using ABEM SAS 4000 Terameter (resistivity meter) for the field data acquisition. The points for the VES were randomly selected based on space availability for spreading, and the coordinates of each VES point were taken, using the global positioning system (GPS), as shown in Figure1. Basically, the Schlumberger VES configuration array was employed with the current spacing (AB/2) that ranged from 1-500 m, while the potential electrode spacing (MN/2), ranged 0.5 – 40 m, with the intent to delineate shallow and deeper subsurface information. The choice of the Schlumberger array was due to its sensitivity to subsurface inhomogeneities, adequate depth penetration as well as less labour required during field operation. The resistance value (R) of the subsurface features was directly obtained from the resistivity meter (ABEM SAS 4000). The product of the obtained R, and geometric factors, gave the apparent resistivity (P_a). The apparent resistivity value (P_a) was first plotted against half electronic spacing (AB/2), on a logarithm graph manually, to obtain the sounding curves, which were interpreted. The quantitative manual interpretation result was modeled, using Win Resist version 1.0 interpretation software to obtain the VES curves (Figure 3), from which the geoelectric parameters/layers resistivities, depth, thickness as well as geo-electric sections were generated. Subsequently, the results were compared with two borehole data/logs of drilled water wells close to VES 3 and VES 7 respectively. The two borehole logs and pumping test data were acquired from Dan Drilling Company. The method involved the drilling of two water wells, from where, well cuttings (rock samples) were collected and analysed at 3 m intervals (figure 4a). The lithological profile/log of the drilled wells showed that the top layer consist of lateritic soil/fine sand. This subsurface formation, typical of the Benin Formation, spans from 0 to 12 m depth.The top layer is underlain by clayey/very fine sand layer(reddish) that extends to 15 m depth (3 m thickness). The second layer is underlain by a fine sand layer, with the subsurface formation changing from reddish to yellowish fine sand (grey-white) at a depth between 15 m and 18 m. The lithology encountered between 15 m and 18 m comprised brownish to whitish fine-medium sand.This layer marks the beginning of the aquiferous region. The last subsurface formation, identified during the drilling programme consist of medium -coarse sand at a depth range of 25-34 m. The borehole drilling terminated at a depth o 34 m. It is noteworthy that the depth range of 25 to 34 m is identified as a more prolific shallow aquifer of great potential than the preceeding layer, as can be seen from the colour of the well cuttings(samples) that changed from grey/brownish colour to whitish as well as the grain sizes that became coarser (figure 4a).

Evaluation of groundwater protective capacity (GPC)

The first–order geoelectric parameters (layers' thickness and resistivity) are crucial in the understanding of the subsurface geological model. They were used to derive the second–order geoelectric parameters (longitudinal unit conductance, S, and transverse unit resistance, R_T). These parameters are called Dar–Zarrouk parameters (Mailet,1947). The parameters (otherwise called second-order parameters) were obtained from first-order parameters and were utilized to evaluate the GPC; using equations 1 and 2, as used by Patra and Nath (1999)., Musa et al. (2023) as:

Longitudinal unit conductance $(S) = h / \mathcal{P}a$ (1)

Transverse unit resistance (R_T) = $h \times \mathcal{P}a$ (2)

where h and $\mathcal{P}a$ represent aquifer thickness (m) and resistivity, (Ωm) respectively.

Evaluation of AHP from the VES data

The AHP such as K and T were evaluated utilizing equations 3 and 4 respectively, as used by earlier scholars such as Heigold et al. (1979), Seli et al. (2021), Musa et al. (2023) as follows:

Hydraulic conductivity $(K) = 386.60\, \mathcal{P}a^{-0.932883}$ (3)

Transmissivity $(T) = K\sigma R_T = KS/\sigma = Kh$ (4)

where $\mathcal{P}a$ represent aquifer resistivity (Ωm), K is the hydraulic conductivity (m/day), σ is the electrical conductivity (Ωm^{-1}), R_T is transverse unit resistance (Ωm^2), S is the longitudinal unit conductance (Ω^{-1}). The values obtained from K, T, S, R_T were used to generate maps (Figures 5 & 6) using surfer 8 terrain software.

Subsurface geology evaluation from borehole data/logs

Two boreholes were drilled around VES 3 and 7 respectively, by Dan drilling company. The drilled wells were logged, using SAS 4000, SAS 200 logging tool to delineate the lithologic units. The procedure involved constant rate pumping method on two drilled boreholes, with the intent of correlating the values of aquifer parameters obtained from the VES and pumping test. Conventionally, the pumping test was carried out separately on the two drilled wells for a maximum period of 180 minutes, applying Cooper Jacobs (1946) straight line analysis, and from the data obtained, hydraulic conductivity (Kp) and transmissivity (Tp) were correlated with the values of aquifer parameters obtaind from VES, as used by Chinyem et al. (2023); Chinyem (2024); Chinyem et al. (2024) as follows:

Transmissibility (Tp)= $\frac{2.25Q}{4\pi\Delta s}$ (5)

Hydraulic Conductivity (Kp) = $\frac{Tp}{h}$ (6)

Where Q is the rate of discharge (m^3/s), Δs is the slope (m), h is aquifer thickness (m)

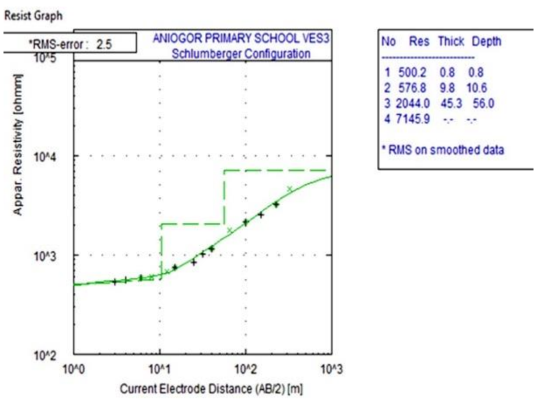


Figure 3: Representative geo-electric sounding curve for VES 3

Results and discussion

Geo-electric assessment

The results from the inverted VES data, shown in Table 1, revealed the dominance of four geo-electric layers, and a five-layer was observed only at the VES 13 location. The findings revealed a superficial (topmost/uppermost) geo-electric layer resistivity that ranged from 119 Ωm (VES 9) to 1113.6 Ωm (VES 8) and a thickness range of 0.7 m (VES 2, VES 7, VES 13) to 1.0 m (VES 6, VES 8). This topmost layer is composed of lateritic topsoil/sand. The second geo-electric layer resistively ranged from 289.9 Ωm (VES 7) to 2773.6 Ωm (VES 8) and a thickness range of 3.5 m (VES 13) to 12.2 m (VES 8). This layer is composed of fine sand. The third geo-electric layer resistivity ranged from 496.5 Ωm (VES 13) to 16,122.6 Ωm (VES 8) and a thickness range of 13 m (VES 6) to 72.5 m (VES 8). The lithology is composed of fine – medium/coarse sand. The fourth geo-electric layer resistivity ranged from 7766 Ωm (VES 10) to 15,821.4 Ωm (VES 6). The upper limit of this layer thickness is 26.5 m (VES 13) while the lower limit of the thickness and depth could not be determined because the deepest geo-electric layer has been located beneath the VES station. This geo-electric layer is composed of medium-coarse sand/gravel. The fifth geo-electric layer, observed only at the VES 13 location, has an upper limit of 4509.6 Ωm while the lower limit is undetermined, as electric current terminated at deeper depths. Also, the upper and lower limits of the thickness and depths could not be determined because the deepest layer has been located beneath the VES location. These geo-electric layers (fourth and fifth) are identified as continuation aquifers (Chinyem, 2024) because electrode separation terminated within these layers. The data obtained suggest that the fourth and fifth geo-electric layers are the best layers to source groundwater. This assertion was correlated with the borehole lithology obtained, which showed the depth of 25-35 m, as the ideal depth to source groundwater. It is noteworthy, based on data collected from Dan Drilling Company borehole drilling company that the fourth and fifth layers represent the shallow groundwater–bearing layers. This fact was corroborated by the VES data obtained from this study(figure 4a). Figure 4a shows drilled borehole log, correlated with VES 3 and VES 7, from where a similar subsurface geologic information was identified. The VES record (data) was utilized in the construction of the geo-electric section (Figures 4b and 4c). Figures 4b and 4c show the modeled geo-electric sections tied to the borehole, close to VES 3 and VES 7 respectively. The modeled geo-electric sections displayed dominance of four layers in all the VES locations, except in VES 13, having five geo-electric layers. The identified geo-electric section displayed a lithologic variation of lateritic topsoil/sand, fine sand, medium sand, medium to coarse sand, and coarse sand respectively in the various layers. The borehole log, on the other hand, displayed the following lithologic succession: lateritic topsoil/sand, clay, and fine sand, the geo-electric section revealed a characteristic heterogeneous lateral lithology that could be attributed to gradational variation in sediment grain sizes across the area. The lithologic succession, as displayed in the geoelectric session, showed an aquifer with some level of protection (poor) from lateritic sand/clay and fine sand. The modeled geo-electric section revealed a great similarity between borehole data (log) and VES data, nevertheless with minimal variations expected of geo-electric data. These findings are in agreement with the report by Chinyem (2024) who posited that “the lateritic sand/clay and fine sand in Nsukwa clan (to which the study area belongs) give some level of protection (poor) to groundwater”

Table 1: Geoelectric layers’ parameters and lithologs delineation deduced from computer iteration

VES	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology
1	1	446.1	0.8	0.8	Lateritic topsoil
	2	803.4	4.1	4.9	Fine grain sand
	3	5944.7	52.4	57.3	Medium grain sand
	4	12792.1	---	---	Coarse grain sand
22	1	265.8	0.7	0.7	Lateritic topsoil
	2	452.4	4.5	5.2	Fine grain sand
	3	1757.5	28.1	33.2	Medium grain sand
	4	7545.3	---	---	Coarse grain sand
3	1	500.2	0.8	0.8	Lateritic topsoil
	2	576.8	9.8	10.6	Fine grain sand
	3	2044.0	45.3	56.0	Medium grain sand
	4	7145.9	---	---	Coarse grain sand

Table 1 (continued)

VES	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology
4	1	278.6	0.9	0.9	Lateritic topsoil
	2	1094.7	5.7	6.6	Fine grain sand
	3	3608.0	51.4	58.1	Medium sand
	4	9802.4	---	---	Coarse grain sand
5	1	206.4	0.9	0.9	Lateritic topsoil
	2	495.6	5.5	6.4	Fine grain sand
	3	1031.8	41.3	47.7	Medium grain sand
	4	2441.9	---	---	Coarse grain sand
6	1	198.1	1.0	1.0	Lateritic topsoil
	2	1712.1	4.9	5.8	Fine grain sand
	3	4768.8	13.0	18.8	Medium grain sand
	4	15821.4	---	---	Coarse grain sand
7	1	149.9	0.7	0.7	Lateritic topsoil
	2	289.9	5.8	6.5	Fine grain sand
	3	1061.7	50.5	57.0	Medium grain sand
	4	2322.4	---	---	Coarse grain Sand
8	1	1113.6	1.0	1.0	Lateritic topsoil
	2	2773.6	12.2	13.2	Fine grain sand
	3	16122.6	72.5	85.7	Medium grain Sand
	4	37071.9	---	---	Coarse grain Sand
9	1	119.0	0.9	0.9	Lateritic Topsoil
	2	353.2	4.7	5.6	Fine grain Sand
	3	3914.2	42.5	48.1	Medium grain Sand
	4	8737.6	---	---	Coarse grain Sand
10	1	502.8	0.8	0.8	Lateritic Topsoil
	2	572.1	4.5	5.2	Fine grain Sand
	3	11620.8	36.4	41.6	Coarse grain Sand
	4	776.0	---	---	Medium grain Sand
11	1	625.6	0.8	0.8	Lateritic Topsoil
	2	1417.2	6.4	7.2	Fine grain Sand
	3	7981.8	58.7	65.9	Medium grain Sand
	4	13696.5	---	---	Coarse grain Sand
12	1	222.6	0.8	0.8	Lateritic Topsoil
	2	783.2	7.9	8.8	Fine grain Sand
	3	3382.5	52.3	61.1	Medium grain Sand
	4	8640.8	---	---	Coarse grain Sand
13	1	639.3	0.7	0.7	Lateritic Topsoil
	2	1103.6	3.5	4.1	Fine grain Sand
	3	496.5	15.3	19.4	Medium grain Sand
	4	1385.4	26.5	45.9	Medium to coarse grain Sand
	5	4509.6	---	---	Coarse grain Sand
14	1	170.5	0.8	0.8	Lateritic Topsoil
	2	561.0	5.8	6.6	Fine grain Sand
	3	4340.6	62.9	69.5	Medium grain Sand
	4	8927.9	---	---	Coarse grain Sand

AHP and GPC assessment

The computed AHP results across the area are summarized and presented in Table 2. The aquifer resistivity ranged from 1031.8 Ωm (VES 5 to 16122.6 Ωm (VES 8), with a mean of 4926 Ωm. This resistivity range suggests a freshwater sandy/gravelly aquifer. This agrees with the assertion made by Jansen (2011) who posited that a "resistivity range of 30-50 Ωm or higher indicates sandy aquifers filled with fresh water or air". This suggests that the parent rock was composed of mainly quartz as well as other stable minerals that later disintegrated into porous and permeable sandy/gravelly aquifers. In addition, this wide range in resistivity values revealed a characteristic heterogeneous lateral lithology that is due to gradational variation in sediment grain sizes deposition across the area. This wide heterogeneity in resistivity value is typical of the BF lithology composed of sand, clay intercalations, sandstone, and gravel. These findings conform to the reports by Chinyem (2013); Chinyem, (2017); Nwachukwu et al. (2019); Anomohanran et al. (2020); Chinyem (2024).

The computed electrical conductivity (EC) of the aquifer (Table 2) reflects the ability with which an electric current can pass through an aquifer (groundwater) unit. It is a reflection of the amount of dissolved material in the aquifer, as well as the aquifer porosity. Mathematically, it is expressed as an inverse of resistivity ($1/p$). The calculated EC ranged from 0.000062 (VES 8) to 0.000969 m/Ω in the area. The EC of groundwater increases as the number of dissolved particles increases. The low values of EC observed reflect the low amount of dissolved material in groundwater and this indicates the potability of the aquifer, as well as the presence of clean sand that has little or no contaminants.

The aquifer thickness (Table 2) ranges from 18.8m (VES 6) to 85.7 m (VES 8) with a mean range of 53.3 m. The results suggest that groundwater exploration should be targeted around 20-90 m for water abstraction to local water supply (communities, plants) as well as for private consumption. This depth range epitomizes the shallow (near surface) area. This result corroborates the findings by Chinyem (2017).

The longitudinal conductance (S) value (Table 2, Figure 5) ranged from 0.0003 Ω^{-1} (VES 6) to 0.048 Ω^{-1} (VES 7), with a mean range of 0.016. S value is crucial in assessing the GPC and can be applied to measure aquifer vulnerability to surface contaminants, as it relates to the ratios of the individual layer thicknesses and their respective lithology. Locations or areas characterized by thicker clayey formations will have higher S, and locations with higher S will have higher GPC and vice-versa from the classification scheme of Oladapo et al. (2004), where he established a longitudinal conductance ranking of < 0.1 (poor), 0.1-0.19 (weak), 0.2 – 0.69 (moderate) 0.7-4.9 (good), 5-10 (very good) and > 10 (excellent). The entire study area showed poor GPC. The result, therefore, suggests an unprotected aquifer, from surface contaminants. It, therefore, becomes imperative that boreholes drilled within the area should be adequately and properly travel-packed to minimize the incidence of contamination from surface sources.

Similarly, the transverse unit resistance (R_T) value (Table 2) ranged from 36713.1 Ω^2 (VES 13) to 1168888.5 Ω^2 (VES 8), with a mean value of 250,754.9 Ω^2. The higher values of R_T indicate areas with higher resistivity and low clay content. These values also suggest intermediate groundwater potential for siting productive boreholes for the supply of water to communities. Nwankwo and Ehirim (2010) and Chinyem (2024) asserted that "high R_T values suggest areas of moderate to high transmission rate and recharge, with good water potentials". Therefore, based on the R_T result, suitable ground-yielding materials, adequate for groundwater exploration are thus identified in the area.

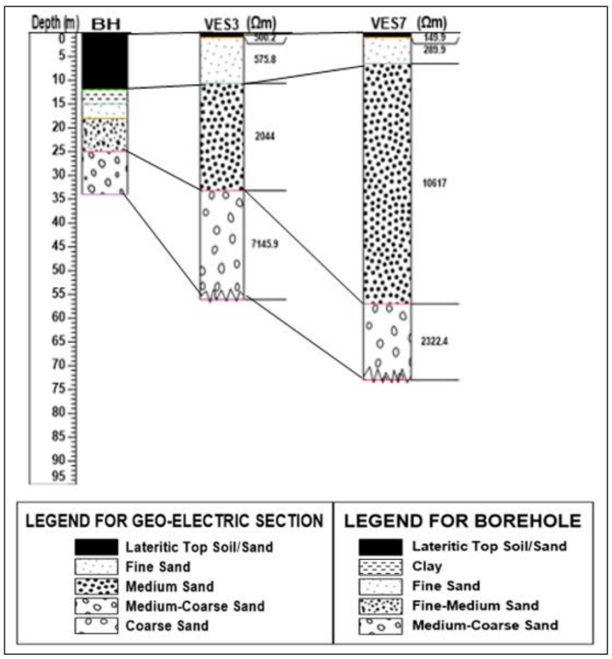
The computed transmissivity T, and hydraulic conductivity, K (Table 2, Figure 6) ranged from 1.86 m^2/day (VES 6) to 29.328 m^2/day (VES 7) and 0.045 m/day (VES 8) to 0.597 m/day (VES 5) with mean values of 10.455 m^2/day and 0.248 m/day respectively. The parameters T and K are indirect indicators of borehole yield and they help to describe groundwater movement (lateral). From Krasny's (1993) classification scheme, and used by Diloha et al. (2018); Ewusi and Seidu (2018); Youssef (2020) Chinyem (2024), low to intermediate aquifer transmitivity was identified in the area. The eastern part of the study area indicated the least transmissivity, the extreme western part showed low-intermediate transmissivity, while the southern region showed the highest ability (intermediate) to transmit water. The result of 12.455 m^2/day and 24.28 m^2/day from pumping test analysis from a borehole drilled close to VES 3 and VES 7, indicate an intermediate transmission rate of groundwater. The result also suggests a prolific aquifer with the capacity to sustain groundwater abstraction for local groundwater supply (to communities/plants). The close similarity of the obtained results from the pumping test for both T and K gives credence to the reliability of VES results in the AHP and GPC assessments in the study area.

Table 2: Summary of calculated aquifer parameters

VES No	Coordinate	$pa\ (\Omega m)$	$h(m)$	$d\ (m)$	$\sigma\ (\frac{1}{pa})$	$S(\Omega^{-1})$	$R\tau\ (\Omega m^2)$	$K\ (m$/day)	$K\sigma$	$Kp(m$ /day)	$T(m^2$/day)	$Tp(m^2$/day)
1.	N6°00'51" E6°21'12''	5944.7	52.4	57.3	0.000168	0.009	311502.3	0.117	0.000020		6.230	
2.	N6°00'54" E6°21'13''	1757.5	28.1	33.2	0.000569	0.016	49385.8	0.363	0.000207		10.223	
3.	N6°00'55" E6°21'34''	2044.0	45.3	56.0	0.000489	0.022	92593.2	0.315	0.000154	0.234	14.259	12.452
4.	N6°01'33" E6°21'26''	3608.0	51.4	58.1	0.000277	0.014	185451.2	0.186	0.000052		9.643	
5.	N6°01'07" E6°21'20''	1031.8	41.3	47.7	0.000969	0.040	42613.3	0.597	0.000578		24.630	
6.	N6°01'00" E6°21'24''	4768.8	13.0	18.8	0.000210	0.003	61994.4	0.143	0.000030		1.860	
7.	N6°01'01" E6°21'25''	1061.7	50.5	57.0	0.000942	0.048	53615.9	0.581	0.000547	0.463	29.328	24.281
8.	N6°01'51" E6°22'41''	16122.6	72.5	85.7	0.000062	0.004	1168888.5	0.045	0.000003		3.507	
9.	N6°01'10" E6°22'26''	3914.2	42.5	48.1	0.000255	0.011	166353.5	0.172	0.000044		7.320	
10.	N6°00'09"	11620.8	36.4	41.6	0.000086	0.003	422997.1	0.062	0.000005		2.115	

	E6^{0}22'23''									
11.	N6^{0}00'52" E6^{0}22'19''	7981.8	58.7	65.9	0.000125	0.007	468531.7	0.089	0.000011	5.154
12.	N6^{0}01'18" E6^{0}18'59''	3382.5	52.3	61.1	0.000296	0.015	176904.8	0.197	0.000058	10.260
13.	N6^{0}03'24" E6^{0}18'29''	1385.4	26.5	45.9	0.000722	0.019	36173.1	0.453	0.000327	12.005
14.	N6^{0}03'39" E6^{0}19'23''	4340.6	62.9	69.5	0.000230	0.014	273023.7	0.156	0.000036	9.829
	Minimum	**1031.8**	**13.0**	**18.8**	**0.000062**	**0.003**	**36713.1**	**0.045**		**1.860**
	Maximum	**16122.4**	**72.5**	**85.7**	**0.000969**	**0.048**	**1168888.5**	**0.597**		**29.328**
	Mean	**926.0**	**45.3**	**53.3**	**0.000516**	**0.016**	**250,754.9**	**0.248**		**10.455**

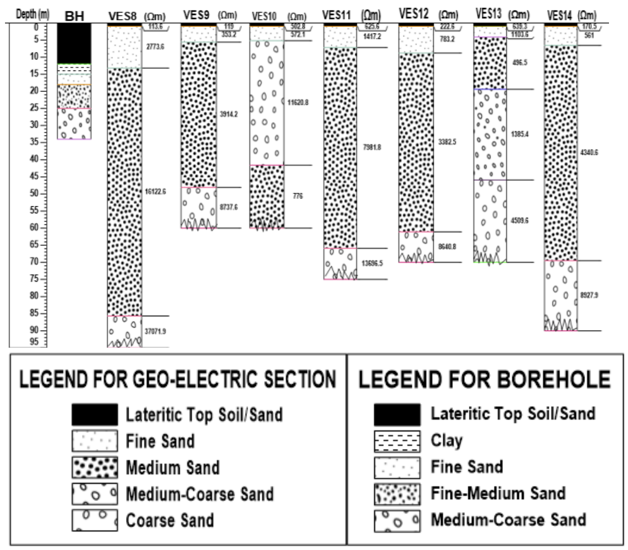
ρa = Aquifer resistivity; h = Aquifer thickness; d = Aquifer depth; σ = Aquifer conductivity; S = longitudinal conductance; R = Transverse resistance; K = Hydraulic conductivity at VES stations, Kσ = Constant; Kp = Hydraulic conductivity from pumping test; T = Transmissivity from VES data; Tp = Transmissivity from pumping test data



(a)

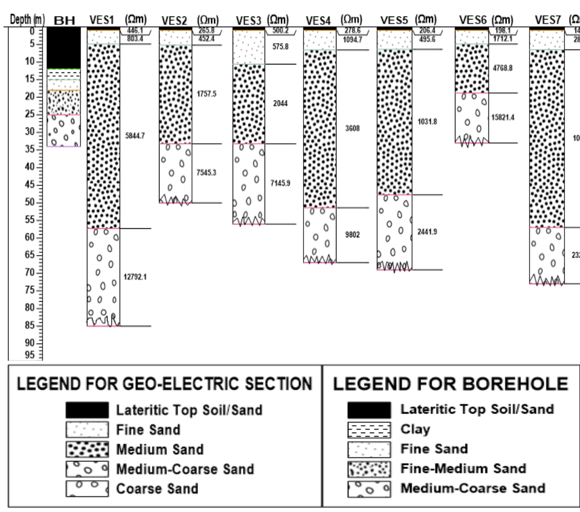
Figure 4a: Correlation of borehole log with VES 3 andVES 7

Figure 4: (b) Geo-electric section tied to borehole log across VES 1-7



(b)

Figure 4: (c) Geo-electric section tied to borehole log across VES 8-14



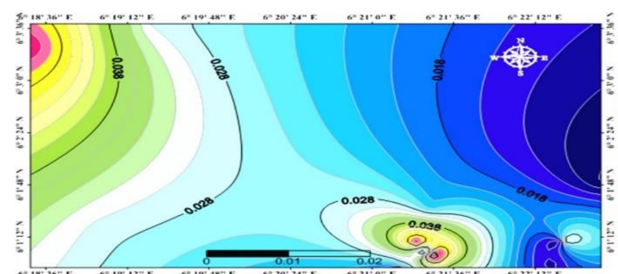


Figure 5: Longitudinal conductance map

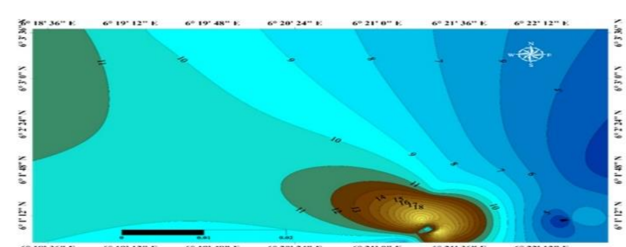


Figure 6: Aquifer transmissivity map

Conclusions

The assessment of aquifer hydraulic parameters (AHP) and groundwater protective capacity (GPC) from shallow groundwater exploration within the Ejeme-Aniogor area, revealed moderate –good groundwater prospects. The integration of VES results and borehole data (obtained from two drilled wells) indicated that prolific boreholes could be drilled to a depth range of 20 – 90 m for local groundwater abstraction to communities and plants. The computed transmissivity (T) and hydraulic conductivity (K) from the VES result showed good porosity and permeability, as confirmed by the high values of transverse unit resistance (T_R). The S value, revealed poor GPC and thus, it is recommended that boreholes drilled within the areas should be properly and adequately gravel-packed to minimize the incidence of contaminants from surface sources. Additionally, based on the results of the hydraulic conductivity obtained from the two drilled wells (borehole logs/data), the subsurface formation in the study area is highly porous, permeable, aquiferous , implying high hydraulic conductivity and intermediate transmissivity with clean sands and clay intercalations, of great potential for groundwater exploration and exploitation, typical of the Benin Formation of the Niger Delta basin. It is therefore significant that groundwater exploration requires the application of VES, as the least expensive approach in assessing AHP and GPC in Ejeme – Aniogor area. However, other aquifer evaluation approaches like the grain size distribution approach are recommended to give certainty to the results. Holistically, from these results, the success rate of drilling prolific water wells will be improved, as the average useful borehole depth to be drilled could be ascertained. It will also provide reliable and high-precision information required for aquifer characterization, regional groundwater assessment as well as groundwater protection management in Ejeme–Aniogor and beyond.

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