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GEOPHYSICAL INVESTIGATION OF AQUIFER PROTECTIVE CAPACITY IN YENAGOA AND ITS SURROUNDINGS USING DAR-ZARROUK PARAMETERS

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ABSTRACT

A geoelectrical investigation was carried out in Yenagoa and its environs to evaluate the protective capacity and groundwater potential of the aquifer system using Vertical Electrical Sounding (VES) data and Dar-Zarrouk parameters. A total of sixteen (16) VES stations were established employing the Schlumberger array configuration with maximum current electrode spacing ranging from 100 to 200 m. The interpreted geoelectric sections revealed three to five subsurface layers comprising topsoil, clay/sandy clay, and sand units of varying thicknesses and resistivities.The Longitudinal Conductance (S) and Transverse Resistance (T) values derived from the VES results were used to classify the aquifer protective capacity and transmissivity potential, respectively. The calculated S values range between 0.016 and 1.13 Ω^{-1}, indicating poor to good protective capacity, while the T values vary from 1,150 to 38,500 $\Omega \cdot m^2$, corresponding to low to very high transmissivity potential. Contour maps of S and T show that aquifers in the northern sectors are better shielded and less susceptible to pollution, while those in the SE and SW regions require careful groundwater management and monitoring..The study demonstrates the effectiveness of integrating Dar-Zarrouk parameters with resistivity data for groundwater assessment and protection zoning. It further emphasizes that aquifer productivity and protection vary significantly across Yenagoa, largely controlled by the thickness and composition of the overlying clayey layers and the nature of the underlying sandy aquifer units.

KEYWORDS: Aquifer protective capacity, Dar–Zarrouk parameters, Yenagoa, Transverse resistance, Longitudinal conductance, Geoelectrical sounding.

1.0 INTRODUCTION

With the increasing reliance on groundwater as a vital source of clean water, there is a growing need for enhanced hydrogeological understanding, advanced exploration technologies, and efficient data processing techniques to support effective investigation and evaluation of groundwater resources (Li et al., 2024). The lack of municipal water supply accounts for why water-borne diseases occur-sometimes at epidemic scale-compelling residents in the area to seek alternative water sources such as streams and boreholes (Mutono et al., 2021).

Yenagoa, located in the heart of Nigeria's Niger Delta region, faces significant challenges with water supply despite its abundant natural resources. The need to address this challenge has prompted exploration into potential aquifers as viable water sources. Traditionally, groundwater exploration in this region has relied on conventional methods, often leading to uncertainties in resource identification and utilization. However, advancements in geophysical techniques now offer a more reliable and efficient approach for delineating and evaluating groundwater potential (Nwankwo, Abam, & Giadom, 2023).

It has therefore become necessary to utilize geophysical data to gain deeper insight into the distribution and deposition of aquifer units within the study area. To achieve this, the Vertical Electrical Sounding (VES) technique is employed to evaluate the Dar–Zarrouk parameters of the subsurface materials. These parameters-such as longitudinal conductance and transverse resistance-serve as vital indicators in groundwater exploration, as they allow for the estimation of the hydrologic properties of potential aquifers, including transmissivity and protective capacity (Henriet, 1976; Zohdy et al., 1974). Near-surface geophysical methods have proven effective in mapping aquifer depth, thickness, and geometry, as well as delineating fluid migration pathways such as fractures and faults.

The electrical resistivity method, upon which VES is based, relies on the earth's response to the flow of electric current. By injecting current into the subsurface and recording the resultant potential differences, variations in resistivity with depth can be determined. The interpretation of VES data thus provides layer resistivities and thicknesses, from which the Dar–Zarrouk parameters are derived. These parameters offer a simplified but powerful means of estimating aquifer characteristics and have become a standard tool in hydrogeophysical investigations (Orellana & Mooney, 1966; Henriet, 1976).

By leveraging these methods, we can delve deeper into the subsurface landscape of Yenagoa and its surroundings to accurately assess aquifer potential. This study aims to demonstrate the effectiveness of geophysical surveys in uncovering reliable groundwater sources, challenging the notion that only subsequent methods can provide such crucial insights. Through this investigation, we seek to contribute valuable data that informs sustainable water resources management strategies tailored to the specific needs of Yenagoa and its communities.

2.0 THE STUDY AREA

The study area lies between longitudes 6°05′ and 6°40′ E of the Prime Meridian and latitudes 4°23.3′ and 4°38.2′ N of the Equator, within the coastal zone of the recent Niger Delta (Fig.1). It covers an areal extent of approximately 100 km² and experiences a tropical rainforest climate characterized by two distinct seasons: the wet season (April–October) and the dry season (November-March). According to Nwankwo, Abam, and Giadom (2023), the mean annual rainfall is about 4500 mm, with nearly 85% occurring during the wet season, serving as the major source of groundwater recharge.

The area is drained by several perennial streams, oxbow lakes, and rivers, including Kolo Creek, Epie Creek, the Yenagoa River, and the Nun River, which form an interconnected drainage network that ultimately discharges into the Atlantic Ocean through the Nun River Estuary. The region is prone to seasonal flooding, with floodwaters reaching depths of 0.5 m to 4 m during the peak of the wet season.

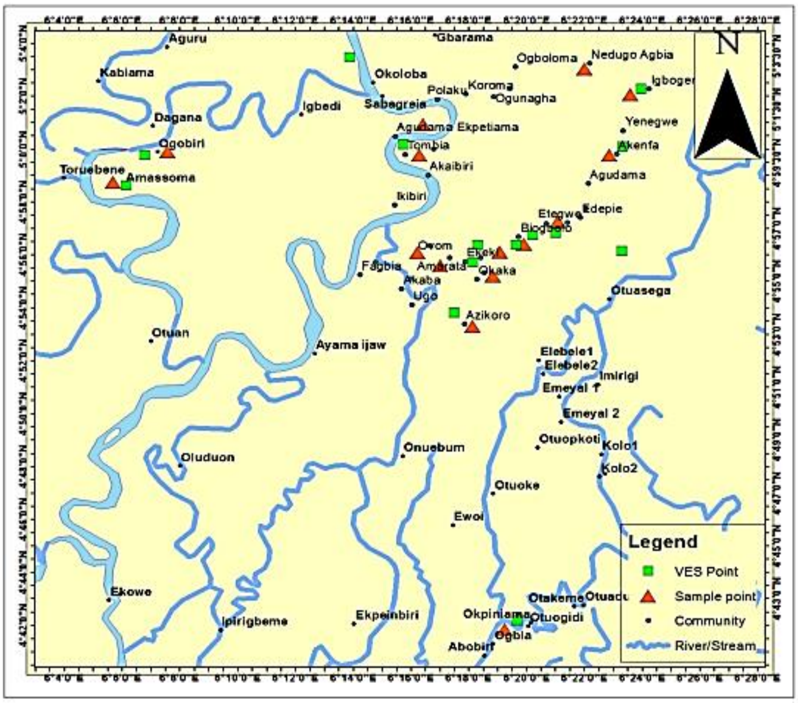

Figure: 1. Map Showing the Study Are.

2.1 Geological setting

a. Lithostratigraphy;

The regional geology of the Niger Delta was obtained from the published works of Reyment (I965); Short and Stauble, (1967); Merk, (1970). The configuration of the Pro-to Niger Delta occurred during the second depositional sequence (Campanian-Maastrichtian) of the southern Nigerian basin. Meanwhile, the present Niger Delta was shaped during the third and last depositional sequence of the Southern Nigeria basin which started in the late Paleocene.

The geology of the Niger Delta consist primarily of three lithostratigraphic units, which are overlain by the quaternary deposits. These quaternary deposits are considered generally to be the recent expressions of the Benin formation and consist of medium to coarse grained sands, sandy clays, silts and subordinate, lenstoid clay bands thought to have been deposited during quaternary interglacial marine transgressions (Durotoye 1989). It was also reported by Amajor (1991) that these sediment are an admixture of fluvial/tidal channel, tidal flats and mangrove swamp deposits. The sands are micaceous and feldspathic subrounded to angular in texture and constitute very good aquifers. However, depth to occurrence and thickness is irregular and may not be predicted with accuracy within the study area due to rapid horizontal and vertical facie changes. The three lithostratigraphic units are: Benin Formation (Top), Oligocene to Recent, Agbada Formation (Eocene), and the Akata Formation.

b. Benin Formation

This is the topmost lithostratigraphic unit, which consist primarily of about 90% sands and few shale intercalations. Shale content increases towards the base, while sand and sandstones are coarse to fine grains, poorly sorted, typically unconsolidated and regularly sub angular to well rounded texture in shape. The colour of the sand and sandstones are white to yellowish brown because of the present of limonite coats.

According to report from Onyeagocha (1980), rocks of this formation are made up of about 95-99% quartz grains, Na +K –Mica 1-2.5%, feldspar 0-1.0% and dark colored minerals 2.3%.These minerals are loosely bound by calcite and silica cement. The presence of clayey intercalations have given rise to multi-aquifer systems in the area. The Benin Formation was deposited in continentalfluviatile environment and back swamp deposits and the age of this Formation is given as Oligocene to Recent by Reyment (1965). This Formation is massively exploited for sand and ground water. The upper section of the Benin Formation is the quaternary deposits which is about 40-150m thick and comprise of sand and silt/clay with the later becoming increasingly more prominent seawards, Merki (1970). It consists of primarily freshwatercontinental friable sands and gravel that have exceptional aquifer properties with irregular intercalations of clay stone /shales.

c. Agbada Formation

Chronologically, the Agbada Formation is late Eocene to Recent as reported by Reyment (1965). This Formation underlies the Benin Formation, with thickness of 300 to 4500 m (Short and Stauble 1967). It consists mainly of an intercalation of sand, sandstone and siltstone. It is broadly, divided into two sections, the upper and the lower units. The upper unit of this formation consist of an intercalation of sandstone and shale, predominantly sandstone, the lower unit is mostly of shale, which in some areas are thicker than that of the upper unit. This Formation was deposited in paralic, brackish to marine fluviatile, coastal and fluio- marine environment. This Formation serves as the core reservoir in the Niger Delta Petroleum system.

d. Akata Formation

The Akata Formation underlies the Agbada Formation. It was deposited in a typically marine environment with maximum thickness of about 6,000 m (Ofoegbu 1985). Chronologically, the age of this formation is late Paleocene to Recent. It is composed mainly of marine shale but consists of silt, turbidite sands and silt forming sinuous lenses which are thought to have been laid down as turbidite and continental slope channel fills. Based on organic matter content, type and maturity, both marine shale Akata and the shale interbedded within the Agbada Formation are the source rocks of the Niger Delta Petroleum System.

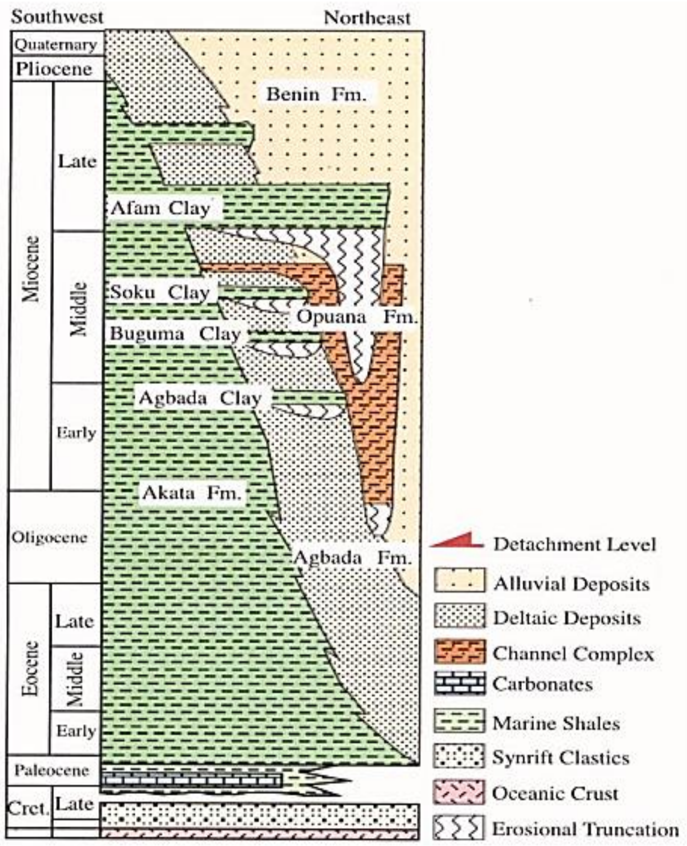

Figure 1.2. Depositional Sequence in The Niger Delta Basin after (Lawrence et al., 2002).

2.2 Hydrogeology;

The Benin Formation which is fluvial in origin is the main aquifer in the study area. Groundwater in this formation occurs mainly under unconfined conditions. Abam (1999) reported that the sediments of the Benin Formation were deposited during the late Tertiary-Early Quaternary period and is about 2100 m thick. The sediments are lenticular and unconsolidated and consists of coarse to medium – fine grained sands with localized intercalations of clay/shale. Gravel and pebbles are minor components. Mbonu et al., (1991) reported that the sands are moderately sorted and poorly cemented. The presence of thin clay beds creates discontinuities in the vertical and lateral 10 continuity of the aquifer, resulting in the presence of local perched aquifer (Amajor,1991). The aquifer is directly recharged through the infiltration of rainwater. Also the water table in many areas of the Niger Delta is close to the surface but subject to seasonal variations .In the dry season, the water table is about 3- 4 m in the study area (Ekine and Osobonye, 1996). During the rainy season, the water table rises considerably, in some cases; the surface of the ground is flooded.

3. MATERIALS AND METHOD

a, Electrical Resistivity Method

The electrical resistivity method embroils the measurement of the apparent resistivity of soils and rock as a function of depth. The most common type of electrical resistivity method used for both hydrogeological and environmental surveys is vertical electrical soundings/resistivity sounding (VES) method. In this method, a current is sent into the earth by a pair of current electrodes, and a potential difference is measured between a pair of potential electrodes. The current and potential electrodes are generally arranged in a line known as an array. The most common arrays used for this method are; Wenner array, Schlumberger array, dipole-dipole array and pole-pole array, (Alabi et al.,2010).

In this regard, the bulk average resistivity of all soils and rock influence the current that is been sent through the pairs of current electrodes. The resistivity is calculated by dividing the measured potential difference by the input current and multiplying by a geometric factor specific to the array and electrode spacing used.

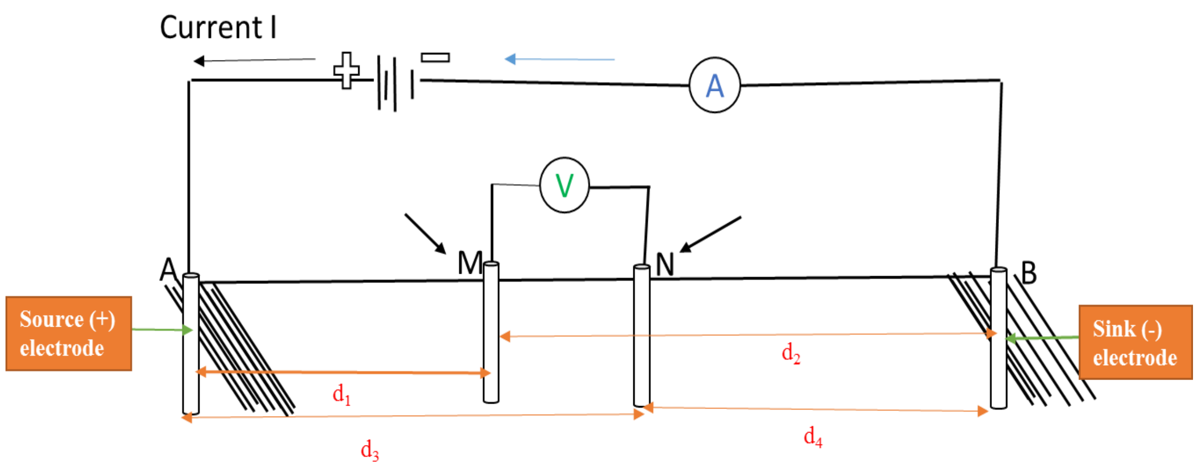

Figure 2: Generalized form of electrode configurations in VES technique.

The voltage between the inner electrodes (*M* and *N*) with respect to electrode *A* and electrode *B* respectively, can be computed as; (Sato and Mooney,1960).

$$V_M = \frac{\rho I}{2\pi}\left[\frac{1}{d_1} - \frac{1}{d_2}\right] \qquad 2.9$$

$$V_N = \frac{\rho I}{2\pi}\left[\frac{1}{d_3} - \frac{1}{d_4}\right] \qquad 2.10$$

where d_1= AM, d_2= BM, d_3= AN, and d_4= BN.

The voltage between the *M* and *N* electrodes can then be calculated as follows

$$V_M - V_N = \Delta V = \frac{\rho I}{2\pi}\left[\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right] \qquad 2.11$$

This is the potential difference that is measured by the voltmeter and is represented by V. thus equation 2.11 can be rewritten as follow for the resistivity ρ.

$$\rho = 2\pi \frac{V}{I}\left[\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right]^{-1} \qquad 2.12$$

Or

$$\rho = G\frac{V}{I} \qquad 2.13$$

Where

$$\mathrm{G} = 2\pi\left[\frac{1}{\mathrm{d}_1} - \frac{1}{\mathrm{d}_2} - \frac{1}{\mathrm{d}_3} + \frac{1}{\mathrm{d}_4}\right]^{-1} \qquad 2.14$$

Where *G* is called geometric factor or configuration factor which depends on the electrode configurations.

For inhomogeneous conditions, equation (2.13) gives the resistivity of an equivalent homogeneous half-space. For this situation the term apparent resistivity (ρ) is introduced and it will be a function of the form of the inhomogeneity. Apparent resistivity is defined as the resistivity of an equivalent electrically homogenous and isotropic half-space that would yield the potential measured on the heterogeneous earth using the same applied current.

b. Electrode Configuration in Vertical Electrical Soundings (VES)

Vertical electrical soundings (VES) are applied to a horizontally or subhorizontally layered earth. Geological targets may be, e.g., sedimentary rocks of different lithologies, layered aquifers of different properties, sedimentary rocks overlying igneous rocks, or the weathered/fractured zone of igneous rocks. The research outcome of VES is to quantity the number of layers, the thicknesses and resistivities of the layered materials. The basic idea of resolving the vertical resistivity layering is to stepwise increase the current-injecting electrodes AB spacing, which leads to an increasing penetration of the current lines and in this way to an increasing influence of the deep-seated layers on the apparent resistivity (ρ_a). The step-wise measured apparent resistivities are plotted against the current electrode spacing in a log/log scale and interpolated to a continuous curve. Common electrode configurations are the Wenner, Schlumberger and Dipole-Dipole configuration/array.

c. Data Acquisition

Data Acquisition using Vertical Electrical Sounding (VES) method The vertical electrical sounding using the Schlumberger array was carried out by applying current into the ground through two current electrodes (A and B). The potential difference (ΔV) between MN of the two potential electrodes was measured. The centre of the electrodes remain fixed, but the spacing of the electrodes were increased in other to obtain information from greater depths. Vertical Electrical Sounding using the Schlumberger array is usually done in an overlapping segment, this is because, at each phase of AB spacing the signals of the resistivity meter gets weaker. Therefore, MN spacing was enlarged and two readings for same AB/2 were measured and recorded, one for the short MN spacing and the other for the longer MN spacings. The VES was preferred, and applied in this research, not only because it is faster and less likely to be influenced by lateral variation, but because it requires a fewer number of field personnel and is cost effective. A total of sixteen (16) Vertical Electrical Soundings were carried out at different locations in the study area (Fig.1. 1). Current electrode spacing (AB/2) range between 100 – 300m while the potential electrodes separation range between 0.6 – 50 m. The data was acquired using Abem Terrameter SAS 1000. Co-ordinates of each VES point were Recorded with a hand held GPS receiver. During the acquisition of VES data, the following precautions were taken.

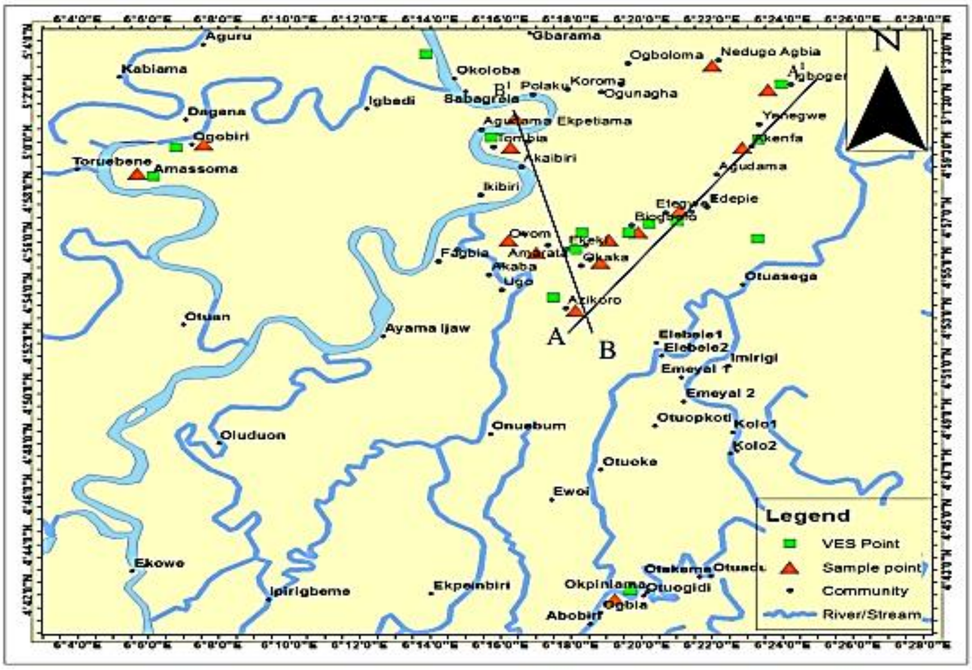

Figure: 3 Map of the study area showing VES stations and borehole locations.

Data Analysis The data was analyzed first by calculating the apparent resistivity. This was done by taking the product of the resistance value that was obtained from the resistivity meter and geometrical factor, K. ρ a = K × R where R is the value of the resistance obtained from the resistivity meter in Ohms (Ω) while K is the geometric factor. The geometrical constant was calculated using the formula, from equation.

$$K = \left[\pi\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2\right] / MN$$

Where AB ≥ 5MN, (AB) is the current electrodes spacing, while MN is the potential electrode spacing. After calculating the apparent resistivity values for each VES points, the apparent resistivity values were plotted against half-current electrode spacing (AB/2) on a log-log scale. The plot obtained yield the electrical sounding curve (field curve). Generally guided by the trend of the field curves, smoothening of the curves were made. The plots obtained constitute the field curves. There-after the data obtained was subjected to a computer assisted iterative modeling using a ID resistivity interpretation software (interplex, U.S.A). This program was used to quantitatively 24 analyze and interpret the field curves. The interpreter arbitrarily divides the subsurface into a number of horizontal layers of given thickness. The programme iteratively changes the resistivity's to obtain a best fit with the field data for layer thicknesses chosen for the model. The resulting true resistivity's represent the best average resistivity for the given layer.

d. Dar- Zarrouk Parameters

For a given layer

$$\text{Longitudinal conductance } S_L = h / \rho$$

$$\text{Tranverse resistance } T = h \cdot \rho$$

For n layers

$$S_L = \sum_{i=1}^{n} \left(\frac{hi}{\rho i}\right) = h_1/\rho_1 + h_2/\rho_2 + h_3/\rho_3 + \ldots\ldots\ldots h_n/\rho_n$$

$$T = \sum_{i=1}^{n} (hi\rho i) = h_1\rho_1 + h_2\rho_2 + h_3\rho_3 + \ldots\ldots\ldots\ldots h_n\rho_n$$

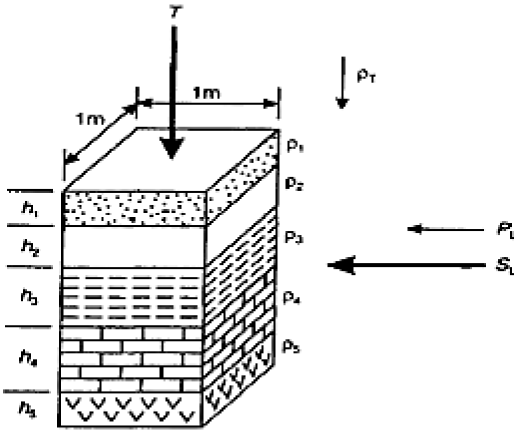

Figure 4: Three-dimensional Eletrostratigraphic model showing total longitudinal conductance (SL) and total tranverse resistance (T)] (Modified from Reynolds, 1997).

The sum of all the longitudinal conductance and of the tranverse resistance for a layer ground are called the Dar-Zarrouk „function" and „variable", respectively. The curiously named Dar-Zarrouk parameters were so called by Maillet (1947) after a place near Tunis where he was a prisoner of war. The importance of the longitudinal conductance for a particular layer is that it demonstrates that it is not possible to know both the true layer resistivity and the layer thickness, so giving rise to layer equivalence. For example, a layer with longitudinal conductance of 0.05 mS can have a resistivity of 100 ohm-m and thickness of 5 m. Layers with the combination of resistivity 80 ohm-m and thickness 4 m, and 120 ohm-m and 6 m, are all equivalent electrically.

4. RESULTS

Table 1.0. Geoelectrical Layer Parameters (Resistivity and Thickness) obtained from the Interpretation of the VES in the study area.

VES NO	Thickness of Layers (m)				Resistivity of Layers (Ohm-m)					RMS Errors (%)	Curve Type
	h_1	h_2	h_3	h_4	$ρ_1$	$ρ_2$	$ρ_3$	$ρ_4$	$ρ_5$		
1.	0.3	4.1	30.1	-	96	59	970	2178	-	1.012	HA
2.	0.3	3.5	12.7	-	27	21	321	49	-	1.031	HK
3.	1.3	9.6	25.6	-	39.2	183	1503	64.4	-	1.791	K
4.	0.9	16.3	18.8	-	230	459	601	480	-	1.403	KH
5.	1.1	2.6	13.6	-	27	195	1637	16.5	-	2.261	K
6.	0.6	1.9	8.4	42.7	35	106	2154	68	2849.5	3.414	KH
7.	0.6	2.3	5	18	16.4	14	152.2	516.9	19.7	2.692	HA
8.	0.6	7.7	27.1	-	89	62	244	212	-	1.031	HA
9.	1.1	2.2	22	-	42	7.1	137	135	-	1.112	HA
10.	0.8	2.7	12	50	175	167	20	284	30	1.906	HK
11.	1.2	10	15.5	-	27	9.2	74	228	-	1.411	HA
12.	0.3	1.7	9	26	28	100	163	355	23	1.035	HK
13.	0.4	9.2	17.2	-	88.6	36.3	137.6	1503	-	2.251	HA
14.	0.8	7.7	25.4	-	33.1	8.4	273.7	2093	-	3.902	HA
15.	1	2.97	8.2	-	192.2	277.1	366.6	126.7	-	1.251	K
16.	1.4	5.6	30.3	-	52.8	18.8	150.3	93.6	-	2.503	H

Table. 2.0: Summary of Dar-Zarrouk Parameters and Aquifer Interpretation.

VES No.	Aquifer Resistivity (Ω·m)	Aquifer Thickness (m)	Conductance (S, Ω^{-1})	Transverse Resistance (T, $\Omega \cdot m^2$)	Interpretation
VES01	970.0	30.1	0.0726	29,197.0	Weakly protected aquifer; high contamination vulnerability. High resistivity suggests clean sand and good groundwater potential. High transverse resistance indicates good aquifer transmissivity.
VES02	321.0	12.7	0.1778	4,076.7	Weakly protected aquifer; high contamination vulnerability. High resistivity suggests clean sand and good groundwater potential. Moderate transmissivity expected.
VES03	1503.0	25.6	0.0856	38,476.8	Weakly protected aquifer; high contamination vulnerability. High resistivity suggests clean sand and good groundwater

					potential. High transverse resistance indicates good transmissivity.
VES04	601.0	18.8	0.0394	11,298.8	Weakly protected aquifer; high contamination vulnerability. High resistivity suggests clean sand and good groundwater potential. High transverse resistance indicates good transmissivity.
VES05	1637.0	13.6	0.0541	22,263.2	Weakly protected aquifer; high contamination vulnerability. High resistivity suggests clean sand and good groundwater potential. High transverse resistance indicates good transmissivity.
VES06	68.0	42.7	0.0390	2,903.6	Weakly protected aquifer; Moderate transmissivity expected.
VES07	516.9	18.0	0.2337	9,304.2	Moderately protected aquifer; susceptible to

					infiltration in areas of thin clay cover. High transverse resistance indicates good transmissivity.
VES08	244.0	27.1	0.1309	6,612.4	Weakly protected aquifer; resistivity indicates moderate sand content with fair yield.
VES09	137.0	22.0	0.3361	3,014.0	Moderately protected aquifer; moderate sand content with fair yield. Moderate transmissivity expected.
VES10	284.0	50.0	0.6207	14,200.0	Moderately protected aquifer; moderate sand content with fair yield. High transverse resistance indicates good transmissivity.
VES11	74.0	15.5	1.1314	1,147.0	Moderately protected aquifer; fair groundwater quality expected.
VES12	355.0	26.0	0.0829	9,230.0	Weakly protected aquifer; high resistivity indicates clean sand and good

					groundwater potential.
VES13	137.6	17.2	0.2580	2,366.7	Moderately protected aquifer; moderate sand content with fair yield.
VES14	273.7	25.4	0.9408	6,952.0	Moderately protected aquifer; fair groundwater quality expected. High transverse resistance indicates good transmissivity.
VES15	366.6	8.2	0.0159	3,006.1	Weakly protected aquifer; high resistivity suggests clean sand and good groundwater potential.
VES16	150.3	30.3	0.32409079511512	4,554.1	Moderately protected aquifer; moderate sand content with fair yield. Moderate transmissivity expected.

Table 3.0 Showing Aquifer vs Aquitard (Hydro stratigraphic Unit).

VES No.	Aquifer Resistivity (Ω·m)	Aquifer Thickness (m)	Conductance (S, Ω^{-1})	Transverse Resistance (T, Ω·m²)	Hydrostratigraphic Unit
VES01	970.0	30.1	0.0726	29,197.0	**Aquitard**

VES No.	Aquifer Resistivity (Ω·m)	Aquifer Thickness (m)	Conductance (S, Ω^{-1})	Transverse Resistance (T, $\Omega\cdot m^2$)	Hydrostratigraphic Unit
					(Unsaturated/Dry Sand)
VES02	321.0	12.7	0.1778	4,076.7	**Aquitard (Unsaturated Sand)**
VES03	1503.0	25.6	0.0856	38,476.8	**Aquitard (Dry Sand/Gravel)**
VES04	601.0	18.8	0.0394	11,298.8	**Aquitard (Dry-Sand Transition)**
VES05	1637.0	13.6	0.0541	22,263.2	**Aquitard (Dry/Resistive Sand)**
VES06	68.0	42.7	0.0390	2,903.6	**Aquifer (Saturated Sand/Clayey Sand)**
VES07	516.9	18.0	0.2337	9,304.2	**Aquitard (Dry Sand)**
VES08	244.0	27.1	0.1309	6,612.4	**Weak Aquifer (Saturated Silty Sand)**
VES09	137.0	22.0	0.3361	3,014.0	**Aquifer (Saturated Sand)**
VES10	284.0	50.0	0.6207	14,200.0	**Aquifer (Saturated Silty Sand)**
VES11	74.0	15.5	1.1314	1,147.0	**Weak Aquifer (Clayey Sand)**
VES12	355.0	26.0	0.0829	9,230.0	**Aquitard (Unsaturated Sand)**
VES13	137.6	17.2	0.2580	2,366.7	**Aquifer (Saturated Sand)**
VES14	273.7	25.4	0.9408	6,952.0	**Aquifer (Saturated Silty Sand)**

VES No.	Aquifer Resistivity (Ω·m)	Aquifer Thickness (m)	Conductance (S, Ω^{-1})	Transverse Resistance (T, $\Omega \cdot m^2$)	Hydrostratigraphic Unit
VES15	366.6	8.2	0.0159	3,006.1	**Aquitard (Unsaturated Sand)**
VES16	150.3	30.3	0.3244	4,554.1	**Aquifer (Saturated Sand)**

Table 4.0 Classification of Longitudinal Conductance.(S)

S Range (Ω^{-1})	Aquifer Protective Capacity	Reference
< 0.10	Poor	Henriet (1976); Oladapo & Akintorinwa (2007)
0.10 – 0.19	Weak	″
0.20 – 0.69	Moderate	″
0.70 – 4.99	Good	″
≥ 5.00	Excellent	″

Table 5.0 Classification of Transverse Resistance (T).

T Range ($\Omega \cdot m^2$)	Aquifer Transmissivity Potential	Reference
< 1,000	Low	Maillet (1947); Zohdy et al. (1974)
1,000 – 3,000	Moderate	″
3,000 – 5,000	Moderate–High	″
5,000 – 7,000	High	″
≥ 7,000	Very High	″

The Dar-Zarrouk parameter analysis reveals significant spatial variation in aquifer protection and productivity across the study area.

- Areas with high longitudinal conductance ($S > 0.7\ \Omega^{-1}$) show better aquifer protection due to thick clay or lateritic overburden.
- Zones with low conductance ($S < 0.2\ \Omega^{-1}$) indicate poor protective capacity, making groundwater more vulnerable to surface contamination.

- The transverse resistance (T) values indicate that most aquifers have moderate to good transmissivity, consistent with fine to medium sand formations common in the Niger Delta region.

Table 6.0 Resistivity Classification with Hydrostratigraphic.

Resistivity Range (Ω·m)	Hydrostratigraphic Meaning	Unit Type	Source (Short Citation)
1 – 20 Ω·m	Clay, shale, silty clay; high conductivity; low permeability	**Aquitard / Confining Layer**	Orellana & Mooney (1966)
20 – 80 Ω·m	Clayey sand, poorly sorted sand; semi-permeable	**Weak Aquifer / Leaky Aquitard**	Zohdy et al. (1974)
80 – 200 Ω·m	Saturated sand, silty sand; good permeability; typical Niger Delta aquifer	**Main Aquifer (Benin Formation)**	Etu-Efeotor & Akpokodje (1990)
200 – 500 Ω·m	Coarse sand to gravel, partially saturated	**Transition Unit (May/not be aquifer)**	Parasnis (1997); Todd (1980)
> 500 Ω·m	Dry sand, unsaturated sand, gravel	**Non-Aquifer (Unsaturated Zone)**	Zohdy et al. (1974); Freeze & Cherry (1979)

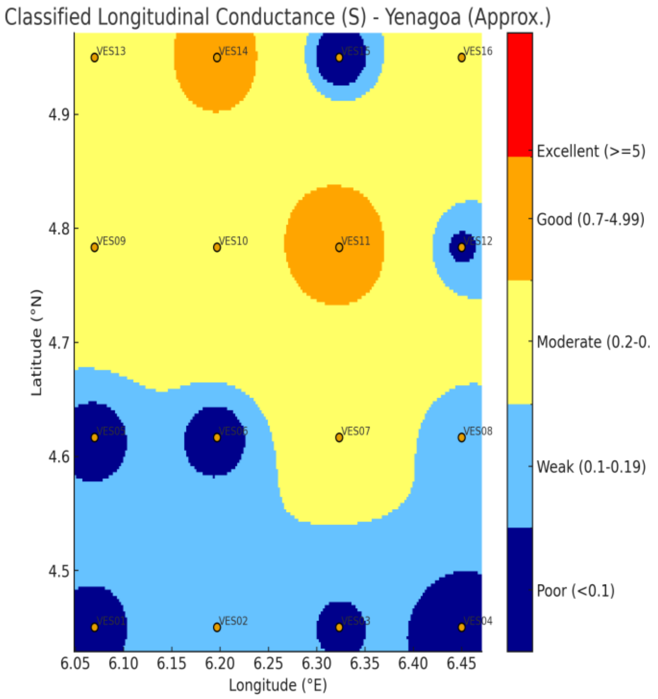

Figure 5: Classified Longitudinal Conductance (S) - color bins: deep blue (poor), light blue (weak), yellow (moderate), orange (good), red (excellent).

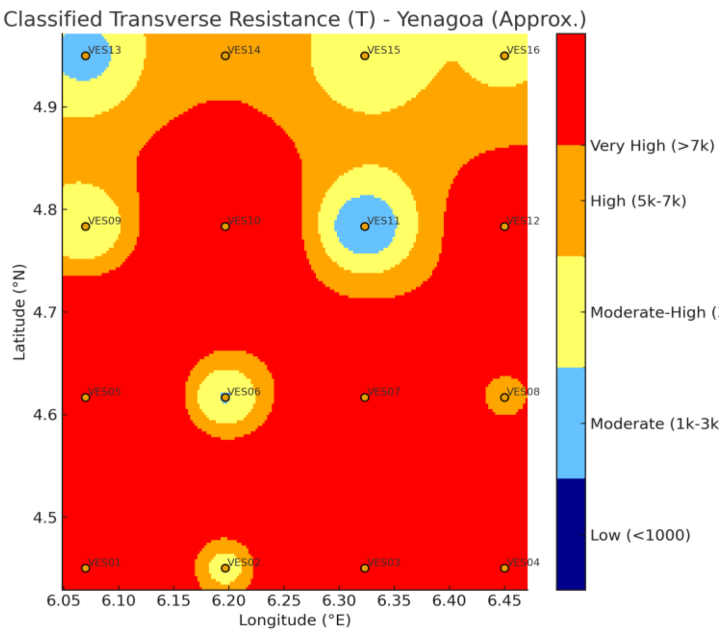

Figure 6: Classified Transverse Resistance (T) - color bins: deep blue (low), light blue (moderate), yellow (moderate-high), orange (high), red (very high).

Interpretation of Dar-Zarrouk Maps for Yenagoa and Environs

1. Longitudinal Conductance (S) Map - Aquifer Protective Capacity

Table 7.0 illustrates the spatial variation in aquifer protective capacity within the study area. The colour codes and their corresponding protective classes are presented below:

Colour	S Range (Ω^{-1})	Protective Capacity Class
□ Deep Blue	S < 0.10	Poor
◈ Light Blue	0.10 ≤ S < 0.19	Weak
□ Yellow	0.20 ≤ S < 0.69	Moderate
□ Orange	0.70 ≤ S < 4.99	Good
□ Red	S ≥ 5.00	Excellent

2 Transverse Resistance (T) Map – Aquifer Transmissivity Potential

Table 8.0 represents the variation in aquifer transmissivity potential - an indicator of the aquifer's ability to store and transmit groundwater. The classification is summarized below:

Colour	T Range ($\Omega \cdot m^2$)	Aquifer Transmissivity / Potential
□ Deep Blue	T < 1,000	Low
◈ Light Blue	1,000 ≤ T < 3,000	Moderate
□ Yellow	3,000 ≤ T < 5,000	Moderate–High
□ Orange	5,000 ≤ T < 7,000	High
□ Red	T ≥ 7,000	Very High

5. DISCUSSION

The geophysical investigation of Yenagoa and its environs using Vertical Electrical Sounding (VES) and Dar-Zarrouk parameters revealed notable spatial variations in subsurface resistivity, aquifer thickness, and protective capacity. These variations reflect the heterogeneity of the Niger Delta's depositional environment and provide valuable insights into groundwater potential and vulnerability across the study area.

The VES interpretation reveals two major lithologic groups-dry/unsaturated sands forming aquitards and saturated sandy units forming aquifers - distinguished primarily by their resistivity and thickness characteristics.

Table 1 - 3. Most of the upper subsurface layers (e.g., VES 01 - 05, 07, 12, and 15) show high resistivity values ranging from about 273 - 1,637 Ω·m with relatively thin to moderate

thicknesses (8 - 30 m). These high resistivities indicate dry, porous sands, occasionally mixed with gravel or silty materials, but with limited moisture. Because these units are largely unsaturated, they act as aquitards, restricting groundwater storage and movement despite their sandy texture.

In contrast, several VES stations mark a transition into saturated sandy or silty-sandy layers, which behave as aquifers. These locations-VES 06, 08, 09, 10, 11, 13, 14, and 16 - are characterized by much lower resistivities (approximately 68 - 355 Ω·m) and larger thicknesses ranging from 15 - 50 m. The reduced resistivity reflects increased pore-water saturation and finer-grained components, while the greater thickness enhances their groundwater potential. These units form active aquifers, particularly where clean saturated sands dominate (e.g., VES 06, 09, 13, and 16).

Some units with intermediate resistivity, such as VES 08 (244 Ω·m, 27 m) and VES 11 (74 Ω·m, 15 m), contain silty or clayey sands, resulting in reduced permeability. These are classified as weak aquifers due to partial clay content affecting groundwater transmission.
Overall, the lithologic pattern clearly distinguishes dry, resistive sand aquitards from saturated sand and silty-sand aquifers. Variations in resistivity and layer thickness across the VES points reflect the heterogeneous Niger Delta sediments, where groundwater potential is governed by both moisture content and grain-size composition.

The computed Dar-Zarrouk parameters support these findings. Longitudinal conductance (S) values across Yenagoa range from 0.016 to 1.13 Ω^{-1}, reflecting aquifer protective capacities from poor to good. Areas with higher S values ($S > 0.7\ \Omega^{-1}$) are associated with thicker clay or lateritic overburden, offering better protection against surface contamination. Conversely, zones with low S values ($S < 0.2\ \Omega^{-1}$) correspond to poorly protected aquifers where contaminants from open dumpsites or septic systems can easily infiltrate Table 2 &3.

Similarly,in Table 2 & 3, transverse resistance (T) values range from 1,150 to 38,500 $\Omega \cdot m^2$, indicating aquifer transmissivity varying from low to very high. High T zones - mainly in the central to southeastern parts suggest productive aquifers with substantial groundwater yield. In contrast, low T zones in the northern and western regions indicate thin or fine-grained sandy units with limited water-bearing capacity.

Based on the map in Fig.5 The northeastern (NE), northwestern (NW), and north-central regions of the studied ares display poor to predominantly moderate longitudinal conductance, indicating a moderate ability of the overburden to protect underlying aquifers. Conversely, the southeastern (SE) and southwestern (SW) zones exhibit poor to predominantly weak conductance, suggesting thin and less protective overburden materials, which may increase aquifer vulnerability to contamination.

Based on the map in Fig. 6 Transverse resistance analysis shows that the SE, SW, and parts of the northern regions possess moderate to generally very high T values, reflecting thicker or more resistive aquifer layers, favorable for groundwater productivity. The northern region, in particular, shows moderate to generally high transverse resistance, indicating the presence of substantial aquifer material, though not necessarily corresponding to overburden protection.
By evaluating the two parameters together, it becomes evident that:
The NE, NW, and north-central regions have moderate longitudinal conductance and moderate T values, suggesting better aquifer protection compared to the SE and SW zones. The SE and SW zones, despite having high transverse resistance (good aquifer thickness), are paired with weak longitudinal conductance, indicating less protective overburden and higher vulnerability to contamination.

Thus, aquifers in the northern sectors are relatively well protected, whereas those in the southeastern and southwestern areas may require priority attention for groundwater protection and monitoring.

Overall, the integration of S and T parameters indicates that Yenagoa’s aquifers are productive but moderately protected. Areas with high transmissivity and low conductance represent high-yield but vulnerable aquifers, while zones with moderate transmissivity and good conductance offer a more balanced hydrogeologic condition suitable for sustainable groundwater abstraction. The spatial variation in aquifer protection underscores the influence of lithologic composition, sediment thickness, and depositional setting on groundwater occurrence and quality.

These findings imply that while the region holds promising groundwater potential, its vulnerability to contamination from surface waste disposal and flood infiltration remains significant-particularly in poorly protected zones. Hence, groundwater development projects should incorporate protective well construction and periodic quality monitoring to mitigate contamination risks.

6. CONCLUSION

The study highlights that aquifers in the northern sectors are better shielded and less susceptible to pollution, while those in the SE and SW regions require careful groundwater management and monitoring. The findings underscore the importance of integrating Dar-Zarrouk parameters in assessing aquifer protection and planning sustainable water resource utilization.

7. RECOMMENDATIONS

1. **Groundwater Development:** Boreholes should preferably be sited in areas with high transverse resistance (T) and moderate conductance (S) for optimal yield and protection.
2. **Protection Measures:** Wells in low S zones should be cased and sealed properly to prevent infiltration of surface contaminants.
3. **Land-Use Control:** Waste disposal and sewage facilities should be located away from poorly protected zones to minimize leachate contamination.
4. **Monitoring and Policy:** Continuous groundwater monitoring and enforcement of groundwater protection guidelines are essential to ensure sustainability.
5. **Further Studies:** Integration with hydrochemical and microbial analyses is recommended to validate contamination risks and support regional groundwater management planning.

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