NJBAS

Available online at http://www.ajol.info/index.php/njbas/index
Nigerian Journal of Basic and Applied Sciences (December, 2022), 30(2):74-84
DOI: http://dx.doi.org/10.4314/njbas.v30i2.10

ISSN 0794-5698

Full Length Research Article

Evaluation of Aquifer Hydraulic Properties and Vulnerability Indices in Mosogar using Geoelectrical Approach

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ABSTRACT

Geophysical investigation employing vertical electrical sounding (VES), pumping test and *in situ* groundwater conductivity measurement were carried out in Mosogar, Delta State in order to determine the aquifer properties and vulnerability indices. The Schlumberger electrode configuration was used for the vertical electrical sounding (VES) survey to acquire electrical resistivity data which were interpreted using the WinResist software, version 1.0 (2004). The results revealed that the lithology is composed mainly of sand with various grades with four to five delineated geoelectric layers. Results of hydraulic conductivity, transmissivity and formation factor of the aquifer were found to vary from 7.9233 to 9.2799 m/day, 45.670 – 235.323 m^2/day and 0.545 – 23.664 respectively. Aquifer vulnerability indices within the study location indicate moderate to extremely high vulnerability as classified by aquifer protective capacity (APC), aquifer vulnerability index (AVI), Geo-electric layer susceptibility index (GLSI) and groundwater confinement, overlying strata and groundwater depth index (GOD) models employed, with values ranging from 0.00766 - 0.038728, -0.5631- 0.3025, 2.25 - 3.00 and 0.4 -0.8 respectively. The results revealed that the groundwater is prone to contamination because of weak protection provided by overlying geologic units. Using the Golden surfer 10 software, maps of geo-hydraulic parameters and vulnerability indices were constructed which characterises the aquifer parameters in the area. This study provides an important tool for sustainable groundwater exploration and management in Mosogar.

Keywords: Vulnerability index, GOD model, Geo-hydraulic parameters, Formation Factor, Aquifer

INTRODUCTION

Groundwater is the major water resource for the inhabitants of Mosogar, Delta State. This is also true for many villages and towns in developing nations, as it serves for domestic, agricultural and industrial purposes. The accessibility of groundwater has reduced the dependence on surface water, thus reducing the risk of water borne diseases which in general increases health status (Sasakova *et. al.*, 2018). As a result of the overburden materials in the Niger Delta area, shallow aquifers are susceptible to contamination from surface sources, hence, the location of permeable clean sands that are capable of yielding useful quantities of water to wells is an important consideration in water supply development (Nwankwoala and Mzaga, 2017). Knowing the aquifer hydraulic parameters like transmissivity, storativity and hydraulic conductivity, are very significant for efficient groundwater resource development and management. Pumping test is conventionally used to measure aquifer hydraulic potentials to obtain discrete information at a given location (Lu *et. al.*, 2021). However, a major limitation is the cost and labour involved to accurately cover large survey areas (Debao *et al.*, 2021). Surface geophysical methods like the vertical electrical sounding (VES) technique is non-invasive and cheap alternative to quantitative methods of determining aquifer parameters (Raji and Abdulkadir, 2020; De Almeida *et al.*, 2021). Several researchers have deployed the use of vertical electrical sounding (VES) methods for groundwater assessment and monitoring such as aquifer potential, characterisation and contamination (Anomohanran, 2015; Mgbolu *et al.*, 2019; Iserhien-Emekeme *et al.*, 2021). Mosogar is in the Niger Delta Basin characterized by three major depositional (sedimentary) environments (marine, mixed, and continental). From bottom is the basal Akata Formation which comprises predominantly of marine shales and sand beds. Overlying this Formation is the Agbada Formation consisting of interbedded sand and shales. The Benin Formation is the youngest and pierces the aquifer at every point in the modern Niger Delta. The aquiferous Sombreiro Warri Deltaic plain sand is indistinguishable from the Benin Formation (Short and Stauble, 1967).

The Benin Formation forms the major source of groundwater supply in the Niger Delta area and it underlies the Quaternary alluvial deposits of sand, silts and clay transported under different hydrological episodes and producing characteristic geomorphological sections. There is also the presence of shale intercalations that acts as protection to the sand aquifer. The hydrogeology of the area is predominantly controlled by environment of deposition and predominance of succession of sand and clays. The sand lithologic units which give rise to multi-aquifer systems in the area varied from fine to medium to coarse grain and are poorly to well sorted. The local geology shows the presence of clay, sand, pebbles, sandstone, gravel, shale, mangrove swamp, lignite, and alluvium (Short and Stauble, 1967; Ibanga and George, 2016). The best locations for citing boreholes are selected depending on the hydro-geophysical parameters derived from VES data including aquifer resistivity, aquifer thickness, longitudinal conductance, transmissivity, formation factor, and porosity. Aquifer vulnerability is another important parameter that is considered for effective groundwater resource management and contamination (Agoubi *et. al.*, 2018; George, 2021). Several methods have been used to investigate aquifer hydraulic properties and vulnerability indices in parts of the Niger Delta area (Oseji *et al*., 2018; George *et al*., 2018; Oseji *et al*., 2018; Ejiogu *et al*., 2019; George, 2021; Ibuot *et al*., 2021). Oseji *et al*. (2020) applied the first order geoelectric and Dar-Zarrouk parameters to study the aquifer in Oghara town, 5 km away from Mosogar which showed the aquifer was extremely unprotected with a capacity of less than 0.1. Also, the physiochemical analysis revealed that the groundwater is slightly acidic, a major consequence of contamination. Anomohanran *et al* (2021) employed the vertical electrical sounding, dipole - dipole and groundwater physico-chemical analysis to study the subsurface structure and aquifer vulnerability to pollution around dumpsites in Sapele. Their findings from the Da-Zarrouk parameters established that the aquifer was contaminated by the dumpsites in the area due to its poor protective capacity. Ohwoghere-Asuma, (2019) demonstrated the application of Da-Zarrouk parameters obtained from vertical electrical sounding of salt water intrusion in the coastal area of Benin River. The study revealed lateral interface between freshwater and saltwater zones around the Benin River. To the best of our knowledge, there is no published work on the application of geoelectric survey for aquifer vulnerability indices study using Da-Zarrouk parameters and other vulnerability indicators in Mosogar area. Hence, for this study, four aquifer protective indices based on geoelectric properties of the aquifer such as Aquifer Protective Capacity (APC) rating, Aquifer Vulnerability Index (AVI), groundwater confinement, overlying strata and groundwater depth index (GOD) and Geo-electric layer susceptibility index (GLSI) were used to determine the aquifer vulnerability. The purpose of this study therefore was to determine aquifer hydraulic parameters based on VES techniques with a single well pumping test to assess aquifer vulnerability index and protective capacity from contamination.

MATERIALS AND METHODS

Study Area

The study area located at Mosogar, Ethiope West of Delta State, Nigeria, lies within Lat 5° 55^{I} 5^{II} N and Long 5° 46^{I} 29^{II} E (Figure 1). The area has a tropical climate having rainy and dry seasons. The rainy season usually lasts from March to September (with a break in August), while the dry season prevails for the rest of the year. Rainfall per annum ranges from 2300 mm to 3000 mm, average temperature of 25.5 ^{0}C and average wind speed estimated at 13 km/h. The area shows the characteristics of seaward sloping flat of the Sombreiro Warri Deltaic plain sand with an elevation of about 15 m and vegetation typical of the fresh water and rain forest drainage.

Figure 1: Satellite image of Mosogar town

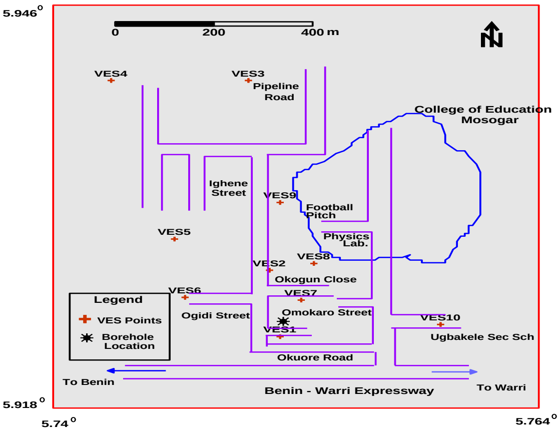

Figure 2: Map of Mosogar Town showing VES and borehole points

Vertical Electrical Sounding Data Acquisition

A total of ten vertical electrical soundings (VES) were carried out with maximum separation of current electrodes being 200 m using the ABEM SAS 1000 Terrameter employing the Schlumberger array technique, with the current and potential electrodes and other materials such as harmers, cutlasses, markers, clips, measuring tapes as well as the global positioning system (GPS). The Schlumberger technique is well documented (Obiora *et al*., 2015; Ekanem 2020, Thomas *et al*., 2020; Obiora and Ibuot 2020). The data acquisition map showing the VES stations is presented in Figure 2.

Basic Theory of the Vertical Electrical Sounding method

The potential electrodes were installed at the centre of electrode array with a small separation, typically less than one fifth of the spacing between the current electrodes. The apparent resistivity (ρ_a) was determined using equation 1.

$$\rho_a = \pi.\left(\frac{\frac{AB^2}{2}-\frac{MN^2}{2}}{MN}\right)\frac{\Delta V}{I} \qquad (1)$$

where AB and MN are the separation between the current electrode pair and the potential electrode pair respectively. Also, I is the injected current and ΔV the measured potential difference.

Vertical Electrical Sounding Data Processing

The modeling of the electrical resistivity results obtained from the field survey was done by plotting a graph of the apparent resistivity (ρa) against half the current electrode spacing on bilogarithmic coordinates for all sounding stations and using the curve matching procedure. This procedure utilises albums of theoretical curves in conjunction with auxiliary point method of partial curve matching. The obtained geoelectric layer resistivity and thicknesses were inputted into the WinResist algorithm for computer iteration (Sharma, 1997) and inversion to true geological model taking cognisance of the local geology of the area. This gave the number of geologic layers, geotechnical description and also degree of water saturation. The generated results were used to construct geoelectric sections, isoresistivity maps and aquifer thickness map.

Measurement of Water Conductivity

The conductivity of ten water samples at each VES points were measured using a digital conductivity meter and the reciprocal of the conductivity for each sample was calculated to obtain the resistivity of the water sample at each station which in turn gave the specific resistivity of pore water.

Data and Statistical Analysis

Aquifer Parameters

Aquifer parameters were calculated using different combination of the thickness and resistivity of each geoelectric layers in the model (Braga *et al*, 2006). For a horizontal, homogeneous and isotropic medium with layer resistivity ρ_i and thickness h_i, the longitudinal conductance (S_L), the total transverse resistance (T_r) and the transmissivity (T) are given by equations 2 - 4 respectively.

$$S_L = \sum_{i=1}^{n}\left(\frac{h_i}{\rho_i}\right) \qquad (2)$$

$$Tr = \sum_{i=1}^{n}(h_i p_i) \qquad (3)$$

$$T = K * h \qquad (4)$$

Formation factor quantity integrates all characteristics of the material influencing electrical current flow like the porosity and diagenetic cementation. Archie (1942) described the resistivity of saturated water clay free material as shown in equation 5,

$$F = \frac{\rho_o}{\rho_w} \qquad (5)$$

where ρ_o, ρ_w and F are resistivity of water saturated sand, pore water and Formation factor respectively.

Voids in rocks and sediments may contain air or water and this describes the porosity of the material. This fraction of void spaces ranges between 0 and 1, and basically varying from less than 0.005 for solid granite and greater than 0.5 for peat and clay. It is given by

$$\emptyset = \left(\frac{a}{F}\right)^{\frac{1}{m}} \qquad (6)$$

where $\emptyset$, F, a and m are Porosity, Formation factor, empirical constant (= 1) and cementation exponent (= 2) respectively (Agbasi, 2013). The APC, AVI, GOD and GLSI models were utilised for the study.

The Aquifer Protective Capacity (APC) or S Model is the ability of the aquifer to retain and sift the movement of potential contamination from the ground surface. This is achieved by the values obtained from the layer thickness to resistivity quotient (Henriet, 1976; Braga *et al.,* 2006; Obiora *et al*., 2020). Aquifer vulnerability index (AVI) is a procedure that determines the degree of vulnerability by hydraulic opposition to perpendicular flow of water through the overlying layers (Stempvoort *et al*., 1992). The protective layer thickness (*h*) and the calculated aquifer hydraulic conductivity (*K)* was used for the estimation of AVI. These two parameters were also used to compute the hydraulic resistance (C) expressed as

$$C = \sum_{i=1}^{n}\frac{h_i}{K_i} \qquad (7)$$

where K_i and h_i are the values of hydraulic conductivity and vadose zone thickness respectively. Hydraulic resistance (C) provides the aquitard rockability to transmit groundwater in a restricted quantity (Kruseman and De Rider 2000). The degree of vulnerability was determined by two factors, the hydraulic resistance (*C*) and the AVI. The relationship between aquifer electrical characteristics and hydraulic property gave an estimation of the aquifer hydraulic conductivity (Niwas and Singhal, 1981),

$$T = K\sigma R = K\rho S = Kh \qquad (8)$$

Where T is the transmissivity, K is the hydraulic conductivity, R is the transverse resistance of the aquifer (computed as the product of aquifer resistivity and aquifer thickness), S is the longitudinal conductance, σ is the aquifer electrical conductivity (inverse of resistivity, ρ) and h is aquifer thickness. The parameters R and S are commonly called the Dar Zarrouk parameters. According to Niwas and Singhal (1981) the product Kσ is always constant where there is no substantial disparity in the geologic setting and water quality. Thus, knowing the value of K generated from pumping test and σ from VES results around the boreholes, transmitted variation across the area was calculated through the estimation of R and S from equation 8.

GOD index

According to Oni *et al*. (2017), the GOD index involves the calculation of aquifer vulnerability index by the product of three parameters, which are, groundwater occurrence (G), lithology of overlying aquifer (O) and depth to the aquifer (D), and is expressed as

GOD Index = G × O × D (9)

Geo-Electric Layer Susceptibility Index (GLSI)

This is a groundwater measurement procedure that utilises the geo-electric parameter indices generated from the electrical resistivity difference between lithological sequences in the subsurface to assess groundwater resource vulnerability (Oni *et al.,* 2017). For GLSI evaluation, first-order geo-electric parameters of layer resistivity and thickness were ascribed indices, and this is different from the conventional longitudinal conductance approach that makes use of the ratio of the first order geoelectric parameters directly. Given that the index rating of layer resistivity and thickness are ρ_{nr} and h_{nr} respectively where n is the layer position, the GLSI was calculated from equation 10 where the number of geoelectric layers overlying the aquifer is represented as N (Oni *et al.*, 2017).

$$GLSI = \frac{\left[\frac{(\rho_{1r}+h_{1r})}{2}+\frac{(\rho_{2r}+h_{2r})}{2}+\frac{(\rho_{3r}+h_{3r})}{2}+\dots+\frac{(\rho_{nr}+h_{nr})}{2}\right]}{N} \quad (10)$$

The assigned parametric indices are normalized by dividing total layer index rating by N, which is the inferred layers above the aquifer.

RESULTS AND DISCUSSION

The layer resistivity and thickness values obtained were interpreted for the ten locations of VES in the study area (Table 1). The interpreted sounding curves were used to generate columnar geoelectric section (Figure 3). The section identified five geoelectric layers which include the topsoil, lateritic sand, fine grain sand, fine to medium sand and coarse sandy. The minimum value of aquifer resistivity (343.0 Ω-m) was recorded in VES 1 and the maximum value (13257 Ω-m) was observed in VES 7. The aquifer resistivity spatial distribution plot is shown in Figure 4. The aquifer thickness was found to be minimum (5.6 m) at VES 2 and maximum (29.6 m) in VES 4 which is an indication that areas around VES 2 will be more prolific in groundwater production. Also, the aquifer thickness spatial distribution plot is shown in Figure 5.

Table 1: Geoelectric layer resistivity and thickness obtained in the study area from VES computer iteration

VES stations	Resistivity (Ωm)					Thickness(m)				Depth (m)			
	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4	d_1	d_2	d_3	d_4
VES 1	160	212	453	343	655	1	1.2	6.1	23.8	1	2.2	8.2	32
VES 2	3720	7028	7414	5813	-	1.1	3.3	5.6	-	1.1	4.4	10	-
VES 3	573	701	596	853	1559	1.1	1.2	4.1	19.6	1.1	2.3	6.3	25.9
VES 4	324	181	600	743	1009	0.8	1.6	8.9	29.6	0.8	2.4	11.3	40.9
VES 5	76.3	579	879	656	1564	0.5	2.8	0.9	10.7	0.5	3.3	4.2	14.9
VES 6	333	246	596	846	1102	1.1	0.7	5.2	20.1	1.1	1.8	7	27.1
VES 7	1028	1508	13257	8099	-	1	2.1	19	-	1	3.1	22	-
VES 8	217.6	573.6	402.8	839.3	29395	1	5.3	9.6	28	1	6.4	16	44
VES 9	83.2	213.8	3657	13608	-	1	1.2	7.4	-	1	2.2	9.6	-
VES 10	1092	6221	4447	10497	-	0.8	2.9	17	-	0.8	3.7	21	-

VES = vertical electrical sounding.; ρ_1.... ρ_5 = resistivity of layers 1 - 5.; h_1..... h_4 = thickness of layers 1 - 4.;h_1-h_4 = depth of layers 1 – 4

Other hydro-geoelectrical parameters were evaluated which include longitudinal conductance, transmissivity, formation factor, and porosity as shown in Table 2. These parameters represent the most influential factors and reflect the quantity and quality of potential groundwater which was extracted from the aquifer in the area. The numeric value of k (hydraulic conductivity) obtained from a single well pumping test conducted in the study area was given as 7.91 m/day. This factor described the dynamic characteristics of hydrogeologic unit which allows the passage of groundwater and also affects the yield of wells and flow of contaminants. Longitudinal conductance was observed to be minimum (0.00073 mhos) at VES 2 and maximum (0.6950 mhos) at VES 1 while the transverse resistance was low in VES 5 (7019.20 Ωm^2) and high at VES 7 (24923.60 Ωm^2). The computed Hydraulic conductivity was minimal at VES 1 (7.9233 m/day) and maximum (9.2799 m/day) at VES 7 while the transmissivity is low (45.670 m^2/day) at VES 2 and high (235.323 m^2/day) at VES 4.

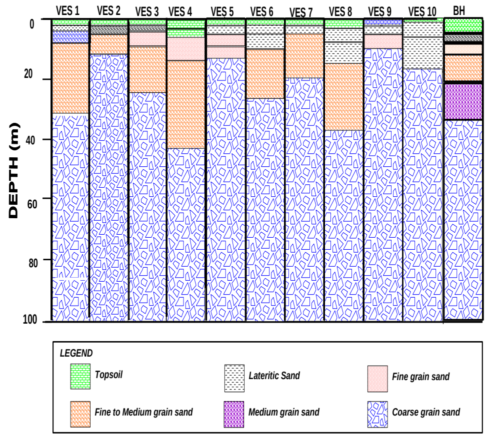

Figure 3: Geoelectric Columnar sections from the VES data inversion

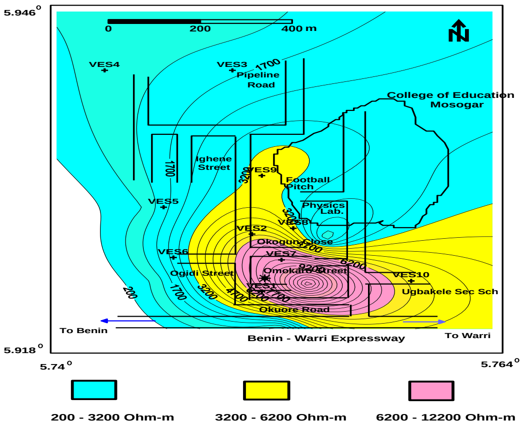

Figure 4: Aquifer resistivity map of the study area

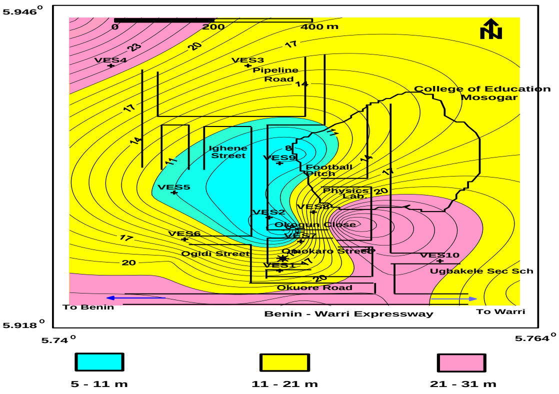

Figure 5: Aquifer thickness map of the study area

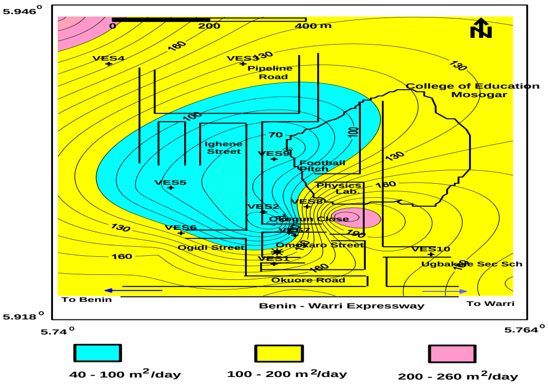

Figure 6: Aquifer transmissivity map of the study area

The spatial dispersion of transmissivity is given in Figure 6. High transmissivity zone corresponds with high aquifer thickness which explains that the aquifer around that area is more prolific. From the classification of transmissivity by Gheorghe (1978) and hydraulic conductivity by Vrbka, *et al*. (1999), the range of values obtained in the study area showed that aquifer has moderate high yield potential and also permeable. The formation factor was the least (0.545) at VES 1 and was maximum (23.664) at VES 7. The spatial distribution of formation factor is shown in Figure 7. The low formation factor values which correspond to areas with low hydraulic conductivity is an indication of the presence of finer geologic particles. This is also applicable to the maximum formation value of 23.664, which indicates the presence of particles with bigger diameter and higher hydraulic conductivity (Soupios *et al*., 2007).

Aquifer Vulnerability Indices

The classification of the vulnerability indices based on the AVI, GLSI, GOD and APC model is presented in Table 3. Aquifer vulnerability is classified as extremely high, moderate, and high according to AVI, GLSI and GOD model respectively.

The AVI Model

The AVI model when compared with standard vulnerability classification (Table 4) by Thomas and Yusrizal (2018) showed that the aquifer vulnerability in the area is mainly weak and is prone to contamination.

Table 2: Calculated aquifer parameters generated from first order geoelectric values and borehole pumping test

VES stations	ρ_a (Ωm)	h_a (m)	σ $(\Omega m)^{-1}$	S $(\Omega)^{-1}$	T_r (Ωm^2)	K(pumping Test)	Tc (m^2/day)	K_c(m/day)	ρ_w (Ωm)	F
VES 1	343.0	23.8	0.00292	0.06939	8163.40	7.910	188.575	7.9233	628.90	0.545
VES 2	7414.0	5.6	0.00013	0.00076	41518.40	7.910	45.670	8.1554	610.13	12.152
VES 3	853.0	19.3	0.00117	0.02263	16462.90	7.910	153.105	7.9329	778.21	1.096
VES 4	743.0	29.6	0.00135	0.03984	21992.80	7.910	235.323	7.9501	711.23	1.045
VES 5	656.0	10.7	0.00152	0.01631	7019.20	7.910	84.932	7.9376	825.08	0.795
VES 6	846.0	20.1	0.00118	0.02376	17004.60	7.910	159.843	7.9524	691.56	1.223
VES 7	13257.0	18.8	0.00008	0.00142	249231.60	7.910	174.462	9.2799	560.22	23.664
VES 8	839.3	28.0	0.00119	0.03336	23500.40	7.910	223.254	7.9734	151.06	5.556
VES 9	3656	7.4	0.00027	0.00202	27054.40	7.910	59.520	8.0432	273.97	13.345
VES 10	4447.4	17.3	0.00022	0.00389	76940.02	7.910	138.492	8.0053	541.42	8.214

VES stations = vertical electrical sounding stations.; ρ_a = aquifer layer resistivity ; h_a = aquifer layer thickness; σ = aquifer electrical conductivity
S = longitudinal conductance; Tr = transverse resistance; K(pumping Test) = hydraulic conductivity from pumping test; Tc = calculated transmissivity;
K_c = calculated hydraulic conductivity; ρ_w = pore water resistivity; F = formation factor.

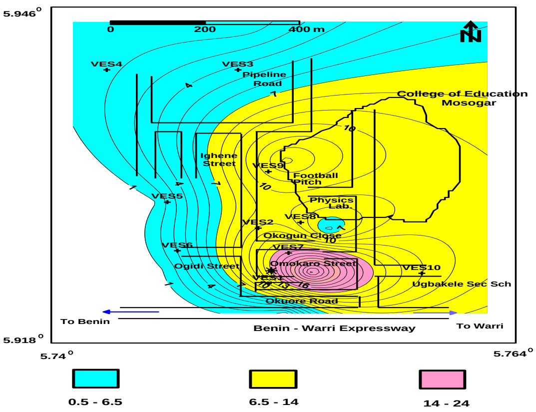

Figure 7: Formation factor map showing ratio of water saturated sand resistivity and pore water

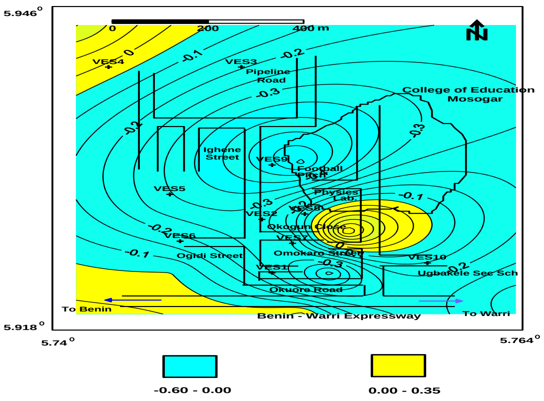

Figure 8: AVI Map showing overlying layers degree of hydraulic opposition

Table 3: Summary of inferred vulnerability indices across Mosogar

VES Point	AVI	GLSI index	GOD Index	APC rating
VES 1	0.015	2.50	0.56	0.025376
VES 2	-0.268	2.25	0.54	0.000766
VES 3	-0.1001	2.33	0.64	0.010511
VES 4	0.1528	2.50	0.56	0.026142
VES 5	-0.2765	2.50	0.40	0.012413
VES 6	-0.0555	2.50	0.80	0.014874
VES 7	-0.4762	2.25	0.42	0.002366
VES 8	0.3025	2.00	0.48	0.038128
VES 9	-0.5631	3.00	0.45	0.017632
VES 10	-0.3352	2.25	0.54	0.001199

AVI = aquifer vulnerability index.; GLSI index = Geo-Electric Layer Susceptibility Index; GOD Index = groundwater occurrence (G), lithology of overlying aquifer (O) and depth to the aquifer (D); APC rating = aquifer protective capacity rating

Table 4: AVI and hydraulic resistance relationship for vulnerability classification

Hydraulic resistance (C)	log C	Vulnerability (AVI)
0–10	< 1	Very high
10–100	1–2	High
100–1000	2–3	Moderate
1000–10,000	3–4	Low
>10,000	> 4	Very low

C = hydraulic resistance; AVI = aquifer vulnerability index (classification described by Thomas and Yusrizal (2018))

The hydrogeological parameters computed from geoelectric data in the form of hydraulic conductivity, aquifer type, and groundwater level depth has a significant effect on the vulnerability. The AVI map shows a distribution from -0.5631 - 0.3025 (Figure 8), which is generally <1 and this is an indication that the aquifer has elevated susceptibility to contamination from the materials on top of it.

The GLSI Model

The ascribed values for inferred lithology based on resistivity and thickness in the GLSI model is given in Table 5 (Oni *et al*., 2017). The rating of vulnerability index classification on the strength of GLSI is summarized in Table 6. The GLSI values obtained across the study area varies from 2.25 - 3.00. This value when compared with the standard index in Table 6 implied that the aquifer is characterised by moderate to high vulnerability because of the protective capacity of overlying bed.

Table 5 : GLSI rating for groundwater resource inferred vulnerability from resistivity and thickness values

Resistivity range (Ω-m)	Lithology	Susceptibility index rating	Thickness (m)	Index rating
< 20	Clay/silt	1	< 2	4
20 – 50	Sandy clay	2	2–5	3
51 – 100	Clayey sand	3	5–20	2
101 – 150	Sand	4	> 20	1
151 – 400	Lateritic sand	2		
>400	Laterite	1		

Table 6: GLSI parametric rating for aquifer vulnerability in Mosogar

Index	Vulnerability rating
1.00 – 1.99	Low
2.00 – 2.99	Moderate
3.00 – 3.99	High
4.00	Extreme

Also, the GLSI index map (Figure 9) showed that the study area is largely moderately vulnerable apart from a small portion at the central part around VES 8. This means that the aquifer is not strongly protected at the event of contamination.

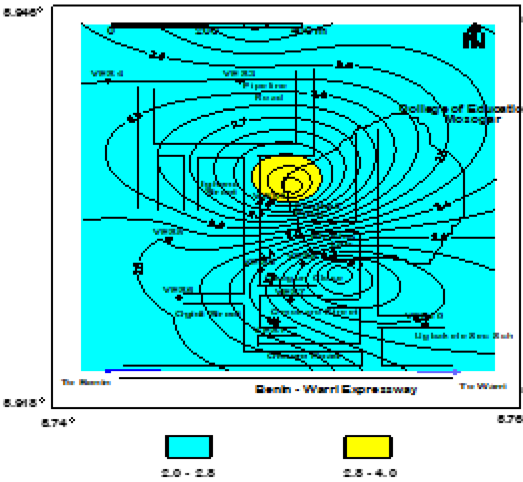

Figure 9: GLSI Index Map of the study area

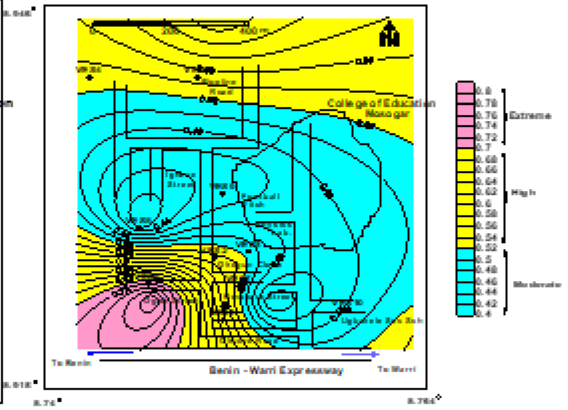

Figure 10: GOD Index Map of the study area

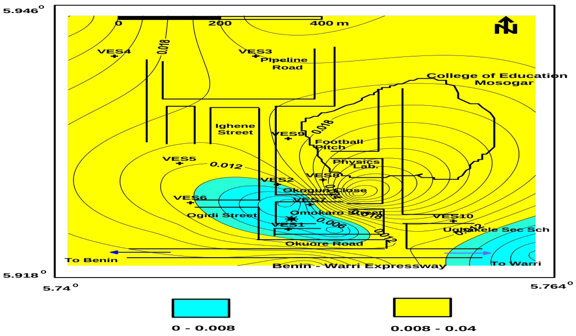

Figure 11: Aquifer protective capacity (APC) Map of the study area

The GOD Model

The ascription of values for GOD model parameters and the vulnerability rating indices (Foster and Hirata 1988; Khemiri *et al.*, 2013) are given in Tables 7 and 8, respectively and was used to attempt a vulnerability classification of the aquifer in the area of study.

Table 7: Attribution of notes for GOD index model parameters from aquifer type, lithology and aquifer depth

Aquifer type	Value	Lithology (Ω-m)	Value	Depth to aquifer (m)	Value
Non-aquifer	0	< 60	0.4	< 2	1
Artesian	0.1	60–100	0.5	2–5	0.9
Confined	0.2	100–300	0.7	5–10	0.8
Semi-confined	0.3–0.5	300–600	0.8	10–20	0.7
Unconfined	0.6–1.0	> 600	0.6	20–50	0.6
				50–100	0.5

Table 8: GOD parametric index rating for vulnerability classification

Vulnerability class	Index rating
Negligible	0.0–0.1
Low	0.1–0.3
Moderate	0.3–0.5
High	0.5–0.7
Extreme	0.7–1.0

Comparing the GOD values with the standard parametric index rating (Foster and Hirata 1988) showed that the aquifer has moderate to extreme vulnerability and this is also influenced by the characteristics of the overlying layer such as its lithology and thickness. The GOD map (Figure 10) also showed that the central part is moderately vulnerable when compared with the northern and south western part that are highly vulnerable.

APC Model

The ranking of protective capability of an aquifer described by Ofomola (2014) was given as < 0.01 (poor), 0.01 – 0.05 (weak), 0.06 –0.09 (moderate), 0.1 –0.49 (good), 0.5 –1(very good) and > 1 (excellent). The APC for Mosogar area ranged from 0.000766 to 0.038728 which signified that the aquifer has poor to weak protective capacity. This is confirmed from the APC map (Figure 11) which showed that the aquifer is highly vulnerable to contamination. All models show that the aquifer has moderate to high vulnerability to contamination. This is in agreement with most studies carried out in the central and southern part of the Delta area using Dar Zarrouk parameters, with the aquifer having weak to poor protective capacity (Iserhien-Emekeme, 2020; Oseji, *et al*., 2020; Atakpo, 2013). Ojoboh *et al*. (2020) also had 25 % low and 25 % moderate aquifer susceptibility in their study of the Warri Sombreiro deposits using VES and the neural network model. The implication is that the aquifer in Mosogar is very prone to contamination due to its moderate to extreme vulnerability established by all the models used for this study.

CONCLUSION

Aquifer first-order geo-electric indices have been successfully determined using geoelectric resistivity method. These parameters in addition to a single well pumping test results and in situ conductivity measurements have been used to estimate aquifer hydraulic properties as well as vulnerability indices in Mosogar, Delta State. Multiple aquifer systems were identified with the thickness of the major aquifer ranging from 5.6 to 29.5 m. The hydraulic conductivity ranged from 7.9233 to 9.2799 m/day, transmissivity: 45.670 – 235.323 m^2/day, and formation factor: 0.545 – 23.664. These values are indications that the aquifer is prolific with sufficient pressure to withstand pumping. Aquifer vulnerability indices calculated within the study location gave values ranged from 0.00766 - 0.038728, -0.5631-0.3025, 2.25 - 3.00 and 0.4 - 0.8 for APC, AVI, GLSI and GOD models respectively. These values compared with standard ratings indicated moderate to extremely high aquifer vulnerability as a result of the weak protection provided by overlying geologic units. Due to the elevated vulnerability indices, careless dumping of wastes from anthropogenic activities must be discouraged so as to preserve the groundwater quality.

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