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# Multi-Criteria Evaluation (MCE) Of Groundwater Potential and Vulnerability in Makurdi-Nigeria

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***Abstract***
*Ground-acquired electrical resistivity data from thirty (30) Schlumberger-VES stations in Makurdi were used to assess the groundwater potential and vulnerability indices by multi-criteria evaluation methodology. The obtained first-order geoelectric variables were exploited in calculating the geo-hydraulic parameters of the aquifer (hydraulic conductivity, resistivity, thickness, transmissivity coefficient of anisotropy) and their vulnerability appraised AVI, GOD, and GLSI indices. The results show that aquifer layers with low resistivity tend to be more saturated as a result to their immense porosity, thus displaying a higher groundwater potential compared to aquifer layers with high resistivity. The geoelectric structures defined in VES 1, 2 and 4 were consistent in their groundwater potential and yield. The AVI model rated most of the VES-locations as high to extremely high in vulnerability to pollution amplified by higher priority to the geologic lithological thickness than the essential characteristics of the geologic layers. The extent of vulnerability in the GOD model was below the AVI model because the GOD model accords greater inclination to inherent characteristics of geologic entities on the grounds of a geologic unit's grain size distribution, extent of compaction, consolidation and other implicit descriptions that alter the hydrogeophysical and geo-electrical structure of a geologic bed. AVI correlates better with GLSI models when validating the adoption of a multi-criteria evaluation methodology for aquifer vulnerability studies and are recommended for possible groundwater development planning and management*

***Keywords;*** *groundwater, VES stations, aquifer, Vulnerability, pollution*

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## I. INTRODUCTION

In the contemporary rural, sub-urban, and metropolitan areas, groundwater constitutes one of the most important natural resources that is pertinent to human existence (Abija, 2018). However, access to safe drinking water enables health, education as well as an economic measure for human development and evolution (Young *et al.*, 2021, Amorocho-Daza, *et al.*, 2023, Ejepu, *et al.,* 2024). In addition to drinking, water is needed for other domestic uses and farm irrigation for food production and sustainability of the ecology (Singh and Singh 2009).

In production and management of groundwater, it is vital to properly evaluate and have a precise definition of its potential zones which depends on porosity and permeability in the water bearing lithology. These two properties are essential to the extraction of groundwater (Chernicoff and Whitney 2009). The water bearing lithology (Aquifer) can be best described in terms of resistivity (ρ) and thickness (h) which are consistent criteria of hydrogeological interest that can be used to assess groundwater inherent in an area (Rao and Briz-Kishore 1991), cited in Adiat *et al.* (2013). These are the first-order geoelectric parameters obtained from geophysical inversion of vertical electrical sounding (VES) data. The hydraulic view of groundwater aquifers is most often predicted by analysis of pumping test data or from the first-order geoelectric parameters using numerical equations (Abija *et al.*, 2019).

Estimating the hydraulic characteristics of an aquifer allows for calculable indication of the hydraulic feedback of the aquifer to recharge and pumping and for discovering the groundwater possibility of an area (Abija *et al.* 2019). However, their measurement has been proved to be quite expensive. Evaluating the groundwater potential of an area is usually a multi-criteria process that relies on several parameters i.e. aquifer resistivity, aquifer thickness, transmissivity and coefficient of anisotropy to mention a few.

While groundwater exploration and production are crucial, the current social demand emphasizes the need for groundwater resource vulnerability/protection. Vulnerability appraisal is a comprehensive and cardinal step in examining groundwater filth (Agoubi *et al.* 2018; Rizka 2018; George 2021a). The applicability of groundwater is most often defiled by leakage of leachate plumes from landfills, oil adulteration and dissipation water (from run-off/flood, toilets, oil-ceiling pipelines, and infected vessels) (Makeig, 1982). This jeopardizes the fate of groundwater (Ugbaja and Edet. 2004), signals for worry, and the demand to experimentally depict the regularly and cost-effectively usable hydrogeological system, largely those that are bound to culpability and vulnerability from superficial intrusions (Vu *et al.* 2021).

The lithology of Makurdi has been investigated by several author (Obiora *et al.*, 2015; Hamidu *et al.,* 2024 etc), there are no documented evidences of the vulnerability of the aquifer formations hence, the focus of the present study. The aim of this study is to holistically investigate groundwater potential and vulnerability index using multi-criteria evaluation (MCE) in Makurdi, investigate and interprets the geolectrical layers from field sounding data of the study area, to evaluate the groundwater potential of the study area and evaluate and classify the vulnerability of the groundwater in the study area

**The Study Area**

The Area is positioned between latitude It is located between latitudes $7^{o} 35^{I}$ - $7^{o}53^{I}$ N and longitudes $8^{o}$ $24^{I}$ - $8^{o}$ $42^{I}$ E along the Benue River bank and covering a total land area of about 670 km². The town is drained by River Benue and its tributaries (Obiora *et al.*, 2015). The south bank has three flood plains namely: Wurukum, Wadata, and Idye. These areas are flooded in the rainy season and are highly populated. The vegetation is Guinea savannah with a few patches of forests. The annual rainfall ranges between 1,500 to 2,000 mm with its peak rainfall in the months of July and September. Temperatures in March and April are about 38 and 48°C respectively, while in December/January, the temperature is about 27°C. Makurdi, belongs to the Makurdi Formation which overlies the Albian Shale consisting of thick current bedded coarse grained deposits. The Makurdi Sandstone has a thickness of about 900 m (Offodile, 1976). The southern part of the Benue valley is generally gently undulating and punctuated by a few low hills. But toward the northeast, the relief is exaggerated by hills like the Lammuder and Ligri hills, which rise up to 600 m above sea level. Geologically, the Benue valley consists of a linear stretch of Sedimentary Basin running from about the present confluence of the Niger and the Benue rivers to the north east, and is bounded roughly by the Basement Complex areas in the north and south of the River (Figure 1). The Makurdi Formation comprises the Lower Makurdi Sandstone, the Upper Makurdi Sandstone and the Wadata limestone.

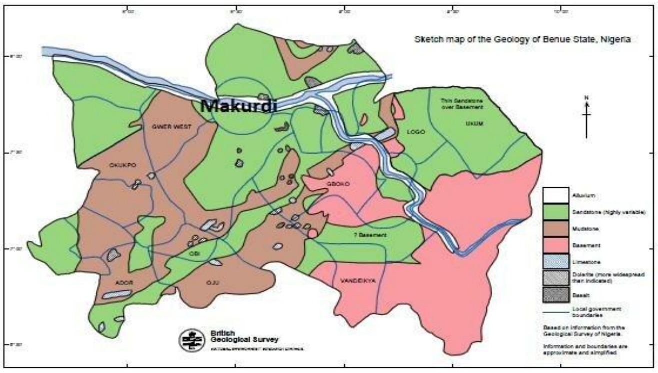


Figure 1: Geological Map of Benue State
Source: British Geological survey (2001)

## II. METHODOLOGY

**Geophysical Data Acquisition**

The geophysical investigation method adopted for the research was the electrical resistivity method.by Schlumberger array because it reveals the variation of resistivity with depth, reflecting more or less horizontal stratification of earth materials which is the basic information that is sought for. Thirty (30) Vertical Electrical Soundings (VES) survey were performed to an AB/2 depth of 100 m and were spread out uniformly across the study area to investigate the subsurface stratification. Operational procedures for VES for schlumberger array were followed At each sounding point's Geographical Positioning System (GPS) location was recorded in the Degree, Minutes and Seconds (DMS) format for each instance.

The resistance was calculated using Ohm‟s law (V=IR) from the observed current (I) and voltage (V) which was then multiplied by the geometric factor to obtain the apparent resistivity. Current electrodes were spread out concurrently to increase the depth of investigation with the potential electrode distance kept constant. Apparent resistivity against electrode spacing was plotted and interpreted to indicate vertical variations in resistivity with depth which in turns depicts the various subsurface stratification or layering. This method was extensively utilized in alleviating hydrogeological and natural problems associated with groundwater potential and vulnerability mapping (George *et al*. 2014; George *et al.* 2017; Obiora and Ibuot 2020).

**Geophysical Data Processing and Inversion**

The VES information was processed by manual curve fitting to create the resistivity demonstrate curves that were additionally curve-fitted to the auxiliary and master curves, and the layer parameters gotten were posted into the Win-Resist freeware application (Vander-Velpen, 2004) to get the one-dimensional resistivity models (which are thickness, depth and layer resistivity), from which the curve type for each VES point was implied from the four (4) recognized curves: A-curve **(ρ1<ρ2<ρ3),** H-curve (ρ1>ρ2< ρ3), K-curve (ρ1< ρ2>ρ3), Q-Curve (**ρ1**>ρ2>ρ3), KH-curve (ρ1< ρ2>ρ3< ρ4), KQ-Curve (**ρ1<**ρ2>ρ3> ρ4), and AH.

**Groundwater potential and vulnerability indices evaluation**

In this study, a Multi Criteria Evaluation Process (MCEP) was utilized in the determination of the groundwater possibility and vulnerability indices. For groundwater possibility evaluation, aquifer resistivity (ρa), aquifer thickness (ha), coefficient of anisotropy (λ), and aquifer transmissivity (Tra) were utilized:. These were mathematically defined as:

$$GW = f(\rho a, ha, \lambda, Tra) \qquad (1)$$

Where; GW is groundwater, ρa is aquifer resistivity, ha is aquifer thickness, λ is the coefficient of anisotropy and Tra is the aquifer transmissivity.

Aquifer resistivity and thickness (water column thickness) have been consistent as criteria of hydrogeologic influence that can be utilized to appraise the groundwater possibility of an area (Rao and Briz-Kishore 1991). However, some studies have shown that coefficient of anisotropy and aquifer transmissivity are important parameters to be examined in assessing the groundwater potential of an area (Abija *et al.* 2019; Olorunfemi *et al.* 1991). For the evaluation of the overburden coefficient of anisotropy (λ) the expression of Christensen (2000) was adopted as follows:

$$\boldsymbol{\lambda} = \sqrt{\frac{\sum_{i=1}^{n-1} \left(\frac{\mathrm{hi}}{\rho\mathrm{i}}\right) \sum_{i=1}^{n} (\rho\mathrm{ihi})}{\left|\sum_{i=1}^{n} hi\right|^2}} \qquad (2)$$

Where; ρi and hi are the resistivity and thickness of the layers.

The approximate purpose of the $\boldsymbol{\lambda}$ is to delimit differences in the overall thickness of low resistivity materials with diverse extents of fracturing. Fracturing aids the water – retention measure in the rock, resulting in greater porosity values (Olubusola *et al.*, 2018). For the determination of transmissivity (Tr) we adopted the expression:

$$Tr = K \times h \qquad (3)$$

Where; the transmissivity in $m^2$ /day, K is the hydraulic conductivity in m/day and h (m) is the thickness of the aquifer layer. The Tr range and groundwater potential of an aquifer system are presented by Oladapo *et al.* (2004) as cited in Abija *et al.* (2019)

The hydraulic conductivity (K) was determined from geo-electric data using the expression of Heigold *et al.* (1979) given as:

$$\mathrm{K} = 368.40\rho\boldsymbol{a} - 0.9383 \qquad (4)$$

Where; K is the hydraulic conductivity in m/day and $\boldsymbol{\rho a}$ is the aquifer resistivity in Ωm. The hydraulic conductivity specifies the affluence upon which groundwater drifts over the porous rock zones.

The MCE models for the study were; Aquifer Vulnerability Index (AVI), groundwater occurrence (G), lithology of the overlying aquifer (O), and depth to the aquifer (D) (GOD) and Geo-electric Layer Susceptibility Index (GLSI,. The two parameters were used for AVI were: the thickness (h) of the protective beds and the predicted hydraulic conductivity (K) of the protective beds. For the estimation of hydraulic conductivity (K) of the protective beds Eqn. (4) was adopted in this case $\boldsymbol{\rho a}$ was taken as a summation of the resistivity of the protective layers protruding from the aquifer layer. The hydraulic resistance (C) was predicted utilizing Eqn. (5).

$$\mathbf{C} = \sum_{i=1}^{n} \frac{\mathbf{hi}}{\mathbf{Ki}} \qquad (5)$$

The logarithm of (C) was also computed and the vulnerability index was rated for C and Log(C).

For computation of groundwater occurrence GOD Index, Eqn, (1) and GOD parametric index rating after Foster (1987) was adopted; the vulnerability index was rated using GLSI rating for resistivity parameters. For computation of the GLSI, Eqn. (3) and index rating for thickness and parametric was adopted. The vulnerability was rated using longitudinal conductance / protective capacity rating after Oladapo and Akintorinwa (2007). To calculate the Transmissivity range and Groundwater potential of aquifer system Transmissivity range and Groundwater potential of aquifer system after Oladapo *et al*,.(2004) was used. Further statistical analysis was perform by correlation of the multicriteria evaluation model at attest their performance in predicting the vulnerability of groundwater.

## III. RESULTS

### Description and Coordinates of VES Locations

The first step was to produce a base map with the use of the ArcGIS software and Google Earth; this was done to have a piece of prior knowledge on the accessibility and topography (physiography) of the study area. Table 2 is detail description of VES locations uniformly distributed within the study area and Figure 1 is the Google earth map identifying the co-ordinates and locations of the VES points**.**

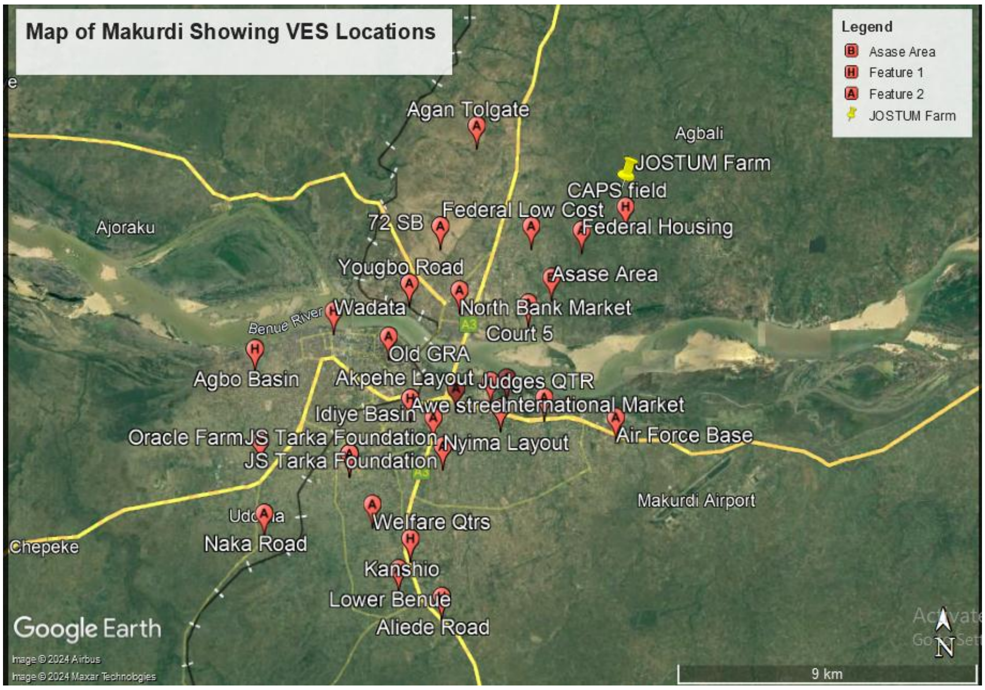


**Figure 1:** Google Earth Satellite Map of Makurdi Showing Sampling Locations

### Vertical Electrical Sounding (VES) Data

The VES is based on measuring the potentials between one electrode pair while transmitting direct current between another electrode pair. The Schlumberger array was chosen due to its better lateral resolution. The Schlumberger soundings were carried out with maximum half-current electrode spacing AB/2 of 1.0, 1.5, 2.0, 3.0, 4.5, 7.0, 10.0, 15.0, 20.0, 30.0, 45.0, 70.0 and 100 m and potential electrode MN/2 of 15.0 m. The VES interpretation from the plot of apparent resistivity against current electrode distances (AB/2) is presented in Table 1. From the plot, 5 or 4 layers were observed at various VES. The result is showing the aquifer layer resistivity, aquifer layer thickness, aquifer layer depth and the inferred lithology for VES 1-30. The minimum resistivity of 7.3 Ω was recorded at VES 30 on AB/2 spacing of 4.5 m while the maximum recorded was 6879.0 Ω at VES 9 on AB/2 spacing of 45.0 m. VES 14 recorded the lowest aquifer thickness of 0.3 m while the highest (49.3) was recorded in VES 3. The depth to water table was minimum (0.3 m) in VES 14 and maximum (86.9) in VES 20. The inferred lithology were either Lateritic top soil, clay, sandstone or sandy clay.

Table 2 is the summary of VES interpretation for model resistivity parameters (layer resistivity and thickness), estimated hydraulic conductivity, transmissivity, coefficient of anisotropy values and curve types. The curve categories consist of H, K and Q curves, with K and Q being predominant. The highest resistivity was recorded in VES 24 while VES 14 recorded the least. In terms of aquifer thickness, VES 11 is rated highest with 47.0 m while VES 19 is rated lowest with 4.6 m thickness. The highest hydraulic conductivity (34.32) was recorded in VES 19 and the lowest was 0.86 in VES 24. The transmisivity ranged between 9.8 at VES 24 and 698.7 in VES 3 classifying the groundwater into intermediate and high potentials. The coefficient of anisotropy values was highest in VES1 and lowest in VES 16 with values as 4.33 and 0.40 respectively.

**Table 1:** Interpreted Geo-Electrical Layer Result Obtained from the Plotted Graphs

| VES No. | Coordinates | Layer Resistivity (Ωm) | Layer Thickness (m) | Layer Depth (m) | Inferred Lithology |
|---|---|---|---|---|---|
| VES 1 72 SFB | N7°43'19.21'' E8°36'33.64'' | 338.3/10.2/178.9/2013.2 | 0.4/4.1/9.3 | 0.4/4.5/13.8 | Lateritic top soil/clay/ sandstone Clay |
| VES 2 Agan Tollgate | N7°44'12.37'' E8°25'12.69'' | 203.9/8.6/479.5/16.5 | 1.0/2.7/13.4 | 1.0/3.7/17.1 | Lateritic top soil/ clay/ sandstone/ siltstone/clay |
| VES 3 North Bank Market | N7°45'26.78'' E8°34'17.12'' | 187.0/63.6/342.7/19.8/43.9 | 3.3/6.3/15.8/49.3 | 3.3/9.6/25.4/74.6 | Lateritic top soil/clay / sandstone/ clayey sand/clay |
| VES 4 Old GRA | N7°44'47.78'' E8°35'01.68'' | 42.9/48.2/132.9/20.4/64.6 | 1.6/9.1/15.2/29.1 | 1.6/10.6/25.8/54.9 | Lateritic top soil /clay /sandstone/ Clay/sandy clay |
| VES 5 Federal low cost | N7°44'19.09'' E8°35'45.37'' | 54.2/12.3/95.3/73.7/716.8 | 1.4/2.6/16.2/15.9 | 1.4/4.0/20.2/36.1 | Lateritic top soil/ clay/ sandstone/sandy clay/clay |
| VES 6 Federal housing | N7°43'42.35'' E8°36'00.80'' | 50.3/422.9/40.0/96.6/119.9 | 3.3/7.0/30.0/19.6 | 3.3/10.2/0.3/59.8 | Lateritic top soil/clay/sandy clay/Sandstone/sandy clay |
| VES 7 CAPS field | N7°44'31.41'' E8°36'09.50'' | 146.2/2325.7/129.8/329.1 | 1.9/5.5/25.5 | 1.9/7.4/32.9 | Lateritic top soil/ clay/ sandstone/sandy clay |
| VES 8 JUSTUM farm | N7°45'20.38'' E8°34'54.95'' | 72.1//2353.8/150.0/29.3 | 2.8/6.3/10.5 | 2.8/9.2/19.7 | Lateritic top soil/clay/sandy clay/Clay |
| VES 9 Asase area | N7°45'13.67'' E8°35'49.77'' | 40.1/6873.2/321.6/28.3 | 0.5/6.2/8.6 | 0.5/6.7/15.3 | Lateritic top soil/ clay/ sandstone/Clay |
| VES 10 Court 5 | N7°44'38.13'' E8°36'42.18'' | 375.2/3018.9/74.8/458.1 | 2.1/7.3/27.1 | 2.1/9.4/36.6 | Lateritic top soil/clay/sandy clay/Clay |
| VES 11 Nyima layout | N7°44'26.59'' E8°36'59.75'' | 99.9/1383.5/153.7/382.5 | 0.7/4.4/47.0 | 0.7/5.1/52.1 | Lateritic top soil/clay/sandy clay/Sandstone |
| VES 12 Wadata | N7°44'39.80'' E8°37'04.87'' | 32.9/1501.9/85.7/728.2 | 0.5/3.5/19.5 | 0.5/4.0/23.5 | Lateritic top soil//lay/sandy clay/Clay |
| VES 13 Oracle Farm | N7°43'46.49'' E8°25'52.10'' | 471.5/20.5/57.5/92.9/362.2 | 0.6/5.9/22.6/11.5 | 0.6/6.5/29.1/40.6 | Lateritic top soil/ clay/ sandstone/sandy clay/clay |
| VES 14 Agbo Basin | N7°44'38.26'' E8°24'33.27'' | 4327.0/57.8/11.5/44.6/251.5 | 0.3/12.1/13.8/13.1 | 0.3/12.4/26.2/39.3 | Lateritic top soil/ sandstone/ clay/clayey sand/sandstone |
| VES 15 Idye Basin | N7°45'10.24'' E8°34'27.48'' | 33.5/326.7/78.8/23.3 | 6.0/7.0/13.0 | 6.0/13.0/26.0 | lateritic top soil/ sandstone/ sandy clay/clay |

Table 1: Interpreted Geo-Electrical Layer Result Obtained from the Plotted Graphs Cont'd

| VES No. | Coordinates | Layer Resistivity (Ωm) | Layer Thickness (m) | Layer Depth (m) | Inferred Lithology |
|---|---|---|---|---|---|
| VES 16 Naka Road | N7°44'57.91'' E8°34'46.25'' | 36.9/78.9/165.8/26.1 | 1.0/10.2/21.0 | 1.0/11.2/32.1 | Lateritic top soil/sandy clay/sandstone/clay |
| VES 17 K/Ala street | N7°44'34.84'' E8°35'21.39'' | 53.1/140.0/94.5/29.6/14.2 | 2.0/5.2/22.6/17.6 | 2.0/7.2/29.8/47.4 | Lateritic top soil/sandstone/clay/ sandy clay/clay |
| VES 18 Yougbo road | N7°44'32.03'' E8°35'25.66'' | 101.4/22.9/542.7/52.5/176.9 | 0.6/1.7/14.2/33.9 | 0.6/2.3/16.5/50.4 | Lateritic top soil/sandstone/clay/ sandy clay/sandstone |
| VES 19 Awe street | N7°44'06.14'' E8°36'05.07'' | 8.2/389.0/13.4/158.7 | 0.6/4.6/23.9 | 0.6/5.2/29.1 | Lateritic top soil/sandstone/clay/ sandy clay |
| VES 20 WurukumMkt | N7°44'15.66'' E8°36'33.48'' | 24.6/288.5/18.3/56.7 | 1.1/24.8/61.0 | 1.1/25.9/86.9 | Lateritic top soil/sandstone/clay/ sandy clay |
| VES 21 BSU Field | N7°44'28.60'' E8°36'13.77'' | 120.4/777.0/184.4/33.1 | 1.3/3.2/27.5 | 1.3/4.6/32.0 | Lateritic top soil/clay/sandstone/ Clay |
| VES 22 Judges QTRS | N7°44'52.44'' E8°35'37.49'' | 147.8/1901.9/68.4/703.6 | 1.0/5.1/25.5/ | 1.0/6.1/31.6 | Lateritic top soil/clay/sandy clay/Clay |
| VES 23 Int. Market | N7°44'54.49'' E8°44'34.36'' | 324.2/21.8/598.6/43.4 | 0.5/1.9/13.8 | 0.5/2.4/16.2 | Lateritic top soil/clay/clayey sand/Clay |
| VES 24 Akpehe layout | N7°45'36.73'' E8°34'43.58'' | 385.0/55.7/679.4/13.8 | 1.1/3.9/11.4 | 1.1/5.0/16.4 | Lateritic top soil/clay/sandstone/siltstone/clay |
| VES 25 JS Tarka Foundn | N7°45'38.66'' E8°34'44.75'' | 1278.4/431.7/121.1/41.0 | 0.4/32.0/17.3 | 0.4/32.4/49.8 | Lateritic top soil/clay/sandy clay/Clay |
| VES 26 Air force base | N7°44'57.13'' E8°36'25.64'' | 692.6/798.1/207.3/402.9/1239.1 | 5.5/11.6/22.8/18.5 | 5.5/17.1/39.9/58.5 | Lateritic top soil/clay/sandy clay/Sandstone/clay |
| VES 27 Warfare QTRS | N7°44'51.07'' E8°36'22.47'' | 2519.9/390.6/818.9/190.5/1208.4 | 0.6/4.2/11.3/26.6 | 0.6/4.8/16.1/2.7 | Lateritic top soil/sandstone/clay/ Sandstone/clay |
| VES 28 Lower Benue | N7°43'33.54'' E8°36'11.80'' | 149.8/9.7/212.4/28.5 | 1.0/2.2/14.7 | 1.0/3.1/17.9 | Lateritic top soil/clay/sandstone/ Clay |
| VES 29 Kanshio | N7°45'06.18'' E8°36'09.97'' | 301.3/1481.9/32.1/282.9/93.9 | 7.4/11.8/47.2/13.4 | 7.4/19.2/66.4/79.8 | Lateritic top soil/clay/sandy clay/Sandstone/clay |
| VES 30 Aliede Road | N7°44'41.55'' E8°35'54.07'' | 7.3/225.4/161.9/4880.4 | 0.4/9.7/13.2 | 0.4/10.1/23.3 | Lateritic top soil/clay/sandy clay/Clay |

Table 2: Summary of VES Interpretation showing the model resistivity parameters (layer resistivity and thickness), estimated hydraulic conductivity, transmissivity and coefficient of anisotropy values and curve types

| VES Stn | $\sum \boldsymbol{\rho}$ $(\boldsymbol{n-1}$ $\boldsymbol{layers}$ (n = aquifer layer) | $\sum$ $\boldsymbol{h}$ $(\boldsymbol{n-1})$ $\boldsymbol{layers}$ (n = aquifer layer) | Hydraulic conductivity $\boldsymbol{Ki}$ (m/day) | Tr<br>Tr = K $_x$ ha (m2 /day) | COA $\boldsymbol{\lambda}$ | Curve type | Remark |
|---|---|---|---|---|---|---|---|
| VES 1 | 178.9 | 9.3 | 3.0601 | 28.4589 | 4.3340 | HA | Good yield |
| VES 2 | 479.5 | 13.4 | 1.2199 | 16.3464 | 2.7053 | HKQ | Fair yield |
| VES 3 | 342.7 | 11.5 | 23.8489 | 698.7736 | 1.9248 | HKA | Good yield |
| VES 4 | 132.9 | 27.1 | 23.1940 | 674.9441 | 1.3247 | KH | Good yield |
| VES 5 | 95.3 | 13.4 | 6.9985 | 111.2768 | 1.1953 | HA | Good yield |
| VES 6 | 96.6 | 19.6 | 5.4374 | 106.5730 | 1.4422 | HKA | Good yield |
| VES 7 | 129.8 | 25.5 | 4.1277 | 105.2571 | 1.3941 | KH | Good yield |
| VES 8 | 150.0 | 10.5 | 3.6067 | 37.8707 | 1.7012 | HKQ | Good yield |
| VES 9 | 321.6 | 8.6 | 1.7707 | 15.2278 | 1.6010 | KQ | Good yield |
| VES 10 | 78.8 | 27.1 | 6.9025 | 187.0574 | 3.4545 | KHA | Good yield |
| VES 11 | 153.7 | 47.0 | 3.5257 | 130.4499 | 1.2173 | KHA | Good yield |
| VES 12 | 85.7 | 19.5 | 6.0799 | 118.5576 | 1.7521 | KHA | Good yield |
| VES 13 | 157.5 | 22.6 | 5.6391 | 64.8501 | 1.1349 | HA | Good yield |
| VES 14 | 44.6 | 13.1 | 11.1812 | 146.4736 | 2.0061 | HA | Good yield |
| VES 15 | 326.7 | 7.0 | 6.5751 | 85.4760 | 1.3778 | HKQ | Good yield |
| VES 16 | 165.8 | 21.0 | 3.2851 | 68.9861 | 0.4014 | KQ | Good yield |
| VES 17 | 140.0 | 5.2 | 16.3897 | 288.4594 | 1.3038 | HKA | Good yield |
| VES 18 | 52.5 | 33.9 | 9.6033 | 325.5522 | 1.5927 | HKA | Fair yield |
| VES 19 | 389.0 | 4.6 | 34.3273 | 820.4230 | 2.1730 | HKA | Good yield |
| VES 20 | 288.5 | 24.8 | 25.6676 | 795.6949 | 1.0617 | KH | Good yield |
| VES 21 | 184.4 | 27.5 | 2.9749 | 81.8088 | 1.0767 | KQ | Good yield |
| VES 22 | 68.4 | 25.5 | 7.5031 | 191.3294 | 2.2377 | KH | Good yield |
| VES 23 | 598.6 | 13.8 | 0.9918 | 13.6874 | 1.9243 | HKQ | Poor yield |
| VES 24 | 679.4 | 11.4 | 0.8601 | 9.8052 | 1.6702 | HKQ | Poor yield |
| VES 25 | 121.1 | 17.3 | 4.4037 | 76.1840 | 1.1260 | HKQ | Good yield |
| VES 26 | 402.9 | 18.5 | 1.4349 | 26.5462 | 0.9540 | HKA | fair yield |
| VES 27 | 190.5 | 26.6 | 2.8859 | 76.7652 | 1.5729 | HKA | Good yield |
| VES 28 | 212,4 | 14.7 | 2.6073 | 38.3279 | 1.8292 | HKQ | Good yield |
| VES 29 | 282.9 | 13.4 | 1.9956 | 26.7415 | 1.6234 | KQ | Good yield |
| VES 30 | 161.9 | 13.2 | 3.3588 | 44.3363 | 1.0205 | HA | Good yield |

Table 3 is the summary of computed Vulnerability indices and ratings in Makurdi urbam cetre. From the Table hydraulic resistance (C) was highest at VES 23 (13.91) while it was lowest at VES 19 with value as low as 0.13. The AVI index is between 0.014 (VES 20) and 1.98 (VES 25) thereby rating them as high to extremely high. Figures 2,3 and 4 represents the 3D visualization of the performance of the AVI, GOD and GLSI indices used for evaluation of groundwater potentials and the vulnerability while Figure 6 presents possible correlation that may exist between in terms of performance in predicting potentials and vulnerability.

From the plot, the AVI indicated increasing vulnerability stretching from the eastern axis towards the west. The possible reason could be increasing concentration of agricultural chemical and abattoir wastewater discharging into groundwater. The GOD index on the other hand is between 0.056 (VES14) and 0.128 (VES 9) thereby rating them as low to negligible across the

Table 3 Summary of computed Vulnerability indices and ratings in the study area

| VES Stn. | $\boldsymbol{C}$ $(\boldsymbol{Years})$ $\sum ( hi / ki )$ | Log (C) = AVI | AVI Rating | GOD Index | GOD Index Rating | GLSI | GLSI Rating |
|---|---|---|---|---|---|---|---|
| VES 1 | 3.03911 | 0.4827 | Extremely high | 0.112 | Low | 3.3066 | High |
| VES 2 | 12.050 | 1.0809 | High | 0.098 | Negligible | 8.2366 | Extreme |
| VES 3 | 0.422 | 0.3545 | Extremely high | 0.098 | Negligible | 4.2366 | Extreme |
| VES 4 | 1.1684 | 0.06758 | **Extremely high** | 0.084 | Negligible | 2.6666 | Moderate |
| VES 5 | 1.9146 | 0.2820 | **Extremely high** | 0.07 | Negligible | 1.8111 | Low |
| VES 6 | 3.6046 | 0.5568 | **Extremely high** | 0.07 | Negligible | 1.9366 | Low |
| VES 7 | 6.1777 | 0.7908 | **Extremely high** | 0.084 | Negligible | 2.5883 | Moderate |
| VES 8 | 1.8727 | 0.2724 | **Extremely high** | 0.098 | Negligible | 2.6750 | Moderate |
| VES 9 | 4.8568 | 0.6863 | **Extremely high** | 0.128 | Low | 5.5033 | Extreme |
| VES 10 | 3.9261 | 0.5939 | **Extremely high** | 0.06 | Negligible | 1.7650 | Low |
| VES 11 | 13.3306 | 1.1248 | **Extremely high** | 0.084 | Negligible | 3.3450 | High |
| VES 12 | 3.2072 | 0.5061 | **Extremely high** | 0.07 | Negligible | 1.7533 | Low |
| VES 13 | 4.0077 | 0.6028 | **Extremely high** | 0.084 | Negligible | 3.0016 | High |
| VES 14 | 1.1716 | 0.2345 | **Extremely high** | 0.056 | Negligible | 0.9616 | Low |
| VES 15 | 1.0646 | 0.0271 | **Extremely high** | 0.128 | Low | 5.5616 | Extreme |
| VES 16 | 6.3924 | 0.8056 | **Extremely high** | 0.06 | Negligible | 3.1133 | High |
| VES 17 | 0.3172 | 0.4986 | Extremely high | 0.112 | Low | 2.4200 | Moderate |
| VES 18 | 3.5299 | 0.5477 | High | 0.048 | Negligible | 1.4400 | Low |
| VES 19 | 0.1340 | 0.8728 | Extremely high | 0.144 | Low | 6.5600 | **Extreme** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| VES 20 | 0.9661 | 0.0147 | Extremely high | 0.084 | Negligible | 5.2216 | **Extreme** |
| VES 21 | 9.2440 | 0.9658 | Extremely high | 0.084 | Negligible | 3.3550 | High |
| VES 22 | 3.3981 | 0.5312 | High | 0.07 | Negligible | 1.565 | Low |
| VES 23 | 13.9140 | 1.1434 | High | 0.112 | Low | 10.4016 | Extreme |
| VES 24 | 13.2542 | 1.1223 | High | 0.084 | Negligible | 11.5133 | Extreme |
| VES 25 | 3.9285 | 1.9820 | High | 0.084 | Negligible | 2.3066 | Moderate |
| VES 26 | 12.8928 | 1.1103 | High | 0.112 | Low | 1.0233 | Low |
| VES 27 | 9.2172 | 0.9645 | **Extremely high** | 0.084 | Negligible | 3.785 | High |
| VES 28 | 5.6380 | 0.7511 | **Extremely high** | 0.098 | Negligible | 3.785 | High |
| VES 29 | 6.7147 | 0.8269 | **Extremely high** | 0.098 | Negligible | 4.9383 | Extream |
| VES 30 | 3.9299 | 0.5943 | **Extremely high** | 0.098 | Negligible | 2.9183 | Moderate |

stretch of the study area (Figure 3). Plausible reason could be discharge from localized industrial (Biotech Nig. Limited, Nigeria Breweries, Nigerian Bottling companies) effluent, agricultural herbicides and pesticides that deeperculated into the porous rock formations Figure (3). The GLSI model index is between 0.9616 in VES 14 and 11.5133 in VES 24 rating the study area as either low in the Northeast axis down and the southwest axis, moderate as you move north, west and central region but extreme at the North eastern zone (Figure 4). Figure 5 compares the performance of individual vulnerability index among the VES points while Figure 6 gives the pairwise correlations between the indices. The individual VES comparism showcases GLSI as having higher coefficient than the rest in all stations except in VES 25. The pairwise correlation was highest between GOD and GLSI

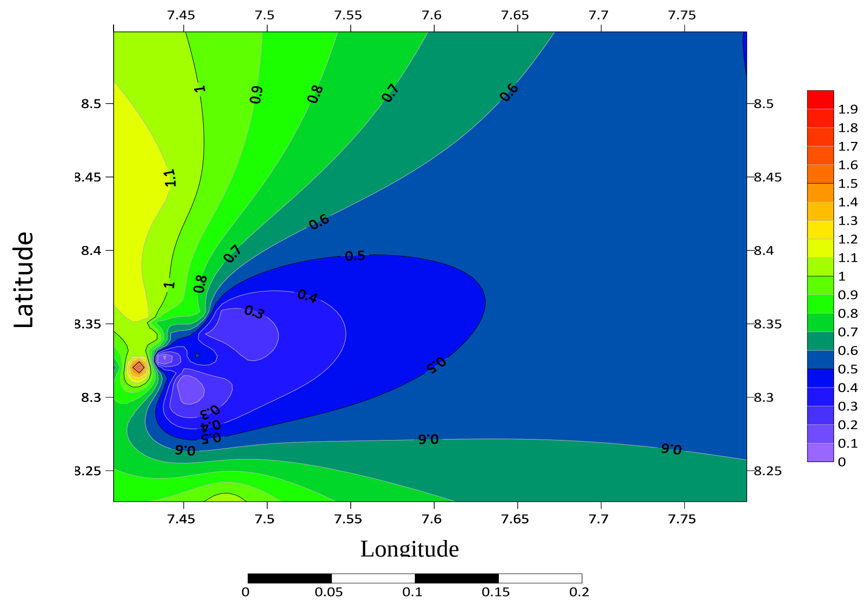


Figure 2: **AVI vulnerability rating for groundwater in Makurdi**

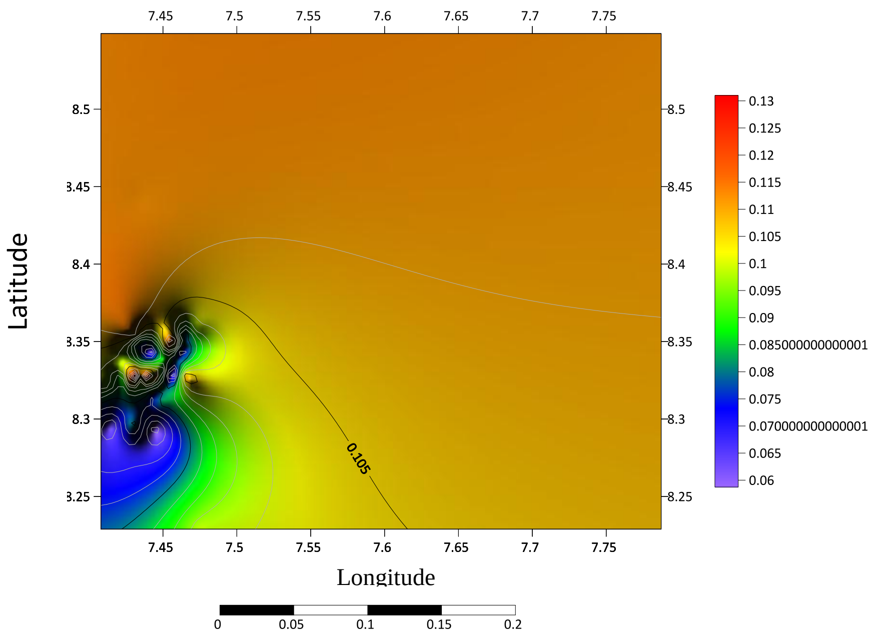


**Figure 3: GOD vulnerability rating for groundwater in Makurdi**

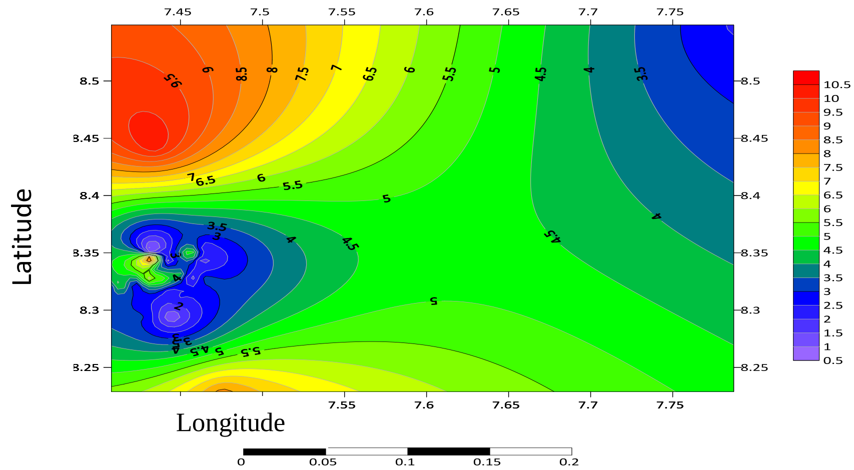


**Figure 4: GLSI vulnerability rating for groundwater in Makurdi**

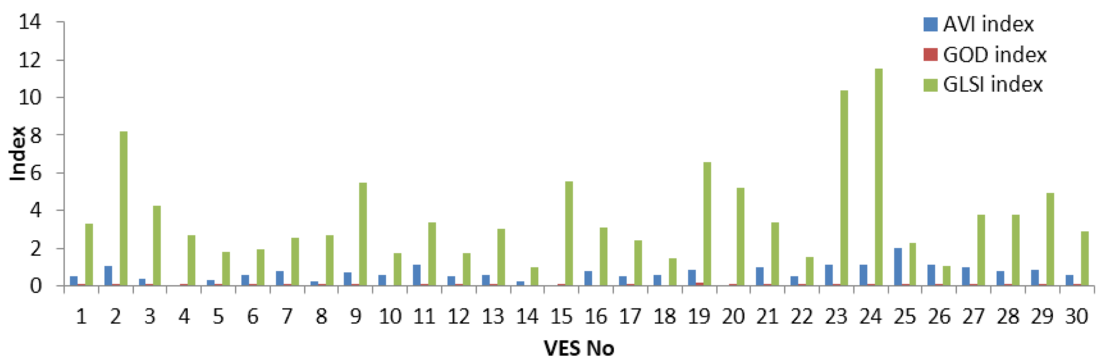


**Figure 5:** 3D Visualization of AVI, GOD and GLSI performance

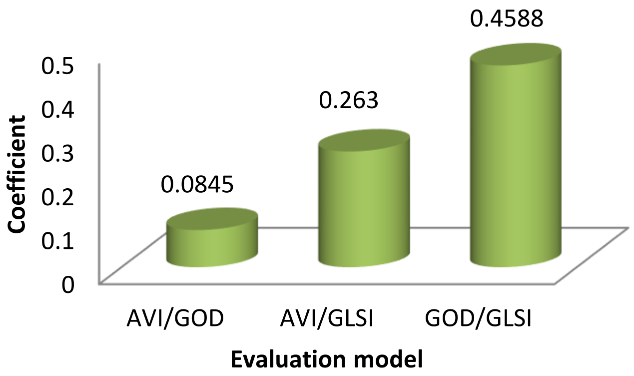


**Figure 6:** Correlation between evaluation model

## IV. DISCUSSIONS

### Geolectrical Layers

The VES points having four geo-electric layers includes; VES 1, 2, 7 – 12, 15 - 16, 19 -25, 28 and 30. The first layer is described to be the lateritic top soil, the second layer is made up of clay, the third layer which is the aquiferous unit is made up of either sandstone or sandy clay or clayey sand. However, places with aquiferous unit made up of sandstone and sandy clay have better groundwater potential. The VES point having five geo-electric layers includes; VES 3 - 6, 13 - 14, 17 - 18, 26 - 27, and 29. The layers are composed of lateritic top soil, clay/clayey sand, sandy clay/clay, sandstone/sandy clay/clay and clay in that order.

### Groundwater Potential Evaluation

The curve categories consist of H, K and Q curves, with K and Q being predominant. The aquifer resistivity, aquifer thickness, hydraulic conductivity, transmissivity and coefficient of anisotropy were utilized to evaluate the groundwater possibility of the study area. The aquifer layer resistivity depicts the alteration of resistivity in the aquifer layers at the study area. The aquifer resistivity outline demonstrates that the area is defined by plausible good groundwater yields: low, moderate and high established on their resistivity values. Essentially, resistivity in sedimentary rocks is determined by drained space, extent of sorting and grain content distribution (Reynolds 1997). Thus, within an aquifer, groundwater discharges from higher resistivity sections (with little porosity) to minor resistivity sections (with large porosity). This gives a hint that, enclosed by the aquifer, sections that are less resistive favor saturation as a result of high porosity and possess a high groundwater potential (GPZ).

The aquifers with relatively low resistivity values (,100) are found in VES 5, 10, 12, 14, 18, and 22 of the investigated areas while moderate and high values are found in VES 2, 3,4, 6, 7, 8, 9, 11, 13, 15, 16, 17, 20, 21, 23 and 24-30 locations of the study area. The aquifer layer thickness ranges from 4.6 to 49.3 m. Sections amidst thicknesses of 2.0 – 8.0 m are expressed as low, thicknesses between 10.0 and 32.0 m; 34.0 and 42.0 m are considered moderate and high respectively and these areas are found in all the VES locations of the investigated area. The hydraulic conductivity outline of the study area displays a divergence of hydraulic conductivity among the aquifer layers identified from VES 1 to 30. The hydraulic conductivity extends from 0.8601-23.8489 m/day (Table 2). These values were used in computing the transmissivity potential of the area which was further used in rating the groundwater possibility of the area.

The transmissivity shows that the groundwater prospect of the area is predominantly classified as good yield in most of the VES points with few VES locations been fair. The coefficient of anisotropy shows an approximate utility to alternate changes in the overall thickness of low resistivity aquifer formations. The estimated values of coefficient of anisotropy ranged from 1.007872 to 6.512143 (Table 2), which delineates the actual alteration of the anisotropy attribute of rock formations. The regions with high magnitudes of coefficient of anisotropy (VES 1 and 2) propose that the fracture framework in this area must have stretched in all directions inside the rock, ensuing in greater porosity as posited by Eze *et al.(*2014); Olaniyan, (2020). Additionally, zones that show low values of coefficient of anisotropy show unidirectional stretch in fracture. Consequently, such zones may not deliver good supply of water.

### Vulnerability Indices Evaluation

The vulnerability indices (AVI, GOD and GLSI) and their respective ratings are presented in Table 3. The Hydraulic resistance (C) is a vital aquifer specification that is employed in gauging the opposition of an aquifer to vertical leakage of fluid through its shielding layers, and the correlation bounded by the aquifer vulnerability index (AVI) and C and log C is shown in Table 3. The AVI rating in the majority of the VES-locations was ranked high to extremely high, and this indicates that aquifers in these locations are vulnerable to pollution. Physical appreciation of the vulnerability for AVI shown in Figure 2 proffer increasing vulnerability towards the North west, south west and south-south region of the study area which could be attributed to; nature of the rock formation, urban antropogenic activities like auto mechanic repairs stations in Northbank and Wadata that dispenses their waste into ground water, abattoir effluent waste in Northbank and Wadata that contribute to leachate in groundwater as well as agricultural pesticides and herbicides used in farms down south west and south south which contributed significantly to groundwater contamination.

The GOD-Index values in the study area is ranked negligible (0.0-0.1), low (0.1-0.3) and moderate (0.3-0.5) with most of the VES-locations. This depicts negligible to low, vulnerability index rating indicating that these locations are susceptible to vulnerability. The GOD-Index outline was fitted in distinction to the layers overlying the aquifer and it incorporates the response of noticeable layer GOD parameters (Figure 3). While the north east zone was moderate in vulnerability and stretched toward the south which could be attested to leachate from industrial sources (Bio-Tech Nig. Limited, Nigeria Breweries), the south west and other zones had low vulnerability.

The GLSI values in Table 3 were fitted from the outcome of lithology and layer thickness in the aquifer vulnerability evaluation (Figure 4). The GLSI shows that the vulnerability index rating in the study area is ranked low (0 – 21.99), moderate (2.00-2.99), high (3.00-3.99) and extremely high (≥ 4.00), with most of the VES-locations ranked moderate to high, with exception of VES 2, 3, 21 and 22 which ranked extremely high . This result pinpoints that the region is prone to vulnerability with a diversity ranging from moderate, high to extremely high vulnerability as marked in Table 12.

The MCE using hydrogeophysical criteria in sync with index-based methods facilitated the evaluation of AVI, GOD and GLSI models for aquifer vulnerability assessment. By relating the AVI, GOD and GLSI results in Table 3, some VES-locations showed convergence in their vulnerability index rating established from the hydrogeological and index-based perspectives. VES 3, 4, 19 and 20 showed high vulnerability indices adjudged from their AVI and GLSI models, VES 1, 2, 3, 11, 16, 21, 23, 24, 27 and 28 showed extremely high to high, moderate and high vulnerability indices adjudged from their AVI, GOD and GLSI models; and VES 22, 24, 29 and 30 scored negligible to moderate vulnerability indices from their GOD, AVI, and GLSI models. VES 23 and 28 scored extremely high to high vulnerability from the AVI and GLSI models, while VES 27 scored extremely high in both the AVI and GLSI indices. These findings validate the adoption of a multi-criteria evaluation methodology in aquifer vulnerability studies.

## V. Conclusion

Ground-acquired electrical resistivity data consisting of thirty (30) Schlumberger-VES were obtained in Makurdi to assess the groundwater potential and vulnerability indices of the area by means of a multi-criteria evaluation methodology. The VES data was used to obtain the first-order geoelectric variables, which were further exploited in calculating the geo-hydraulic parameters of the aquifer (hydraulic conductivity and transmissivity) and vulnerability indices (AVI, GOD, and GLSI) for an aquifer vulnerability appraisal of the area. The groundwater prospect of the area was graded based on the aquifer resistivity, thickness, transmissivity and coefficient of anisotropy values of the aquifer layers defined for VES 1-30. The results show that aquifer layers with low resistivity tend to be more saturated as a result to their immense porosity, thus displaying a higher groundwater potential compared to aquifer layers with high resistivity. The geoelectric structures defined in VES 1, 2 and 4 were consistent in their groundwater potential and yield judging from the multi-criteria evaluation employed (aquifer resistivity, thickness, transmissivity and coefficient of anisotropy values). The multi-criteria evaluation of vulnerability indices using hydrogeophysical parameters and index-based methods facilitated the computation of AVI, GOD and GLSI models for aquifer vulnerability assessment. The models depend on the symbiotic effects of geologic array and thickness as the basis for the magnitude of conservation imparted to any particular aquifer involved. The AVI model shows that most of the VES-locations were rated high to extremely high in their vulnerability and indicates that aquifers in these locations are vulnerable to pollution. The extent of vulnerability was amplified by the AVI model more than the GOD and GLSI models because the AVI model accords higher priority to the geologic lithological thickness than the essential characteristics of the geologic layers.

The extent of vulnerability in the GOD model was below the AVI model because the GOD model accords greater inclination to inherent characteristics of geologic entities on the grounds of a geologic unit's grain size distribution, extent of compaction, consolidation and other implicit descriptions that alter the hydrogeophysical and geo-electrical structure of a geologic bed.

The study also showed that the GLSI model, because of each individual's conjunction support for superimposed layer thicknesses, is a useful method for identifying hydrogeological entities that are affected by pollution. Aquifer-superimposed layers that are excessively thick may slow down the rate at which pollutants enter the aquifers underneath. The comparable zone is only somewhat susceptible to pollution from linked toxins as a result of this process, which delays and reduces contaminants resulting from the symbiotic fallout of geology and biogenic activities. By correlating the results of vulnerability index for the AVI, GOD, and GLSI models for the VES-locations, more correlation was observed for the AVI and GLSI models. These findings validate the adoption of a multi-criteria evaluation methodology for aquifer vulnerability studies and are stoutly recommended for possible groundwater development planning and management.

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