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Evaluation of Geological Formation for Sustainable Groundwater Resources in Parts of Aguata, Anambra State, Southeastern Nigeria, using Electrical Resistivity Method.

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Abstract
The study was designed to evaluate the geological formation for sustainable groundwater resources in Aguata, Anambra State, Southeastern Nigeria. Geological formation of the subsurface were investigated using the electrical resistivity methods. The study undertaken incorporates compilation and integration of the acquired VES data of 14 locations in Aguata Local Government Area and consideration of factual reviewed literature in the study area. The outcomes of the IPI2WIN modelled apparent resistivity of the near surface in this research highlight hydraulic properties of water bearing units as thus; depth 50 m – 300 m, thickness 35 m – 400 m, transmissivity 49.70 m2/day – 384.37 m2/day, hydraulic conductivity 1.5 m/day – 9.1 m/day and hydraulic resistance 36764 - 431034. Evaluation of protective capacity rating of the water bearing unit to proffer the sustainability of the groundwater resources of the study area involved knowledge of volume of shale/clay of the overburden layers which is their longitudinal conductance which ranges from 0.003 – 8.10, except VES 7 that good protective capacity (PC), other locations revealed low protective capacity (PC). The research assessed the vulnerability the water bearing units in the study area to potential sources of contamination for sustainability. The hydraulic resistance rate to contamination was evaluated extremely low as the formation of the study area do not constitute much filtering agents. The indexed low resistance of the aquifer proved the vulnerability rate of the aquifer in the study to contamination very high, only few locations tend moderate which was assessed using Groundwater occurrence, Over-layering and Depth (GOD) Indexing.

Keywords: Vertical Electrical Sounding, Over-Layering Depth, Groundwater Occurrence, Geological Formation, Good Protective Capacity.

1. Introduction

Electrical resistivity study helps to understand the subsurface for sustainability of groundwater resources. The subsurface information inferred from the application of electrical survey unveils the aquifer systems and gives more realistic picture of groundwater potential in sedimentary terrain and other geological settings. Mostly, projects of groundwater exploration are basically carried out with single geophysical techniques, especially geoelectrical methods. This method provides guidance in siting of groundwater wells, especially in developing countries [1]. these techniques have proven to be quick and reliable, in complex geological or hydrological settings, in regards, a single technique may not serve efficiently and give the information required to access groundwater resource and flow dynamics. The use of electrica resistivity method does not only obtain the type of rock layers, but can also be used to interpret potential groundwater such as aquifer depth and its rate of distribution in the subsurface. Groundwater movement can also be investigated based on the type of rock layers through their revealed resistivities using the geophysical exploration methods. According to Eslamian (2014) groundwater movement can be investigated with hydrogeochemical modeling. From the Geoelectric section the relationship between hydraulic parameters and geoelectric properties of aquifer with a mathematical formulation such as hydraulic conductivity value, transmissivity, and storativity can be shown. The aim of employing geoelectric survey using vertical electrical sounding is to determine the subsurface resistivity by measuring the surface of the earth. Resistivity of the earth materials is related to minerals, fluid content and degree of water saturation in rocks. The accessibility to potable water is an essential matter in the universe. Naturally the only reliable water supply for drinking and irrigation purposes happened to base on groundwater.

2. The Study Area

2.1 Location and Accessibility

The study covered two locations in the towns of Aguata local government area in Anambra State, Southeast Nigeria. Aguata LGA in Anambra State is made up of the following 14 towns; Ekwulobia, Akpo, Achina, Uga, Igbo – Ukwu, Isuofia, Umuchu (Umuchukwu), Aguluezechukwu, Ezinifite, Ikenga, Amesi, Ora-eri, Umuona and Nkpologwu. This research focused on the application of principles of electrical resistivity study of geological formations to ensure sustainable resources in parts of the towns the Aguata LGA, Anambra State, Nigeria. The study area lies within the southeast of Anambra State on Latitude: 6° 55' N and 6° 58' N and Longitude: 6° 58' E and 7° 10' E (Figure. 1). Aguata is bounded at the north by Orumba North LGA, Orumba South LGA at the East, at the west by Nnewi South LGA, north-west by Aniocha LGA of Anambra state and at the south by Ideato Local Government Area (L.G.A) of Imo state [2].

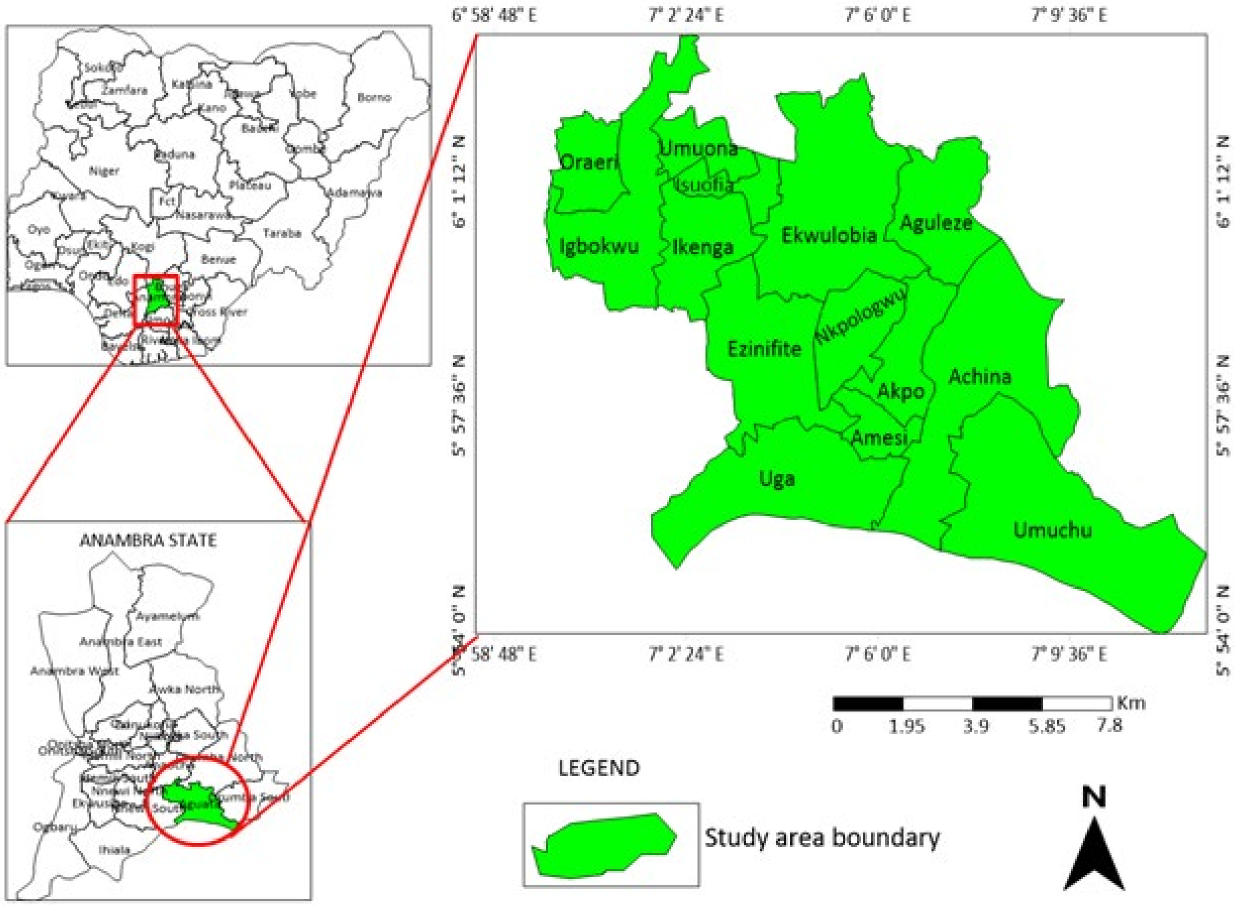

Figure 1: Map of Aguata Local Government Area

2.2 Geological Setting of the Study Area

Aguata Local Government Area, Anambra State lies within the sedimentary region of Southeastern Nigeria. It is underlain by Bende Ameki formation. Ameki Formation belongs to the Bende-Ameki Group and is dominated by alternating shale, sandy shale, clayey sandstone, and fine-grained fossiliferous sandstone with thin limestone bands. The Ameki Group consists of the Nanka Sand, Nsugbe Formation, and Ameki Formation, which are laterally equivalent. At last cycle, from Eocene to recent, marks the continuous growth of the main Niger delta with the successive deposition of the Ameki, Lignite and Benin Formations. Ameki Formation is a clastic unit that overlies the marine Imo Formation and it consists of sandstone, shales, limestone, ironstone and siltstones. The Figure. 2 shows the geologic map of the study area which is characterized by Eocene Ameki Formation in southeastern Nigeria consists, in its type locality of five lithologic units; calcareous sandstone, pebbly bioturbated sandstone, grey-dark shale, argillaceous sandstone and Nanka sand which is the basal sandstones.

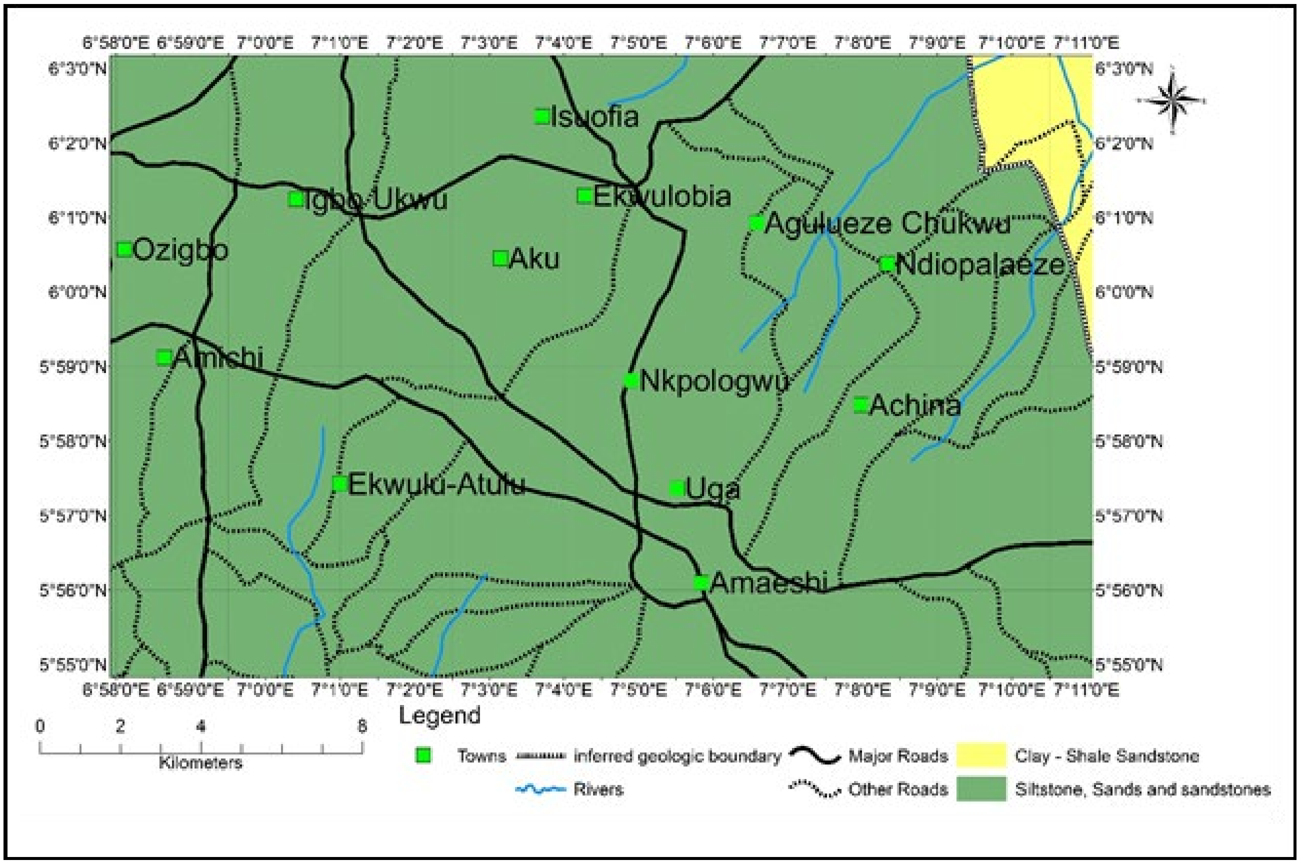

Figure 2: Geologic map produced from field data showing the formation of the study area, drawn with ArcGIS software.

3. METHODOLOGY

3.1 Electrical Resistivity Method

Direct Current (DC) resistivity methods use artificial sources of current to produce electrical potential field in the ground. In almost all resistivity methods, a current is introduced into the ground through point electrodes (C1 C2) and the potential field is measured using two other electrodes (the potential electrodes P1 and P2). The source current can be direct current or low frequency (0.1 – 30 Hz) alternating current. The aim of generating and measuring the electrical potential field is to determine the spatial resistivity distribution (or its reciprocal – conductivity) in the ground. As the potential between P1 and P2, the current introduced through C1 and C2 and the electrode configuration are known, the resistivity of the ground can be determined, this referred to as the "apparent resistivity". The general field layout requires two pairs of electrodes thus; Electrodes A and B are used for injecting current while M and N are for potential measurements.

Apparent resistivity values are gotten from the measured voltage and the other parameters of the survey result specifically the geometric factor, K. In schlumberger configuration the apparent resistivity is calculated using the given equation below, Ogungbemi et al, 2013.

$k = \pi (L^2 - b^2) R/2$ ……………Equation (1)

But, $\rho a = K \times R\alpha$ ……….................(2)

The product of geometric factor and resistance is equal to apparent resistivity.

Where L = current electrode spacing (AB/2), b = potential electrode spacing (MN/2), ρa = the apparent resistivity in ohm-m, and Rα = resistance reading in ohm.

Resistivity measurements may be made at the Earth's surface, between boreholes or between a single borehole and surface. With special cables, measurements can be made underwater in lakes, rivers and coastal areas. The first qualitative result of a 2-D resistivity survey is a pseudosection along the profile. Pseudosections display the apparent resistivity as a function of location and electrode spacing, which is indirectly, related to the depth of investigation of the array. Pseudosections provide an initial picture of the subsurface geology. A 2-D inversion of the measured data is necessary for the final interpretation. This process transforms the apparent resistivities and pseudodepth into a 2-D model. In recent year, several computer programs have been developed to carry out such inversion (SHIMA, 1990, BARKER, 1992 and IPI2WIN. Depending on the algorithm used, the result is a smoothed layer model or a block model showing sharp layer boundaries, comparable to the result of 1-D inversion. In spite of the various capabilities of different programs, the final assessment of inversion results has to be done by the user. The software applied in this research is IPI2WIN. Using IPI2WIN, Curve interpretation is achieved from the plot of apparent resistivity against half current electrode spacing AB/2, thus at negligible root mean square of less than 5% which gives accuracy of the respective geological characteristics of the formations as regards to resistivity, depth, number of lithology occurred, thickness and curve signatures or types encountered (Adeniji et al. 2013). Fig. 3 below shows the schematic diagram of resistivity type curves.

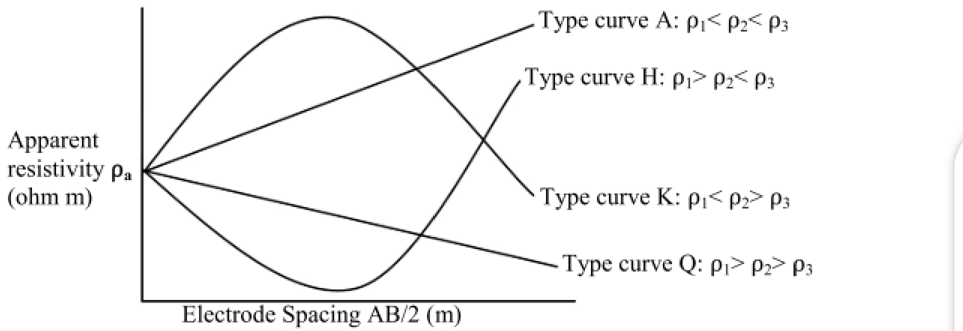

Figure 3: Schematic diagram of resistivity type curves for layered structures.

Telford et al. (1998) further described the characteristics of resistivities of different subsurface layers in a three layered earth model based on curve shapes as follows; H type ($p1 > p2 < p3$), which is called minimum curve type, K type (maximum curve type) as $p1 < p2 > p3$, A type ($p1 < p2 < p3$) as an ascending curve type and Q type ($p1 > p2 > p3$) being the descending curve type. These can be combined to produce further curve types in more than three layered, thus, HA is ($p1 > p2 < p3 < p4$), HK curve type as $p1 > p2 < p3 > p4$, QH curve type ($P1 > P2 > P3 < P4$), KH curve type ($p1 < p2 > p3 < p4$), KQ curve type ($p1 < p2 > p3 > p4$), AA curve type ($p1 < p2 < p3 < p4$), AK curve type ($p1 < p2 < p3 > p4$), HKK curve type ($p1 > p2 < p3 > p4 < p5$) etc. These techniques of curved classifications were employed in this study for the resistivity layer distributions of the VES IPI2WIN plots

3.2 Field Procedure of VES Data Acquisition

The field procedure involved in this research is the use of Schlumberger Electrode Configuration for Vertical Electrical Sounding (VES) date acquisition which is known to have greater depth of investigation and resulting power of resistivity layer. 14 VES locations were conducted in Uga, Ekwulobia Ezinifite Nkpologu Achina Aguluezechukwu and Isuoffia of Aguata Local Government Area using Schlumberger electrode array, also geophysical well log (SP = Spontaneous Potential and Resistivity Logging) was conducted on one existing well of two VES locations in each surveyed towns of Aguata Local Government Area (Fig. 4). Abem Terrameter (SAS 1000), four electrodes, four reels of Cables, Direct Current Source (12 Volts Car battery), hammers, field Survey Data sheet, Global Positioning System (GPS) and measuring tapes were all used for data acquisition.

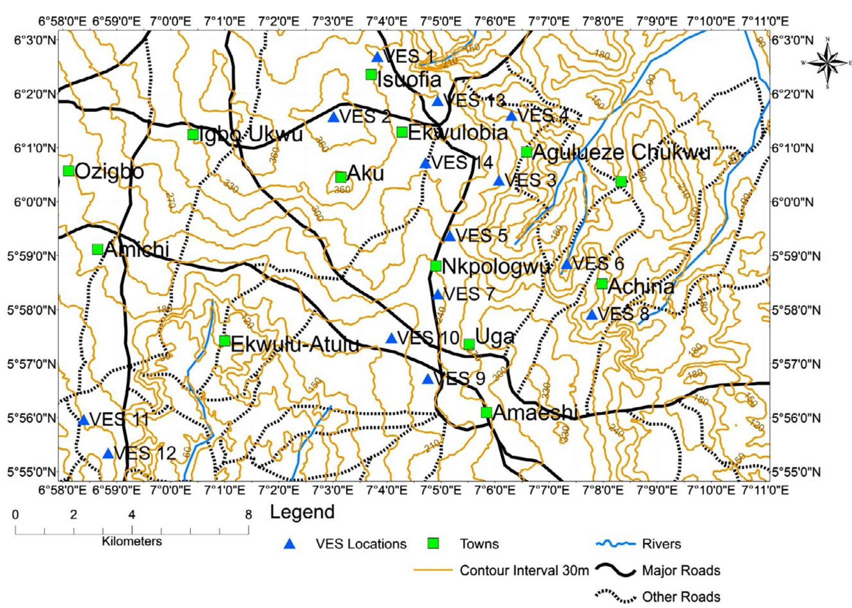

Figure 4: Topographic map of the study area produced from field data showing 14 VES Locations and 7 Logged well drawn with ArcGIS software

3.3 Field Data Presentation and Calculation Procedure of Groundwater Resources Parameters.

The vertical electrical sounding (VES) data were established from the product of resistance (ohms) and geometric factor (k) to obtain the apparent resistivity (ohms-m). The apparent resistivities were plotted against electrode spacing which was acquired at transverse of different locations. The plots of apparent resistivities against electrode spacing using IPI2WIN were geologically modelled into their resulting layer resistivities, layer thicknesses, depths and inferred lithological constituents of the study area. Parameters such as hydraulic conductivity, transmissivity, hydraulic resistance (Rc) porosity and permeability and aquifer vulnerability were calculated to ascertain the sustainability of groundwater resources in the study area.

3.3.1 Hydraulic Conductivity Evaluation

Symbolically representation of hydraulic conductivity is K, which is a property of rock that describes the ease with which water can move through pore spaces or fractures.

It depends on the intrinsic permeability of the material and on the degree of saturation. Saturated hydraulic conductivity, Ksat, describes water movement through saturated media.

Kc=1/p ...………………… where Kc is the calculated hydraulic conductivity and p is the resistivity of the saturated layer from VES.

3.3.2 Transmissivity Evaluation

Transmissivity is a measure of how much water can be transmitted horizontally. It is directly proportional to the hydraulic conductivity (K) and aquifer thickness (b). Expressing K in m/day or cm/s and b in m, the transmissivity (T) is found in units m2/day or cm2/s.

T=Kb …………….. …………4

The transmissivity (T) of aquifer is related to the field hydraulic conductivity (K) by the equation above. According to Niwas, S. and Singhal, D. C., in a porous medium transmissivity is calculated by; TC = Kcb ……… 5

where, TC = Calculated transmissivity (m2/day) from VES data. Kc = Calculated hydraulic conductivity (m/day) from VES data. b = Thickness of saturated layer (m).

The classifications of Hydraulic conductivity and transmissivity as modified by Bouwer (1978) and Krasny (1993) are given in Table 1 and Table 2 respectively.

Material	Range of K (m day^{-1})
Clay soils	0.2
Deep clay beds	10^{-8}, 10^{-2}
Sandy loamy	0.1 – 1
Fine sand	1 – 5
Medium sand	5 – 20
Coarse sand	20 – 100
Gravel	100 – 1000

Table 1: Range of Hydraulic Conductivity K –Values (Bouwer 1978)

TRANSMISSIBILITY VALUE (M^2/DAY)	RATING	SUSTAINABILITY RATE POTENTIAL
T > 1000	Very high	Withdrawal for great regional purpose
100- 1000	High	Withdrawal for less regional purpose
10 – 100	Intermediate	Withdrawal for local purpose
1 – 10	Low/Fairly Good	Small withdrawal for local purpose
0.1 – 1	Very low	Small withdrawal for local purpose (limited)
< 0.1	Impermeable	Sources for water supply are difficult.

Table 2: Classification of Aquifer Based on Transmissivity (Modified after Krasny, 1993)

3.3.3 Transverse Resistance Longitudinal Conductance and Hydraulic Resistance of the Aquifer

Transverse Resistance, Tr (ohm-m^2) and Longitudinal Conductance, Lc (ohm-1) are parameters used to define target areas of good groundwater.

Tr = hp……………………………...6

And Longitudinal Conductance S = h/ρ ……..........7

Where ρ and h are the resistivity's and thicknesses of the individual layers respectively, the parameters Tr and S are commonly called Dar-Zarrouk parameters.

3.3.4 Hydraulic Resistance (Rc)

The basis of hydraulic resistance (Rc), as a ratio between the thickness of each lithologic unit above the uppermost aquifer which is refers to as (h) and the estimated hydraulic conductivity of the protective layer (kc) is used to interprets aquifer vulnerability index. Aquifer vulnerability index (AVI) which was proposed by (Van Stempvoort et al., 1992) involved quantifying the vulnerability through hydraulic resistance to vertical flow of water through the protective layers. Hydraulic Resistance (Rc) is expressed as;

Rc = h/kc…………………………………..8

Where, h and kc are thickness of the lithologic units above the aquifer and Hydraulic conductivity of the protective layers respectively.

3.3.5 GOD model for Overburden Layer (OLC) and Aquifer Vulnerability Evaluation

GOD model was first introduced by Foster (1987) which is used in vulnerability assessment of groundwater for sustainability. The acronyms of the method were gotten from the first word of the parameters, thus, Groundwater occurrence, Overall lithology, and Depth to groundwater (GOD). Vulnerability determination using GOD model is rated with a range of 0 and 1 where the overall values in evaluating the rate of vulnerability is determined by multiplying the three factors (G = groundwater occurrence, O = overlying lithology and D = depth to water table). the GOD model is an empirical approach in which the vulnerability is defined according to the inaccessibility under saturated areas, which regulate pollutant penetration and attenuation efficiency overburden layer in the saturated zone (Bouselsal et al. 2015). Overburden layer Capacity (OLC) of an aquifer described the ability of the layers above the saturated zone to filter pollutants which applicable to the rate at which the aquifer is vulnerable to contamination. OLC of the saturated zone can be evaluated as the sum of the longitudinal conductance of all the layers above the aquifer. The higher value of GOD model, impact the ground water vulnerability. Table 3.4 below illustrates the processes and procedures involves for GOD method.

God Parameter	Range-	Rating
G = Groundwater Occurrence	Overflowing	0
	Confined	0.2
	Semi – confined	0.4
	Unconfined (covered)	0.6
	Unconfined	1.0
O = Overlying Strata (lithological character and degree of consolidation of vadose zone or confining beds)	Soil	0.4
	Alluvial, fine lime stone, clay	0.5
	Sand, clay – silt, Igneous rock	0.6
	Sand and Gravel, Sandstone	0.7
	Silt, Gravel	0.8
	Silt – Sand	0.9
D = Groundwater Depth (m)	> 100 m	0.4
	50 – 100 m	0.5
	20 – 50 m	0.6
	10 – 20 m	0.7
	5 – 10 m	0.8
	2 5 m	0.9
	< 2 m	1.0
Groundwater Contamination Vulnerability	Absence of Vulnerability	0 .0 – 0.1
	Negligible Vulnerability	0.1 – 0.2
	Low Vulnerability	0.2 – 0.4
	Moderate Vulnerability	0.4 – 0.6
	High Vulnerability	0.6 – 0.8
	Extreme Vulnerability	0.8 – 1.0
Longitudinal Conductance	Extreme	0
	High	0.2 – 0.4
	Moderate	0.8
	Low	2.8

Table 3: GOD – Model Vulnerability of Groundwater to Contamination (Modified after Foster et al., 2002)

4. Data Analysis and Interpretation of Results

4.1 Quantitative Interpretation of VES Locations from the IPI2WIN Plots of the Study Area.

The VES locations acquired based on geology, topography and accessibility were plotted using IPI2WIN software. The data collected were processed and interpreted by combination of curve matching and computer iterative modeling according to Telford. The quantitative interpretation of resistivity IPI2WIN plots revealed predominant of H curve type ($P_1 > P_2 < P_3$) which is of 50 % occurrence. The most occurrence H-type with the three-layer curve types accounting 50 percent of all curve types is as a result of rapid increase in the resistivity of the undulating terrain of the study area as recorded with the meter electrodes. The interpretation of the resistivity curves was based on the number of layers depicted on the observed curves and models that are geologically reasonable. The geoelectric parameters of different layers are obtained after a number of iterations with minimal root mean square (RMS) error ranged from 0.0365 % - 2.23%. Pseudo cross sections and resistivity cross section of the 14 VES location were generated based on the apparent resistivity of the soundings Figure 5 show the IPI2WIN plot of VES 1 - VES 4 which revealed a modeled curve of the resistivity invasion resulting the type – H, thus, location is mainly of sand with thin silt stone or shale also, VES 3 and VES 4 showed K and KHK type other 5 VES locations (VES 6, VES 8, VES 9, VES 10 and VES 11) that was surveyed using electrode metre indicated a modeled curve of type – H. The curve types range from three-layer A-type (14.2 %) and H-type (50%) to four-layer KH-type (14.2 %) and AK-type (7.14 %) and five-layer KHK-type (7.14 %) at a total of 99.82 percent (Table 4 and Figure 6).

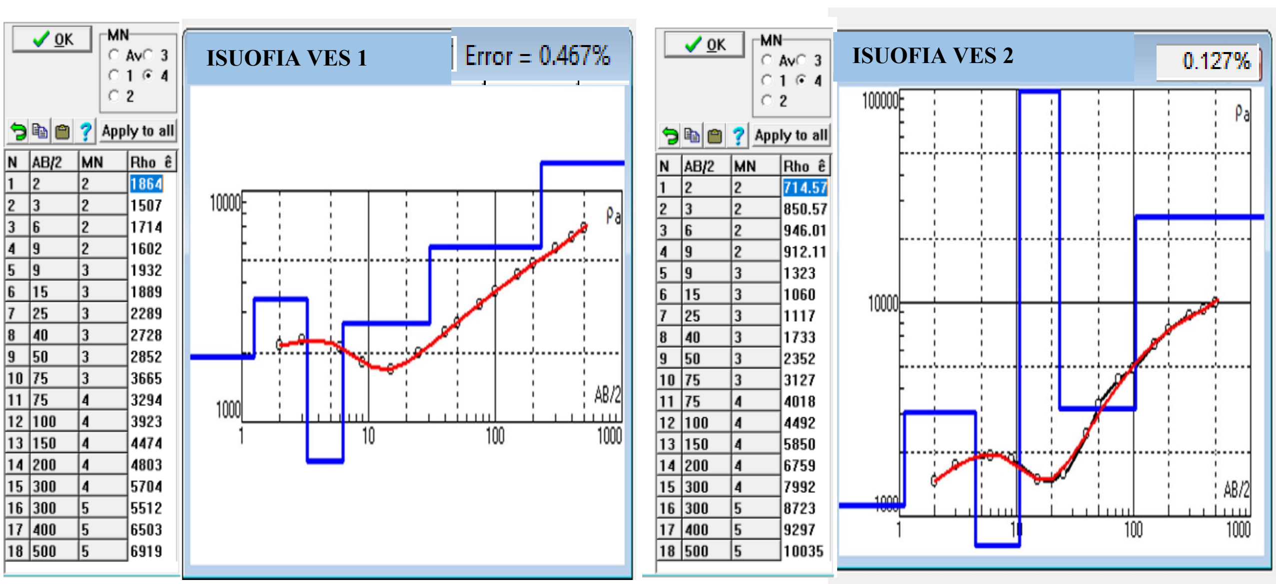

Figure 4.1. Modelled VES curve of VES 1 – VES 4 using IPI2WIN Software.

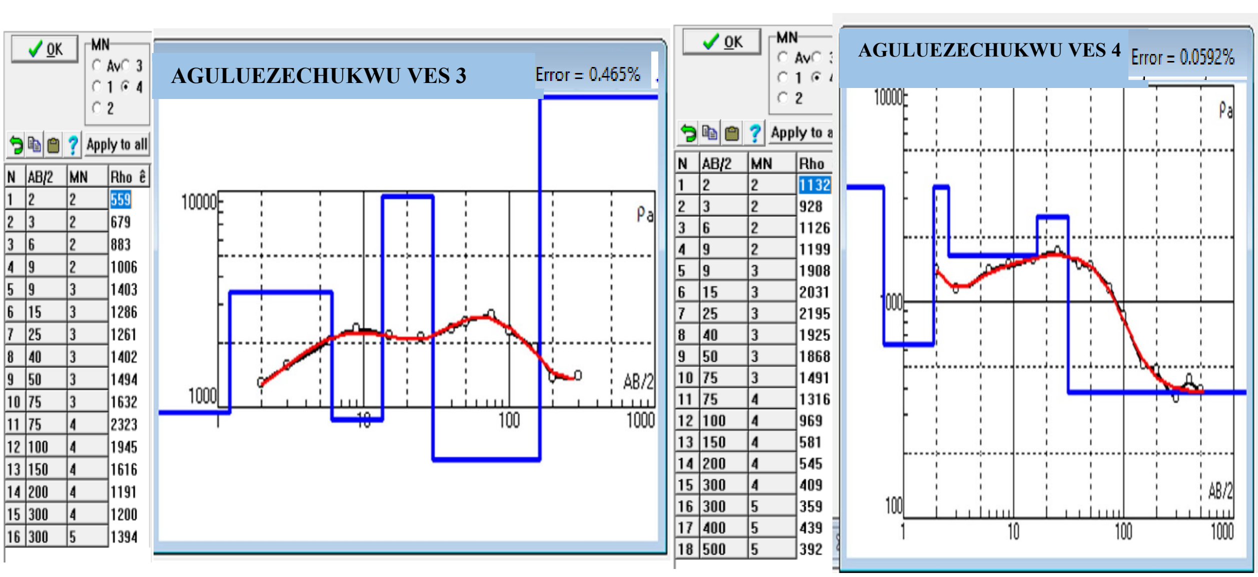

Figure 5: Modelled VES Curve of VES 1 – VES 4 using IPI2WIN Software.

Ves No.	Electrical well Log	Ves Site Location	Latitude (Degrees Minutes Seconds)	Longitude (Degrees Minutes Seconds)	Elevation	Curve Matching	Curve Type	Common Occurred Curved Type		
									Frequency	Per. %
VES 1		Isuoffia	N6^0 1' 44.04"	E7^0 3' 14.04"	355 m	$P_1>P_2<P_3$	H	A	2	14.2
VES 2	A	Isuoffia	N6^0 4' 6.96"	E7^0 15' 45.72"	370 m	$P_1>P_2<P_3$	H			
VES 3		Agulueze Chukwu	N6^0 10' 59.16"	E7^0 17' 11.6"	177 m	$P_1<P_2>P_3$	K	H		
VES 4	B	Agulueze Chukwu	N6^0 3' 6.84"	E7^0 8' 22.92"	253 m	$P_1<P_2>P_3<P_4>P_5$	KHK		7	50
VES 5		Nkpologu	N5^0 58' 52.32"	E7^0 5' 10.32"	249 m	$P_1<P_2<P_3$	A	K	1	7.14
VES 6	C	Nkpologu	N6^0 14' 38.76"	E7^0 18' 51.84"	259 m	$P_1>P_2<P_3$	H			
VES 7		Achina	N6^0 14' 38.76"	E7^0 18' 10.8"	128 m	$P_1<P_2>P_3<P_4$	KH	AK	1	7.14
VES 8	D	Achina	N6^0 9' 1.8"	E7^0 11' 18.96"	169 m	$P_1>P_2<P_3$	H			
VES 9		Uga	N5^0 56' 7.08"	E7^0 4' 45.84"	165 m	$P_1>P_2<P_3$	H	KH		14.2
VES 10	E	Uga	N6^0 7' 48.72"	E7^0 9' 22.68."	196 m	$P_1>P_2<P_3$	H		2	
VES 11		Ezinifite	N5^0 54' 24.84"	E6^0 58' 17.76"	187 m	$P_1>P_2<P_3$	H	KHK	1	7.14
VES 12	F	Ezinifite	N6^0 10' 32.88"	E7^0 3' 16.92"	252 m	$P_1<P_2<P_3<P_4$	AK			
VES 13		Ekwulobia	N6^0 1' 28.56"	E7^{0}4' 45.84"	319 m	$P_1<P_2>P_3<P_4$	KH			
VES 14	G	Ekwulobia	N6^0 11' 17.88"	E7^0 19' 50.88"	280 m	$P_1<P_2<P_3$	A	**TOTAL**	**14**	**99.82 %**

Table 4: Global Positioning System Information and IPI2WIN Quantitative Modelled curve of the Study Area.

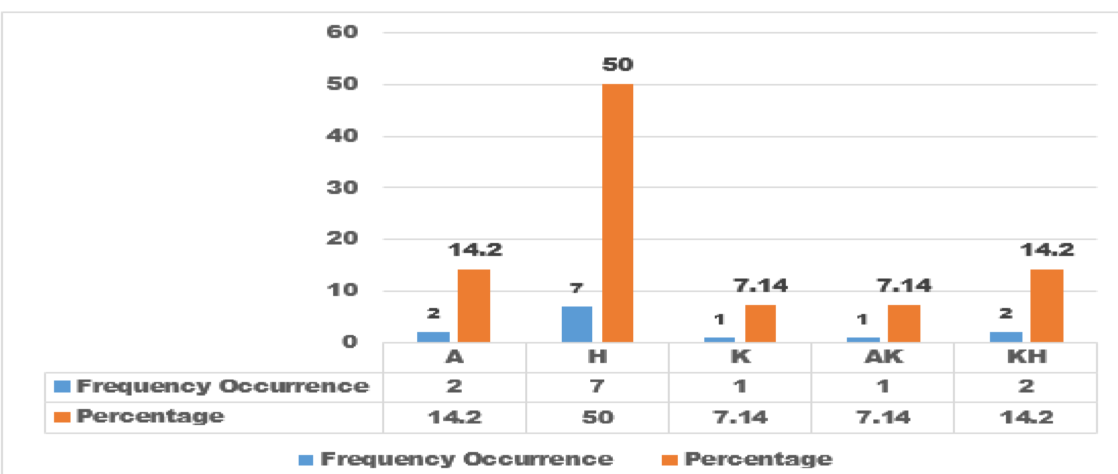

Figure 6: Column Chart Classification of Vertical Electrical Sounding (VES) Curve Type of Study Area from IPI2WIN Plots.

4.2 Parameters from Electrical resistivity survey and Inferring of Geoelectric Characteristics of the Study Area

The inferred geoelectric characteristics indicate the degree of heterogeneity within the formation of the study area. Three to eight geologic sequences were discovered by the geoelectric interpretations. The geologic sequences are; topsoil (263.36 –3046.89 minimum and maximum resistivity respectively), thicknesses (3 - 9 m; 5.36 m avg.), composed of clay, and sandy clay. Below the topsoil is a layer composed of shale - shaly sand (142.52 - 576.91 ohm-m avg. respectively), thicknesses (100 – 101.5 m avg. respectively), the fine – medium sandstone layer, which is composed of clay/sandy clay and clayey sand (916.56 – 2787.65 ohm-m avg. respectively), thicknesses (133.5 – 52.56 m avg. respectively), the free shale/clay which is coarse – very coarse layer ranged (3835.19 - 1278.68 ohm-m avg.), thicknesses (60.00 – 184.4 m avg.). The water bearing units is basically found in the porous and permeable layers which are predominantly unconfined aquifer as the geological setting of the study area constrained. Table 5 and figure 7 show summarized parameters and inferred geoelectric characteristics show geoelectric section of each 14 VES locations from manual inference. The pore spaces of the rock are where the fluids are contained. Permeability is a measure of the ease with which a fluid can flow through the pore spaces of a rock. The water bearing units indicate layers with good percentage of pore spaces which can contain a large amount of fluid. However, VES 7 and VES 8 locations were observed to be poorly saturated zones, being that pores of the two locations VES 7 and VES 8 are not interconnected the permeability results to be low. Better permeabilities as revealed in other VES locations result that more pores are interconnected. The distribution of different layers which revealed the geological formation of the study area which corresponds to the predominantly occurred unconfined type of aquifer, though at high risk to contamination due to absence of substantial shale volume in the study area.

Parameter	Laterite	Shale	Shaly sand	Fine sand	Medium sand	Coarse sand	Very coarse sand	Saturated sand
Average Apparent Resistivity ρa (Ωm)	1666.48	142.52	576.91	916.56	2787.65	3835.19	1278.68	5059.95
Average thickness (m)	5.36	100	101.5	133.5	52.56	60.00	184.4	231.07
Average top depth (m)	2	58.33	153.00	30.25	42.44	16.50	175	79.64
Average terminated depth (m)	5.36	206.25	254.50	253.75	95.00	75.00	310.00	310.71
Minimum Apparent Resistivity ρa (Ωm)	263.36	56.32	559.35	454.23	1144.342	1676.07	12178.26	1090.11
Maximum Apparent Resistivity ρa (Ωm)	3046.89	216.56	594.47	1308.22	4027.57	5251.19	18924.93	8523.73
Minimum thickness (m)	3	25	3	12	12	22	25	25
Maximum thickness (m)	9	200	200	400	91	100	300	400
Minimum top depth (m)	2	25	6	3	3	3	25	25
Maximum top depth (m)	2	75	300	100	300	50	300	150
Minimum terminated depth (m)	3	75	9	15	15	25	50	75
Maximum terminated depth (m)	9	300	500	500	400	150	500	500

Table 5: Summarized Result from Parameters of Geoelectric Survey of the Study Area

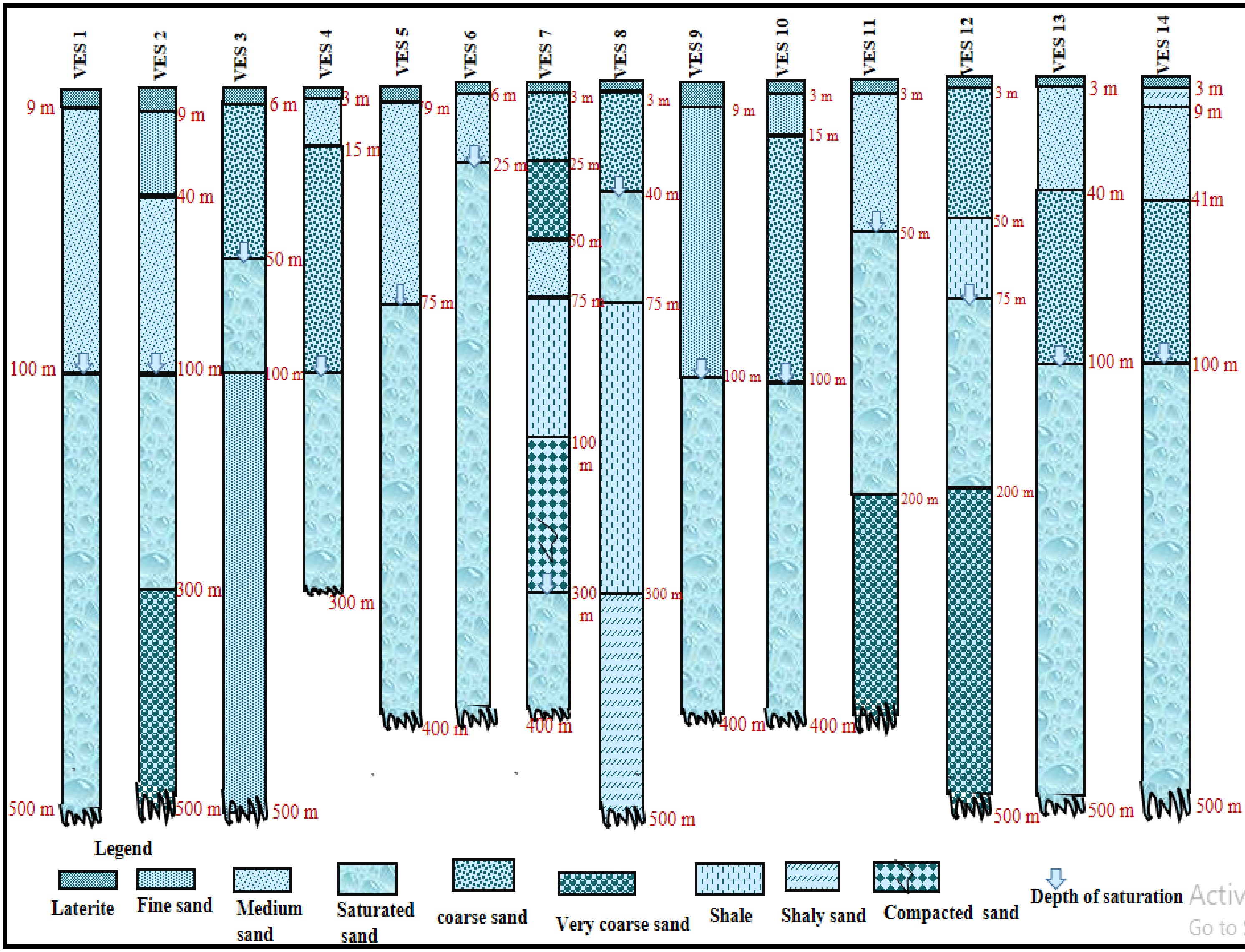

Figure 7: Profile Showing Inferred Geoelectric Characteristics with variation in Depth and Thickness in Different Locations of the Sounding of the Study Area.

4.3 Evaluation of Hydraulic Properties of Water Bearing Units from VES for Groundwater Resources Potentials in the Study Area

Evaluating the parameters of water – bearing units from Vertical Electrical Sounding (VES) data for groundwater resources potentials in the study area, hydraulic properties estimation is carefully considered. Hydraulic properties of the water-bearing units are estimated based on their lithological characteristics. These hydraulic properties observed in this research include; Depth above Mean Sea Level "MSL" (m), Saturation depth of penetration from VES, Calculated Hydraulic Conductivity constant (Kcσ), Calculated Transmissivity constant (Tcσ), Thickness of Saturated Layer (m), Transverse Resistance "Tr" of Saturated Layer, Longitudinal Conductance "S" of Saturated Layer, Transmissivity "T" of Saturated Layer (m2/day) and Hydraulic Conductivity "K" of Saturated Layer (m day-1). Mean sea level (MSL) serves as a reference point for measuring land elevation and tidal variation which was estimated by subtracting the saturated depth from the georeferenced elevation of the study area. The saturated depth and thickness are an important parameter in groundwater resources studies. The evaluation of saturated depth and thickness was based on field observations, soil and rock characteristics. Calculated aquifer hydraulic conductivity constant (Kcσ) which is measured in siemens (S/m) is the reciprocal of saturated resistivity, Kc=1/p which was multiplied by saturated layer thickness to generate the constant of the aquifer transmissivity Tc. The transverse resistance (Tr = hp, where, h = thickness of the saturated layer and p = resistivity of the saturated layer) of an aquifer refers to the measure of resistance encountered by groundwater flow in a direction perpendicular to the direction of flow. Whereas, Longitudinal Conductance S = h/ρ measures the ease with which groundwater can flow through the aquifer over long distances.

Transmissivity is typically represented by the symbol "T" and is measured in units of length squared per unit time. It is calculated by multiplying the hydraulic conductivity ("K") of the aquifer by its thickness ("b") such that T = K x b. Hydraulic conductivity ("S") of the aquifer material which is S = h/ρ is measured in meter per day. The evaluated hydraulic properties of the water bearing units for groundwater resources sustainability of the study area are presented in table 6 below.

VES NO.	Coordinates		Depth above Mean Sea Level "MSL" (m)	Saturation depth of penetration from VES	Calculated Aquifer Hydraulic Conductivity constant (Kcσ)	Thickness of Saturated Layer (m)	Calculated Transmissivity constant (Tcσ)	Transverse Resistance "Tr" of Saturated Layer	Longitudinal Conductance "S" of Saturated Layer	Transmissivity "T" of Saturated Layer (m^2/day)	Hydraulic Conductivity "K" of Saturated Layer (m day^{-1})
VES 1	N6^0 1' 44.04" E7^0 3' 14.04"	355 m	-255	100	0.00017	400	0.068	2261028	0.0707	384.37	3.0
VES 2	N6^0 4' 6.96" E7^0 15' 45.72"	370 m	-270	100	0.00013	200	0.026	1466190	0.0272	190.60	1.7
VES 3	N6^0 10' 59.16" E7^0 17' 11.6"	177 m	-127	50	0.00079	50	0.039	62920.5	0.0397	49.70	6.1
VES 4	N6^0 3' 6.84" E7^0 8' 22.92"	253 m	-153	100	0.00074	200	0.148	270056	0.1481	199.84	5.4
VES 5	N5^0 58' 52.32" E7^0 5' 10.32"	249 m	-174	75	0.00019	325	0.061	1673122.75	0.0631	317.89	3.6
VES 6	N6^0 14' 38.76" E7^0 18' 51.84"	259m	-234	25	0.00012	375	0.045	2938646.25	0.0478	352.63	1.5
VES 7	N6^0 14' 38.76" E7^0 18' 10.8"	128 m	172	300	0.00091	100	0.091	109011	0.0917	99.20	8.3
VES 8	N6^0 9' 1.8" E7^0 11' 18.96"	169 m	-128	40	0.00016	35	0.005	208730.2	0.0058	33.39	2.3
VES 9	N5^0 56' 7.08" E7^0 4' 45.84"	165 m	-65	100	0.00039	300	0.117	755925	0.1190	294.81	1.5
VES 10	N6^0 7' 48.72" E7^0 9' 22.68."	196 m	-96	100	0.00011	300	0.033	2557134	0.0351	281.28	1.2
VES 11	N5^0 54' 24.84" E6^0 58' 17.76"	187 m	-137	50	0.00014	150	0.021	1043215.5	0.0298	146.05	2.0
VES 12	N6^0 10' 32.88" E7^0 3' 16.92"	252 m	-177	75	0.00016	125	0.020	739187.5	0.0211	118.27	2.7
VES 13	N6^0 1' 28.56" E7^{0}4' 45.84"	319 m	-219	100	0.00012	400	0.048	3169220	0.0504	380.30	1.5
VES 14	N6^0 11' 17.88" E7^0 19' 50.88"	280 m	-180	100	0.00029	350	0.101	1180889.5	0.1037	342.45	9.1

Table 6: Hydraulic properties of Water Bearing Units from VES for Groundwater Resources Potentials in the Study Area.

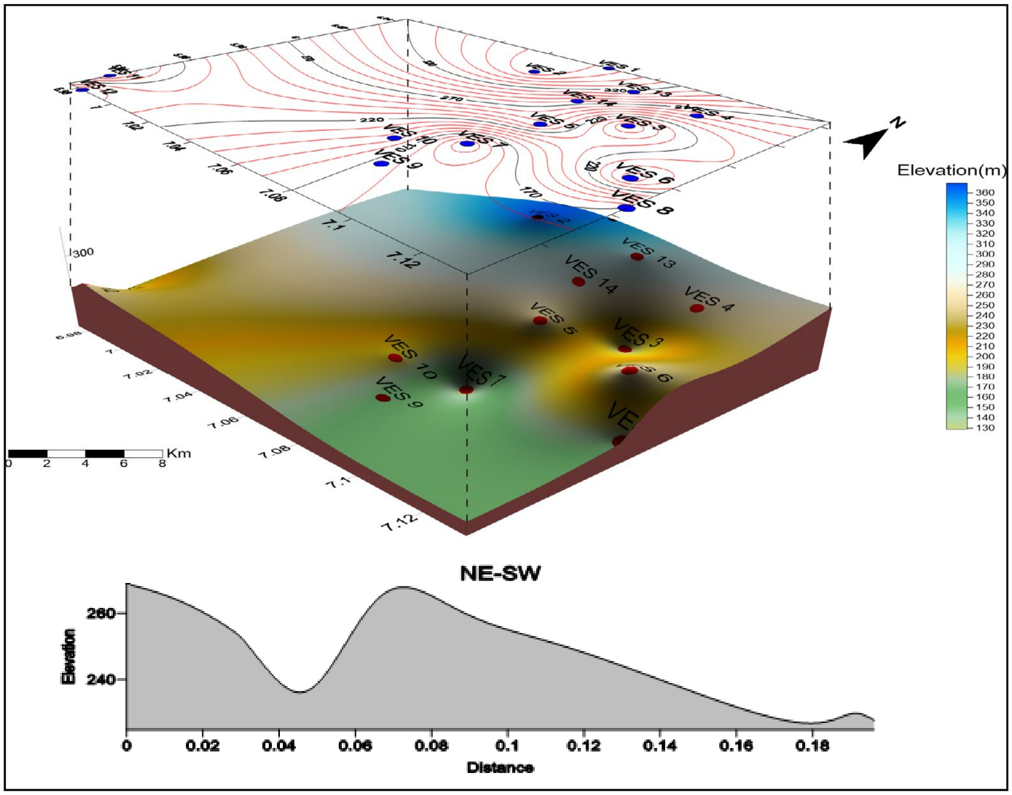

Figure 8: Digital Elevation Map of the Study Area

Figure 8 above shows the elevation of the study area which was measured using global positioning system (GPS), it reveals the height of locations above reference points. Elevation helps in understanding the topography of the study area. The profile of the elevation revealed that the study area is characterized by undulating topography, typical series of smooth, wavelike rise and fall terrain. A gentle slope and rolling hills discovered which could be factored by erosion. The height of the locations above georeferenced points of the study area ranges from 128 m – 355 m. Mean sea level is influenced by factors such as tides, weather patterns, atmospheric pressure and ocean current. Mean sea level refers to the average height of oceanic water at high and low tides in an area. It is an essential parameter that helps in understanding the vulnerability of coastal towns to sea level rise or fall due to climate change which serve as a reference point for measuring the elevation and assessing potential impacts on the local population and infrastructure. Aguata's geographical location and its proximity to the coastline play a significant role in determining the mean sea level. Topographical features such as elevation and slope can affect the exposure and susceptibility of towns to rising sea levels. Climate change is an important aspect to consider when discussing sea level rise. With increasing global temperatures, the melting of glaciers and polar ice caps contribute to a rise in sea levels. The study revealed that some parts of Aguata towns experience land subsidence and rising topography at mean sea level range of -65 m – 172 m.

The saturated layer of an aquifer is the portion of the aquifer where the pore spaces between rock or sediment particles are completely filled with water, the region where groundwater is stored and flows. Above the delineated saturated layer there is an unsaturated zone, which is known as the vadose zone. The saturated depth of an area depends on various geology, climate and water usage pattern. These factors help to explain the concept related to soil or rock properties, such as water table level, permeability, porosity of an aquifer or groundwater resources. In this study the water table level defining the saturated layer of the study area ranged from 40 m – 100 m, being that the geology of the study area is predominately of sandstone members. The saturated thickness explains the vertical distance between the upper and lower boundaries of the saturated layers. It determines the volume of water an aquifer can hold and its sustainability as a water source. The study area revealed essential volume of sustainability in thickness range of 35 m – 400 m except VES location 8 that distinct 35 m thickness. The digital maps of the parameters; mean seal level "MSL", saturated layer depth of penetration and layer thickness depth in meters are presented in figure 9 below.

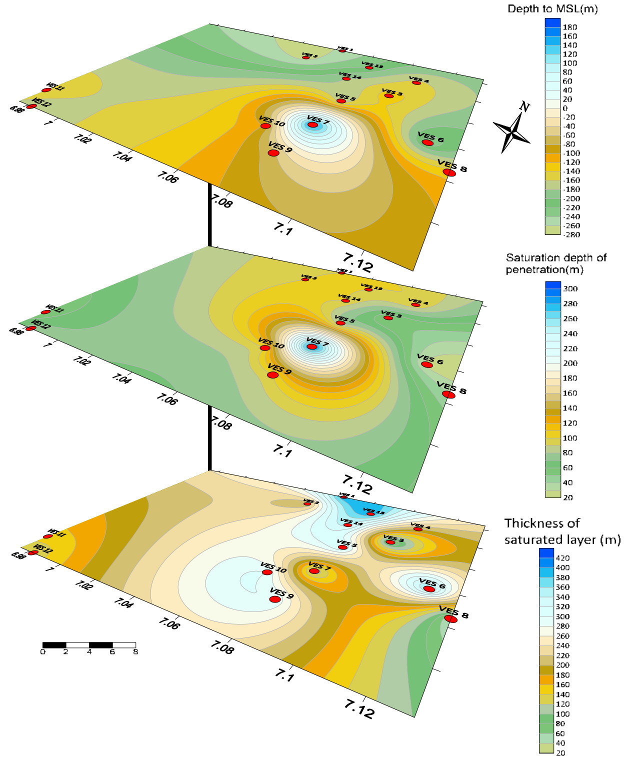

Figure 9: The digital Maps of Mean Seal Level "Msl", Saturated Layer Depth of Penetration and Layer Thickness Depth in Meters Modelled with Surfer Software.

The constant σ is modified by Croft to show the relationship between transmissivity and hydraulic conductivity of an aquifer [7-8]. The figure 10 below shows contour map of spatial distribution of calculated hydraulic conductivity and transmissivity constant used to estimate the hydraulic conductivity and transmissivity prospective of the aquifer in the study area from VES geoelectric.

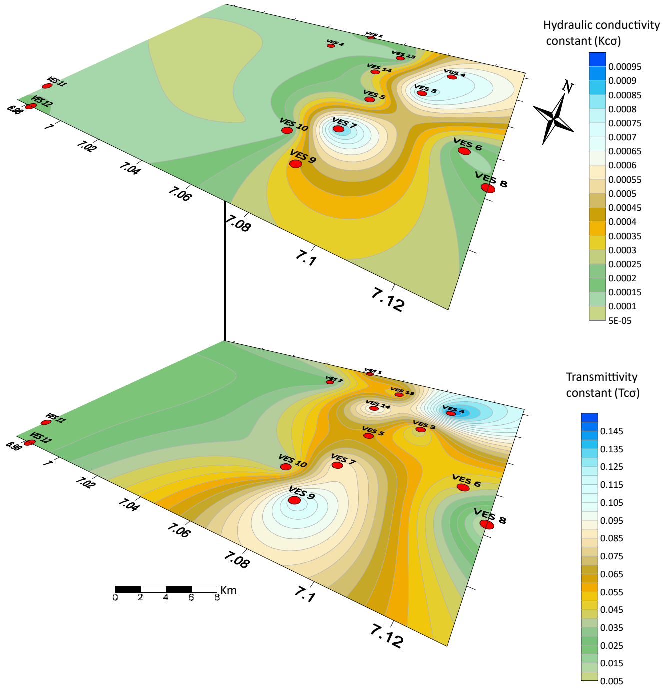

Figure 10: Contour Map Showing the Spatial Distribution of Calculated Hydraulic Conductivity and Transmissivity Constant for Sustainability Prospect of the Aquifer in the Study Area.

The transverse resistance of an aquifer refers to the measure of resistance encountered by groundwater flow in a direction perpendicular to the direction of flow. It represents the hydraulic resistance that groundwater encounters as it moves through the aquifer. The longitudinal conductance of an aquifer refers to its ability to transmit water in the direction of the hydraulic gradient. Figure 11 represents that the transverse resistance of the saturated layer (aquifer) in the study area is essentially revealed to negligible with good longitudinal conductance in NE – SW direction regarding the geological formation.

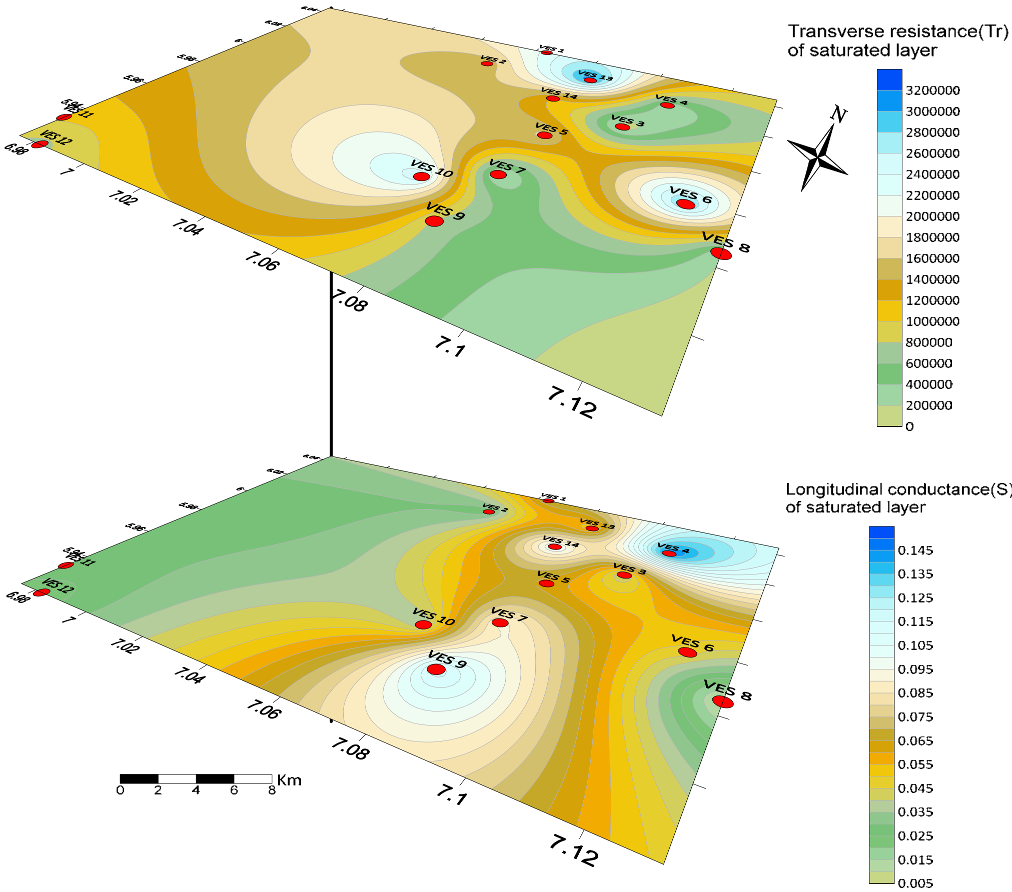

Figure 11: Contour Map Showing the Transverse Resistance and Longitudinal Conductance of Aquifer in the Study Area.

Transmissivity is a fundamental property of an aquifer that describes its ability to transmit water. It is a measure of the volumetric flow rate of water through a unit width of the aquifer under a unit hydraulic gradient. In simpler terms, transmissivity quantifies the ease with which water can flow through the aquifer. Transmissivity is influenced by various factors, including the hydraulic conductivity of the aquifer material, the thickness of the aquifer, and the hydraulic gradient. Hydraulic conductivity is the property of the aquifer material that describes its ability to transmit water and is a key factor in determining transmissivity. Figure 12 shows the contour map of transmissivity and hydraulic conductivity of the study area that ranged 49.70 m^2/day – 384.37 m2/day and 1.2 m/day – 9.1 m^2/day respectively.

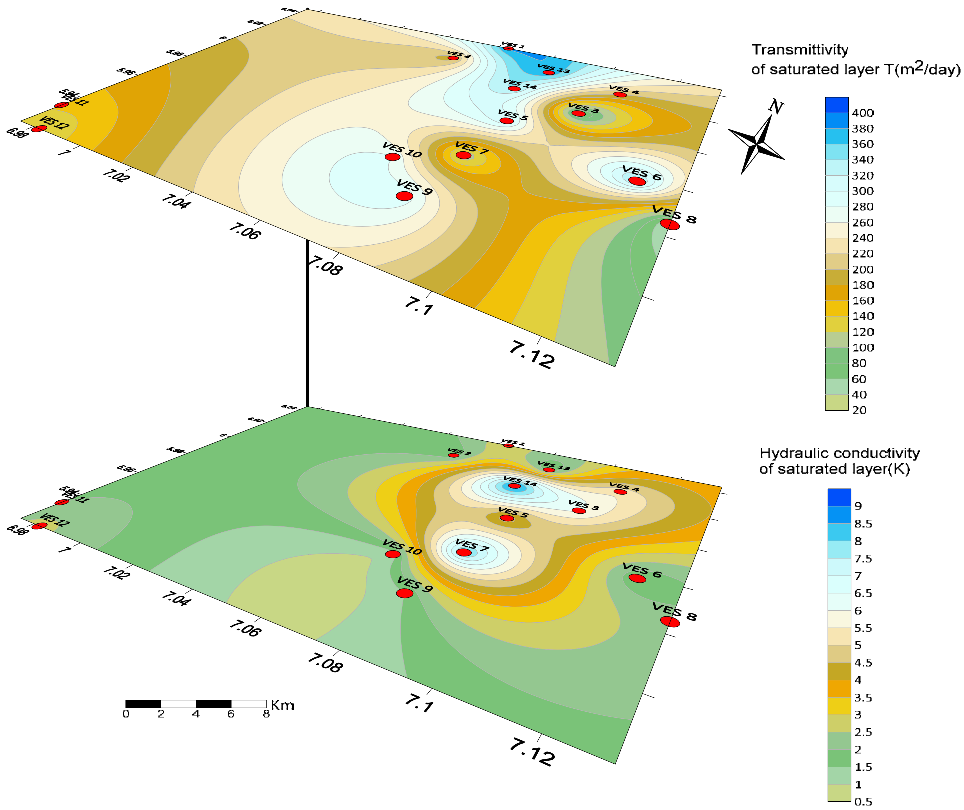

Figure 12: Contour map showing the transmissivity and hydraulic conductivity of aquifer in the study area.

4.4 Evaluation of protective capacity of aquifer in the study area

Aquifer protective capacity refers to the ability of an aquifer to naturally safeguard and preserve the quality of groundwater resources. It is an important concept in water resource management as it helps in determining the vulnerability of an aquifer to potential sources of contamination.

The protective capacity of an aquifer depends on various factors, including its geology, hydrogeology, and the presence of natural protective barriers. The geology of an aquifer plays a crucial role in determining its vulnerability to contamination. For example, aquifers composed of permeable materials like sand and gravel may be more prone to contamination as they allow pollutants to easily pass through. On the other hand, aquifers with layers of impermeable clay or rock act as natural protective barriers, limiting the movement of contaminants.

Hydrogeological properties such as groundwater flow patterns and recharge rates also influence the protective capacity of an aquifer. Rapid groundwater flow can facilitate the transportation of contaminants over large distances, while slower flows may provide more time for natural attenuation processes to remove or reduce contaminants. Another important aspect of aquifer protective capacity is the presence of natural filtration processes. Aquifers often contain microorganisms and porous materials that can degrade or filter out contaminants as groundwater moves through them. These natural processes can help in reducing the concentration of pollutants and maintaining the quality of groundwater resources.

Generally, the protective capacity of an aquifer is determined by its ability to filter and attenuate contaminants, its recharge rate, and its geological characteristics. Understanding and preserving the protective capacity of aquifers is vital for maintaining the quality and sustainability of groundwater resources. Adequate groundwater protection is characterized by overburden layers of enough impermeable layers' thicknesses and low hydraulic conductivity leading to high rate of percolating water (Mosuro et al. 2017). Areas with high longitudinal conductance (thick overburden and shale resistivity volume) is appreciably of excellent – good aquifer protective capacity in that case safe from infiltration of groundwater contamination. Locations with moderate aquifer protective capacity are less susceptible or rare to contamination while areas with weak – poor APC are susceptible to contamination (Atakpo and Ayolabi, 2009).

The vulnerability/susceptibility of the aquifer to contamination, the longitudinal conductance of overburden layers was evaluated using its resistivity and the thickness of overburden layers from electrical sounding results (Adeniji et al. 2017). The geological constituent of the study area posed chances to constrain the sustainability of the groundwater resources thus, the areas with little or no retard agents like impermeable overburden layers let direct infiltration down the aquifer thereby rating poorly in protective capacity. The protective capacity of the aquifer must be considered as being proportional to the rate between the thickness to the resistivity and to that of the longitudinal conductance (L). Thus, the criterion of detectability of the underlying geological layers and an approached thickness on the geoelectric section recommend a significant investigation approach in groundwater resources sustainability. This means that the detectability of protective capacity of the saturated layer is the proportionality of the thickness/resistivity ratio of the overlaying layers. The evaluated protective capacity of the aquifer in the study area is presented in table 7-8.

VES No/	No of Layers	Coordinate	Elevation	Thickness (m)	Depth (m)	Average Apparent Resistivity (Ωm)	Inferred Lithology	Longitudinal Conductance	APC Indexing
VES	1	N6^0 1'44.04"	355 m	9	9	1723.83	Laterite	0.0052	0.018
1	2	E7^0 3' 14.04"		91	100	2948.44	Medium sand	0.0308	Poor
	3			400	500	5652.57	Saturated sand	Sd	
VES	1	N6^0 4' 6.96"	370 m	9	9	855.82	Laterite	0.0105	0.017
2	2	E7^0 15' 45.72"		31	40	1308.22	Fine sand	0.0256	Poor
	3			60	100	3497.26	Medium sand	0.0172	
	4			200	300	7330.95	Saturated sand	Sd	
	5			200	500	966.23	Very coarse sand	NA	
VES	1	N6^0 10' 59.16"	177 m	6	6	1062.30	Laterite	0.0056	0.014
3	2	E7^0 17' 11.6"		44	50	1854.24	Coarse sand	0.0237	Poor
	3			50	100	1258.41	Saturated sand	Sd	
	4			400	500	454.23	Fine sand	NP	
VES	1	N6^0 3' 6.84"	253 m	3	3	618.89	Laterite	0.0048	0.021
4	2	E7^0 8' 22.92"		12	15	1144.342	Medium sand	0.0104	Poor
	3			85	100	1676.07	Coarse sand	0.0507	
	4			200	300	1350.28	Saturated sand	Sd	
VES	1	N5^0 58' 52.32"	249 m	9	9	433.56	Laterite	0.0207	0.051
5	2	E7^0 5' 10.32"		66	75	2326.36	Medium sand	0.0283	Poor
	3			325	400	5148.07	Saturated sand	Sd	
VES	1	N6^0 14' 38.76"	259 m	3	3	188.07	Laterite	0.0015	0.003
6	2	E7^0 18' 51.84"		22	25	4029.98	Medium sand	0.0054	Poor
	3			375	400	7836.39	Saturated sand	Sd	
VES	1	N6^0 14' 38.76"	128 m	3	3	1638.78	Laterite	0.0018	8.10
7	2	E7^0 18' 10.8"		22	25	5251.19	Coarse sand	0.0041	Good
	3			25	50	13185.48	Very coarse sand	0.0018	
	4			25	75	1959	Medium sand	0.0127	
	5			75	150	216.56	Shale	0.3463	
	6			197	300	12178.26	Very coarse sand	0.0161	
	7			NO	300	56.32	Shale	56.32	
	8			100	400	1090.11	Saturated sand	Sd	
VES	1	N6^0 9' 1.8"	169 m	3	3	3211.45	Laterite	0.0009	0.004
8	2	E7^0 11' 18.96"		37	40	4867.78	Coarse sand	0.0076	Poor
	3			35	75	5963.72	Saturated sand	Sd	
	4			225	300	168.72	Shale	NA	
	5			200	500	594.47	Shaly sand		

NA = Not Applicable, APC = Aquifer Protective Capacity & Sd = Saturated depth.

Table 7: Evaluated Aquifer Protective Capacity Rate of the Study Area.

VES No/ No of Layers		Coordinate	Elevation	Thickness (m)	Depth (m)	Average Apparent Resistivity ((Ωm))	Inferred Lithology	Longitudinal Conductance	APC Indexing
VES 9	1	N5^0 56' 7.08"	165 m	9	9	3046.89	Laterite	0.0029	0.063 Poor
	2	E7^0 4' 45.84"		91	100	738.467	Fine sand	0.1232	
	3			300	400	2519.75	Saturated sand	Sd	
VES 10	1	N6^0 7' 48.72"	196 m	3	3	1911.42	Laterite	0.0015	0.009 Poor
	2	E7^0 9' 22.68"		12	15	1165.32	Fine sand	0.0102	
	3			85	100	5030.71	Coarse sand	0.0168	
	4			300	400	8523.78	Saturated sand	Sd	
VES 11	1	N5^0 54' 24.84"	187 m	3	3	2116.27	Laterite	0.0014	0.006 Poor
	2	E6^0 58' 17.76"		47	50	4027.57	Medium sand	0.0116	
	3			150	200	6954.97	Saturated sand	Sd	
	4			200	400	9979.36	Very coarse sand	NA	
VES 12	1	N6^0 10' 32.88"	252 m	3	3	1127.59	Laterite	0.0026	0.075 Poor
	2	E7^0 3' 16.92"		47	50	2183.70	Coarse sand	0.0215	
	3			25	75	123.48	Shale	0.2024	
	4			125	200	5913.50	Saturated sand	Sd	
	5			300	500	18924.93	Very coarse sand	NA	
VES 13	1	N6^0 1' 28.56"	319 m	6	6	3434.5	Laterite	0.0017	0.008 Poor
	2	E7^0 4' 45.84"		34	40	3100.93	Medium sand	0.0109	
	3			60	100	4976.11	Coarse sand	0.0120	
	4			400	500	7923.05	Saturated sand	Sd	
VES 14	1	N6^0 11' 17.88"	280 m	6	6	263.36	Laterite	0.0227	0.0171 Poor
	2	E7^0 19' 50.88"		3	9	559.35	Shaly sand	0.0053	
	3			41	41	2054.97	Medium sand	0.0199	
	4			100	100	4841.86	Coarse sand	0.0206	
	5			350	350	3373.97	Saturated sand	Sd	

NA = Not Applicable, APC = Aquifer Protective Capacity & Sd = Saturated depth.

Table 8: Continued Evaluated Aquifer Protective Capacity Rate of the Study Area.

4.5. vulnerability Assessment of Aquifer for Sustainable Groundwater Resources in the Study Area

Vulnerability assessment of an aquifer is a systematic evaluation of the potential risks and threats to the sustainable use of groundwater resources. It involves analyzing various factors that may influence the vulnerability of the aquifer to depletion or contamination. Here are some key steps and conditions involved in conducting a vulnerability assessment:

1. Hydrogeological Characteristics: Assess the physical properties of the aquifer, such as its geological formation, porosity, permeability, and recharge rates. These factors determine the aquifer's ability to store and transmit groundwater.
2. Water Demand and Extraction: Determine the current and projected water demand within the aquifer's boundaries. Assess the withdrawal rates and extraction practices to understand if they are within sustainable limits.
3. Climate Change and Variability: Analyze the potential impacts of climate change on the aquifer's recharge rates, water availability, and quality. This assessment should consider factors like precipitation patterns, temperature changes and sea-level rise.
4. Land Use and Land Cover: Evaluate the land use practices and land cover changes within the aquifer's catchment area. Identify potential sources of contamination, such as agricultural activities, industrial sites, or urban development, and their impact on groundwater quality.
5. Groundwater Quality: Assess the vulnerability of the aquifer to contamination from various sources such as point sources (e.g., leaking storage tanks) and non-point sources (e.g., agricultural runoff). Analyze the chemical composition and monitor any changes in water quality over time.
6. Stakeholder Engagement: Engage with local communities, water authorities, and other stakeholders to gather insights about their water needs, concerns, and potential risks. Incorporate their knowledge into the assessment process.
7. Modeling and Data Analysis: Utilize hydrological models and

data analysis techniques to integrate and interpret various datasets collected during the assessment. These may include geological maps, groundwater monitoring data, remote sensing imagery, and socio-economic information.

8. Vulnerability Mapping: Develop vulnerability maps that depict the spatial distribution of vulnerability levels across the aquifer. These maps can help identify areas prone to overexploitation, Contamination or other risks.

9. Risk Mitigation Strategies: Based on the assessment findings, propose and prioritize appropriate risk mitigation strategies. These may include groundwater management plans, water conservation measures, land-use regulations, and groundwater recharge initiatives.

10. Continual Monitoring and Evaluation: Establish a monitoring system to track changes in the aquifer's vulnerability over time. Periodic evaluation will help assess the effectiveness of implemented measure and guide future decision making.

Overall, a vulnerability assessment of an aquifer is a critical step towards sustainable management of groundwater resources, providing valuable insights for policymakers, water resource managers, and other stakeholders involved in water planning and management. The concept of vulnerability assessment in this research involved the resistance to contamination rating which is presented in table 4.7, Groundwater occurrence, Over-layering and Depth (GOD Indexing) in table 4.8 and physiochemical analysis of water quality.

VES NO.	Coordinates	Elevation	Average ρa of Protective Layer (Ωm)	Calculated Hydraulic Conductivity Constant (Kcσ) of Protective Layer	Average Thickness of Protective Layer (m)	Hydraulic Resistance (Rc)	Resistant Rating to Contamination
VES 1	N6^0 1'44.04" E7^0 3' 14.04"	355 m	2336.13	0.00042	50	119047	Extremely low
VES 2	N6^0 4' 6.96" E7^0 15' 45.72"	370 m	1887.10	0.00052	50	96153	Extremely low
VES 3	N6^0 10' 59.16" E7^0 17' 11.6"	177 m	1458.27	0.00068	25	36764	Extremely low
VES 4	N6^0 3' 6.84" E7^0 8' 22.92"	253 m	3439.30	0.00029	50	172413	Extremely low
VES 5	N5^0 58' 52.32" E7^0 5' 10.32"	249 m	1596.74	0.00062	37.5	60483	Extremely low
VES 6	N6^0 14' 38.76" E7^0 18' 51.84"	259 m	2958.02	0.00033	12.5	37878	Extremely low
VES 7	N6^0 14' 38.76" E7^0 18' 10.8"	128 m	4926.51	0.00020	173.5	145637	Extremely low
VES 8	N6^0 9' 1.8" E7^0 11' 18.96"	169 m	4039.61	0.00024	20	83333	Extremely low
VES 9	N5^0 56' 7.08" E7^0 4' 45.84"	165 m	1892.67	0.00052	50	96153	Extremely low
VES 10	N6^0 7' 48.72" E7^0 9' 22.68"	196 m	2702.48	0.00037	50	135135	Extremely low
VES 11	N5^0 54' 24.84" E6^0 58' 17.76"	187 m	3071.92	0.00032	25	78125	Extremely low
VES 12	N6^0 10' 32.88" E7^0 3' 16.92"	252 m	1144.92	0.00087	37.5	431034	Extremely low
VES 13	N6^0 1' 28.56" E7^0 4' 45.84"	319 m	3837.18	0.00026	50	192307	Extremely low
VES 14	N6^0 11' 17.88" E7^0 19' 50.88"	280 m	1953.84	0.00051	75	147058	Extremely low

Table 9: Results of Aquifer vulnerability Assessment using Hydraulic Resistance (Rc)

VES NO.	Coordinates	Elevation	G = Groundwater Occurrence	O = Over-layering Lithology Protective Layer	D = Depth	GOD	GOD Index	Vulnerability Assessment
VES 1	N6^0 1'44.04" E7^0 3' 14.04"	355 m	Unconfined	Medium sand	500	1.0 1.0 0.6	0.6	High
VES 2	N6^0 4' 6.96" E7^0 15' 45.72"	370 m	Unconfined	Medium sand	300	1.0 1.0 0.6	0.6	High
VES 3	N6^0 10' 59.16" E7^0 17' 11.6"	177 m	Unconfined	Coarse sand	100	1.0 1.0 0.6	0.6	High
VES 4	N6^0 3' 6.84" E7^0 8' 22.92"	253 m	Unconfined	Coarse sand	300	1.0 1.0 0.6	0.6	High
VES 5	N5^0 58' 52.32" E7^0 5' 10.32"	249 m	Unconfined	Medium sand	400	1.0 1.0 0.6	0.6	High
VES 6	N6^0 14' 38.76" E7^0 18' 51.84"	259 m	Unconfined	Medium sand	400	1.0 1.0 0.6	0.6	High
VES 7	N6^0 14' 38.76" E7^0 18' 10.8"	128 m	Unconfined	Medium sand	400	1.0 1.0 0.6	0.6	High
VES 8	N6^0 9' 1.8" E7^0 11' 18.96"	169 m	Unconfined	Lenses of shale	35	1.0 0.5 0.6	0.3	Moderate
VES 9	N5^0 56' 7.08" E7^0 4' 45.84"	165 m	Unconfined	Coarse sand	400	1.0 1.0 0.6	0.6	High
VES 10	N6^0 7' 48.72" E7^0 9' 22.68"	196 m	Unconfined	Coarse sand	400	1.0 1.0 0.6	0.6	High
VES 11	N5^0 54' 24.84" E6^0 58' 17.76"	187 m	Unconfined	Medium sand	200	1.0 1.0 0.6	0.6	High
VES 12	N6^0 10' 32.88" E7^0 3' 16.92"	252 m	Unconfined	Lenses of shale	200	1.0 0.5 0.6	0.3	Moderate
VES 13	N6^0 1' 28.56" E7^0 4' 45.84"	319 m	Unconfined	Coarse sand	400	1.0 1.0 0.6	0.6	High
VES 14	N6^0 11' 17.88" E7^0 19' 50.88"	280 m	Unconfined	Coarse sand	350	1.0 1.0 0.6	0.6	High

Table 10: Results of Aquifer Vulnerability Assessment using Groundwater Occurrence, Over-layering and Depth (GOD Indexing)

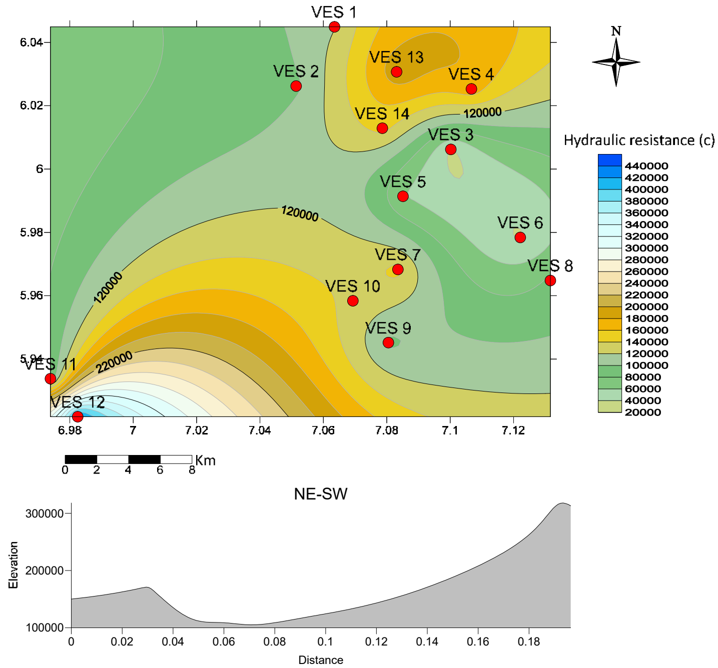

Figure 13: Contour Map of Hydraulic Resistance Rating of the Study Area

The figure 13 above show the result of the hydraulic resistance of the groundwater potential of the study area. Aquifer hydraulic resistance refers to the measure of the resistance a groundwater system encounters when water flows through an aquifer. It is a property that describes the ease or difficulty with which water can move through the subsurface sediment or rock formations that make up the aquifer. Because of the formation of the study area resistance to infiltration and recharge rate of the groundwater system termed very negligible, therefore permits the immediate inflow of contaminants as it lacks sufficient filtrating agents which is clay/shale.

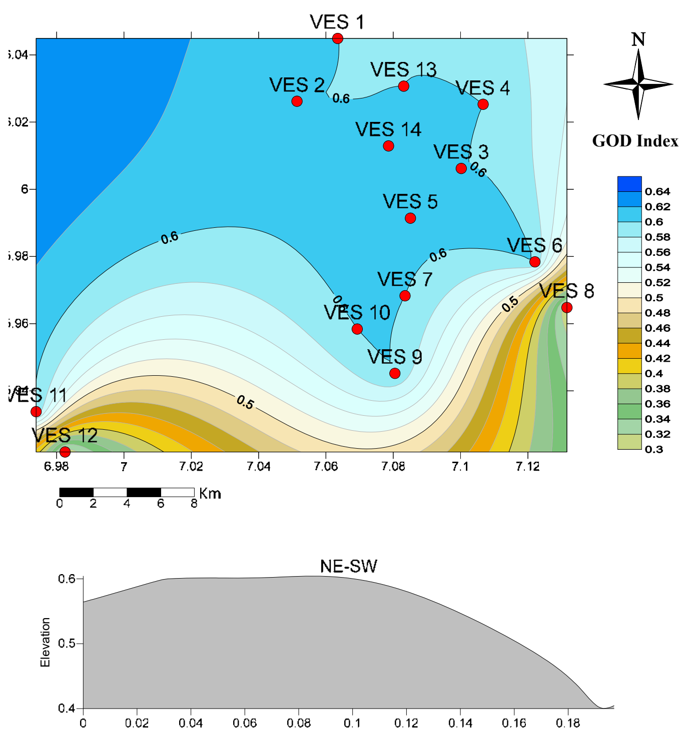

Figure 14: Contour Map of the Groundwater Occurrence, Over-layering and Depth Indexing of the Study Area

The GOD indexing map in the figure 14 revealed that the vulnerability of groundwater resources in the study area is evenly high consequently to the geological formation of the study area. VES 8 and VES 12 tend moderately vulnerable to contamination. The high rating of vulnerability to contamination of the groundwater resources of the study confirmed presence of little or no filtering agents, thus the hydraulic resistance is low.

5. Conclusion

The research aimed at evaluating the geological formation of the study area with the adoption of near–surface (electrical) resistivity studies for sustainability of the resources. From the integrated and analyzed data, results of the hydraulic parameters of the study area were revealed. Longitudinal conductance calculations and transversal resistance are reliable indicators for aquifer used for groundwater extraction and they produce contour maps showing an area for groundwater exploration and potential depth of saturation. Potential depths of saturation in the study area range from 50 m – 300 m with thickness of 35 m – 400 m. Transmissivity and hydraulic conductivity of saturated layer ranged 49.70 m^2/day – 384.37 m^2/day and 1.5 m/day – 9.1 m/day respectively with hydraulic resistance of 36764 – 431034. According to Freeze and Cherry, 1979 rating of transmissivity, VES 1, VES 2, VES 4, VES 6, VES 9, VES 10, VES 13 and VES 14 revealed good transmissivity, VES 7, VES 11 and VES 12 are moderately good in transmissivity rate and VES 3 and VES 8 are fairly good in transmissivity. Smedema and Rycroft, 1983 range of hydraulic conductivity values proved medium – coarse sand texture of the formation in the study area. From the results aquifer in the study area are predominantly unconfined. Consequently, the insufficiency of protective capacity of the hydraulic parameters which rated poor in the study area contributes to extreme low resistance to contamination. The vulnerability assessment of the study area using GOD indexing rated predominantly high [11-26].

Competing Interests

Authors have declared that no competing interests exist.

References

1. Abiola, O., Enikanselu, P. A., & Oladapo, M. I. (2009). Groundwater potential and aquifer protective capacity of overburden units in Ado-Ekiti, southwestern Nigeria. *International Journal of Physical Sciences, 4*(3), 120-132.
2. George, N. J., Nathaniel, E. U., & Etuk, S. E. (2014). Assessment of economically accessible groundwater reserve and its protective capacity in Eastern Obolo Local Government Area of Akwa Ibom State, Nigeria, using electrical resistivity method. *International Scholarly Research Notices, 2014.*
3. Asiwaju-Bello, Y. A., Olabode, F. O., Duvbiama, O. A., Iyamu, J. O., Adeyemo, A. A., & Onigbinde, M. T. (2013). Hydrochemical evaluation of groundwater in Akure Area, south-western Nigeria, for irrigation purpose. *Eur Int J Sci Technol, 2*(8), 235-249.
4. Mazáč, O., Císlerová, M., Kelly, W. E., Landa, I., & Venhodová, D. (1990). Determination of hydraulic conductivities by surface geoelectrical methods. In *Geotechnical an Environmental Geophysics: Volume II: Environmental and Groundwater* (pp. 125-132). Society of Exploration Geophysicists.
5. Aweto, K. E. (2011). Aquifer vulnerability assessment at Oke-Ila area, southwestern Nigeria. *Int J Phys Sci, 6*(33), 7574-7583.
6. George, N. J., Ibuot, J. C., & Obiora, D. N. (2015). Geoelectrohydraulic parameters of shallow sandy aquifer in Itu, Akwa Ibom State (Nigeria) using geoelectric and hydrogeological measurements. *Journal of African Earth Sciences, 110,* 52-63.
7. Braga, A. C. D. O., Malagutti Filho, W., & Dourado, J. C. (2006). Resistity (DC) method applied to aquifer protection studies. *Revista Brasileira de Geofísica, 24,* 573-581.
8. Jain, C. K., Bandyopadhyay, A., & Bhadra, A. (2010). Assessment of ground water quality for drinking purpose, District Nainital, Uttarakhand, India. *Environmental monitoring and assessment, 166,* 663-676.
9. Mosuro, G. O., Omosanya, K. O., Bayewu, O. O., Oloruntola, M. O., Laniyan, T. A., Atobi, O., ... & Adekoya, F. (2017). Assessment of groundwater vulnerability to leachate infiltration using electrical resistivity method. *Applied Water Science, 7,* 2195-2207.
10. Adelakun, A. (2009). Enhancing Nigerian competitiveness in the global economy through strategic alliances. *Economics and Management,* (14), 649-654.
11. Akinlalu, A. A., Adegbuyiro, A., Adiat, K. A. N., Akeredolu, B. E., & Lateef, W. Y. (2017). Application of multi-criteria decision analysis in prediction of groundwater resources potential: a case of Oke-Ana, Ilesa Area Southwestern, Nigeria. *NRIAG Journal of Astronomy and Geophysics, 6*(1), 184-200.
12. Adeyemo, I. A., Olowolafe, T. S., & Fola-Abe, A. O. (2016). Aquifer vulnerability assessment at Ipinsa-Okeodu area, near Akure, southwestern Nigeria, using GODT. *Journal of Environmental and Earth Science, 6*(6), 9-18.
13. Afonso, M. J., Freitas, L., Pereira, A., Neves, L., Guimarães, L., Guilhermino, L., ... & Chaminé, H. I. (2016). Environmental groundwater vulnerability assessment in urban water mines (Porto, NW Portugal). *Water, 8*(11), 499.
14. Ait El Mekki, O., & Laftouhi, N. E. (2016). Combination of a geographical information system and remote sensing data to map groundwater recharge potential in arid to semi-arid areas: the Haouz Plain, Morocco. *Earth Science Informatics, 9,* 465-479.
15. Aladejana, O. O., Anifowose, A. Y. B., & Fagbohun, B. J. (2016). Testing the ability of an empirical hydrological model to verify a knowledge-based groundwater potential zone mapping methodology. *Modeling Earth Systems and Environment, 2,* 1-17.
16. Nadjla, B., Abdellatif, D., & Assia, S. (2021). Mapping of the groundwater vulnerability to saline intrusion using the modified GALDIT model (Case: the Ain Temouchent coastal aquifer,(North-Western Algeria)). *Environmental Earth Sciences, 80*(8), 319.

17. Salim, B. K., Abdellatif, D., Bouhadjar, M., & Cherif, K. (2019, May). GIS Application for Groundwater Vulnerability Assessment: Study Case of Hammam-Bou-hadjar Area-NW of Algeria. In *GISTAM* (pp. 207-211).
18. Civita, M., & De Maio, M. (2004). Assessing and mapping groundwater vulnerability to contamination: the Italian combined approach. *Geofísica internacional, 43*(4), 513-532.
19. Evans, U. F., Abdulsalam, N. N., & Mallam, A. (2017). Natural vulnerability estimate of groundwater resources in the coastal area of Ibaka Community, using Dar Zarrouk geoelectrical parameters. *Journal of Geology & Geophysics, 6*(4), 1000295.
20. Ezeigbo, H. I. (1989). Groundwater quality problems in parts of Imo State, Nigeria. *Nig Jour. Min and Geol, 25.*
21. Lawal, T., & Oluwatoyin, A. (2011). National development in Nigeria: Issues, challenges and prospects. *Journal of Public Administration and policy research, 3*(9), 237-241.
22. Niwas, S., & Singhal, D. C. (1981). Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *Journal of hydrology, 50*, 393-399.
23. Obiora, D. N., & Ibuot, J. C. (2020). Geophysical assessment of aquifer vulnerability and management: a case study of University of Nigeria, Nsukka, Enugu State. *Applied Water Science, 10*(1), 1-11.
24. Oladapo, M. I., & Akintorinwa, O. J. (2007). Hydrogeophysical study of ogbese south western Nigeria. *Global journal of pure and applied sciences, 13*(1), 55-61.
25. Olabode, O. F. (2019). Potential groundwater recharge sites mapping in a typical basement terrain: a GIS methodology approach. *Journal of Geovisualization and Spatial Analysis, 3*(1), 5.
26. Standards Organisation of Nigeria, “Nigerian standard for drinking water quality,” NIS, vol. 554, pp. 1–30, 2007.