Original Research Article

Assessment of Aquifer Vulnerability and Groundwater Prospects Using Electrical Resistivity Method in parts of Nnewi Southeastern Nigeria.

ABSTRACT

The assessment of the aquifer vulnerability and groundwater potential of Umudim, Okpunoeze, Umudimkwa and Okpunoegbu all in Nnewi town of Anambra state southeastern Nigeria was carried out. It is located between latitudes 5°59' 30"N and 6°01' 30"N and longitudes 6°53' 30"E and 6°55' 30"E. Electrical resistivity survey using vertical electrical sounding (VES) employing Schlumberger electrode array was conducted in fifteen locations (A-0). The datagenerated was used to interpret the aquifer thickness which ranged from 23.12-108.83m and depth to water table ranged from 25.41-99.42m. The aquifer properties such as hydraulic conductivity (0.1227 to 3.0931m/day) and transmissivity (3.9139 to 79.3152m^2/day) and the Dar-Zarrouk parameters longitudinal conductance (0.00107 to 0.0246Ωm) and transverse resistance (3.6 x 10^3 to 2.3 x 10^{5}Ωm^2) were obtained.The VES curves identified were mostly K with some A and H types. Five to six geoelectric layers were identified with the aquiferous units occurring in the fourth and fifth layers respectively. Multi-aquifer types such as unconfined and semi-confined aquifers exist in the study area. The area has good prospects for groundwater development with the potential increasing towards the western parts of the study area. The protective capacity was rated as poor implying the aquifers are vulnerable to pollution from surface infiltration. The protective capacity was positively influenced by the overburden thickness and the clay content of the geologic materials.

Keywords: Groundwater potential, Aquifer vulnerability, Protective capacity, hydraulic properties and longitudinal conductance

1. Introduction

Water is essential to all forms of life. Surface water is more readily accessible and at a cheaper cost than groundwater hence, in areas where it is available it is mostly used. However, with the advent of industrialisation and consequent population growth and urbanisation the surface water bodies are increasingly being endangered by wastes from anthropogenic activities. Groundwater has becomes a viable alternative to surface water. It is deemed to be of good quality, less polluted and less vulnerable to contamination (Freeze and Cherry, 1979, Reilly *et al.,* 2008). However, where aquifers are in hydraulic continuity with the ground surface, groundwater could be vulnerable to pollution from surface sources (Bayewu*et al.,* 2018,Emecheta*et al.,* 2023). Groundwater is readily available in humid areas of the world. Therefore, groundwater exploration and exploitation to evaluate quantity and quality has become very essential. Though in recent times both the quantity and quality of water is steadily decreasing due to poor management and poor waste management especially in developing countries such as Nigeria (Okolo *et al.,* 2020)

Groundwater occurs in porous and permeable geologic units termed aquifer. An aquifer is a saturated porous and permeable geologic unit which can transmit significant quantities of water under ordinary hydraulic gradients (Todd and Mays, 2005).Different geologic materials are classified according to their capability to store and transmit water as aquifer, aquiclude, aquifuge and aquitard (Fetter, 2000). These materials play important roles in water management in terms of storing water, confining units and protecting the aquifer from pollution from infiltration from the surface. It is one thing to explore and obtain groundwater but it is another thing to protect groundwater from pollution through proper management. The potential of a material to store water and the ability to transmit water in a hydrologic system is governed by the hydraulic properties of the porous medium. These properties are known as the aquifer hydraulic properties and include hydraulic conductivity (K), transmissivity (T), Storativity (S) and specific storage (Ss). These characteristics are influenced by porosity, particle size distribution, shape of particle, arrangement of particle, and other factors (Freeze and Cherry, 1979). These properties can be calculated from particle size distribution curves, pumping test analysis and geophysical methods.

Therefore, the need to sustain groundwater development has increased theincorporation of appropriate geophysical and geological methods in the search for water (Anakwuba et al, 2020, Tijani *et al.,* 2021). The vertical electrical sounding (VES) has been variously applied in the characterisation of aquifer protective capacity and hence evaluation of groundwater vulnerability to pollution (Gemail*et al.*, 2011, Achilike, 2020), determination of aquifer parameters (Okonkwo and Ugwu, 2015, Nfor et al, 2007) among others. The Schlumberger array has been proved to be the method of choice because of the easy of application, low-cost and capability (Ankidawa*et al.*, 2018).

The Dar-Zarrouk parameters were originally developed and advanced by Maillet (1947). The Dar-Zarrouk parameters were applied to determine the aquifer protective capacity and groundwater potential (Henriet, 1976, Okonkwo and Ugwu, 2015). The Dar-Zarouk parameters are determine from VES and are useful in understanding the spatial distribution of aquifer characteristics. The parameters are fairly constant in areas where the regional geology and water quality do not show much variation (Nwosu *et al.,* 2014). For a homogeneous and isotropic layer of resistivity pi, thickness hi, the longitudinal conductance S, and transverse unit resistance T' is given as

$$S = \sum_{i=1}^{n} hi/pi \qquad 1$$

$$T' = \sum_{i=1}^{n} hi.pi \qquad 2$$

The correlation between the Dar-Zarrouk parameters and the aquifer transmissivity T was established by Duprat et al (1970). Transmissivity is the product of the saturated aquifer thickness (b) and the hydraulic conductivity (K), (T = Kb). Variation in stratigraphy has resulted in different aquifer types such as unconfined, confined, perched and semi-confined aquifers.These aquifer types are made up of permeable geologic materials and confining units (aquitards).

The study area covers Umudim, Okpunoeze, Umudimkwa and Okpunoegbu all in Nnewi town of Anambra state southeastern Nigeria. It is located between latitudes 5°59' 30"N and 6°01' 30"N and longitudes 6°53' 30"E and 6°55' 30"E.The study area is stratigraphically located in the Niger Delta basin (Nwajide, 2013) and is the youngest basin in Benue Trough. The proto-Niger Delta consisted of deposits of the regressive interval into the late Cretaceous into the early Paleocene (Short and Stuble, 1967). The Paleocene facies were thus the proto-delta on which the early Eocene regression began to deposit the modern Niger Delta. The origin and formation is believed to be related to the mega-tectonic structural pattern correlated with the breakup of the Gondwanaland during the Late Jurassic to Early

Cretaceous (Onuigbo et al., 2015)The area of the onshore Cenozoic Niger Delta has its base as the Paleocene Imo Formation. The Paleocene facies were the pro-delta on which the Early Eocene regression deposited the Modern Niger Delta. The lithostratigraphic units outcropping in the Niger Delta include the Imo Formation, Ameki Group, the Ogwashi-Asaba Formation and the Akata Formation and Agbada Formation as the subsurface units (Nwajide, 2013). The study area is underlain by the Oligocene-Miocene Ogwashi-Asaba Formation (Okezie and Onuogu, 1985) (Fig. 1).

The study area has an undulating topography with prominent gully sites located at lower elevations. The gully sites have become good sites for surface waste dumpsites. The residents of the study area depend mostly on groundwater as their major source of water supply for drinking and other uses. Therefore, it has become imperative to assess the geology of the study area to ascertain the level of vulnerability by characterising the protective capacity of the overburden. Groundwater being the resource of choice in the study area it would be economical and ideal to determine the groundwater potential of the geologic materials for proper planning and management of groundwater resources in the area.The previous researches alluded to the regional transmissivity and depth to drilled depth. Therefore, it has become imperative to integrate the use of geophysics and Dar-Zarrouk parmeters to assess the protective capacity and groundwater potential of the area. Hence, the present research seeks to characterize the protective capacity of the overburden on aquifers using electrical resistivity data and the Dar-Zarrouk parameters and to evaluate the groundwater potential of the study area.

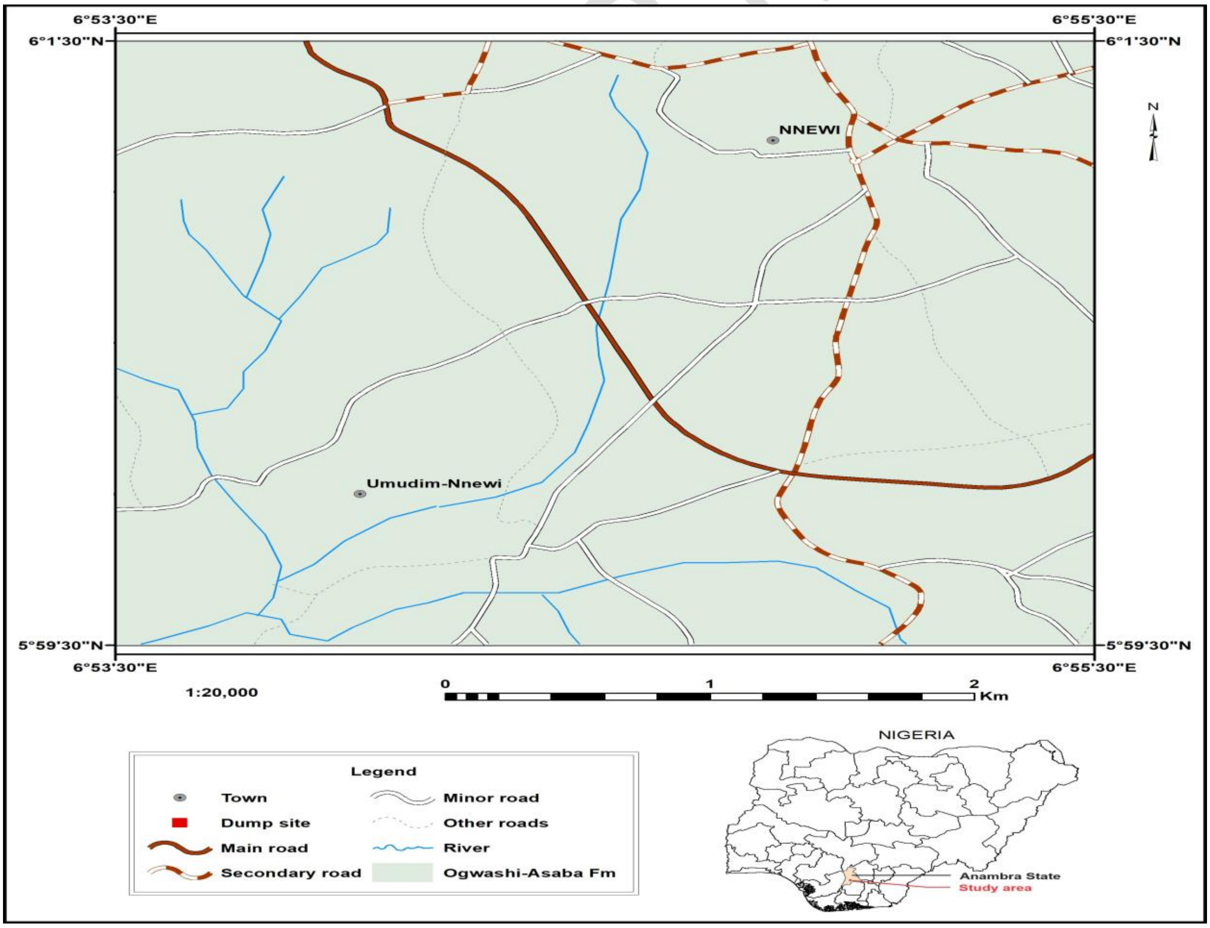


Fig. 1: Geologic, accessibility and drainage map of the study area

2. Methodology

The study area parts of Nnewi is located between latitudes 5°59' 41'N and 6°01' 30"N and longitudes 6°53' 30"E and 6°55' 30"E. The study is focused in parts of Uruagu and Umudim area of Nnewi. The surface drainage is controlled by the Mmili Eze River and its tributaries which flow in the southwestern direction into the Ulasi River.The climate is the Equatorial type, warm and humid (Egboka, 1993). There are two major seasons the wet (April to October) and dry (November to March) seasons (Igbozurike, 1995). The wet season generally influence groundwater recharge and infiltration of surface pollutants into the groundwater system.

Geophysical method (vertical electrical sounding VES) was used to assess the subsurface and interpretations were made from the acquired data to determine the lithologic units, aquiferous units and their different depths.The Schlumberger electrode array was employed for each VES profile with half current (AB/2) electrode separation of 150 m and half potential (MN/2) electrode separation of 15m. This procedure is known to generate reliable subsurface stratigraphic contrasts. This technique uses two pairs of electrodes technically referred to as the current and potential electrodes connected to a resistivity meter.

Fifteen (15) VES (Fig. 2) were carried out in the study area using OHMEGA SAS1000 Terrameter with its accessories. The electric soundings were taken at the site of existing boreholes for the purpose of comparison to establish the interrelationship between the geoelectric sections and subsurface geo-electrical layer.The apparent resistivity values obtained were plotted on a bi-logarithmic graph against the half current electrode separation spacing and the curves generated were smoothened to remove the effects of lateral inhomogeneity and other forms of noisy signatures (Bhattacharya and Patra 1968; Chakravarthi *et al*. 2007).

From these plots, qualitative deductions, such as the resistivity of the first or top layer, the depth of each layer, and the curve types were made. The resistivity and thicknesses of the various layers were improved upon by employing an automatic iterative computer program following the main ideas of Zohdy and Martin (1974). The ZOND computer software was employed for carrying out the iteration and inversion processes.

Aquifer's protective capacity or vulnerability was determined using the Dar Zarrouk and aquifer parameters. These parameters were estimated from electrical resistivity measurements. Aquifer vulnerability maps were also produced.

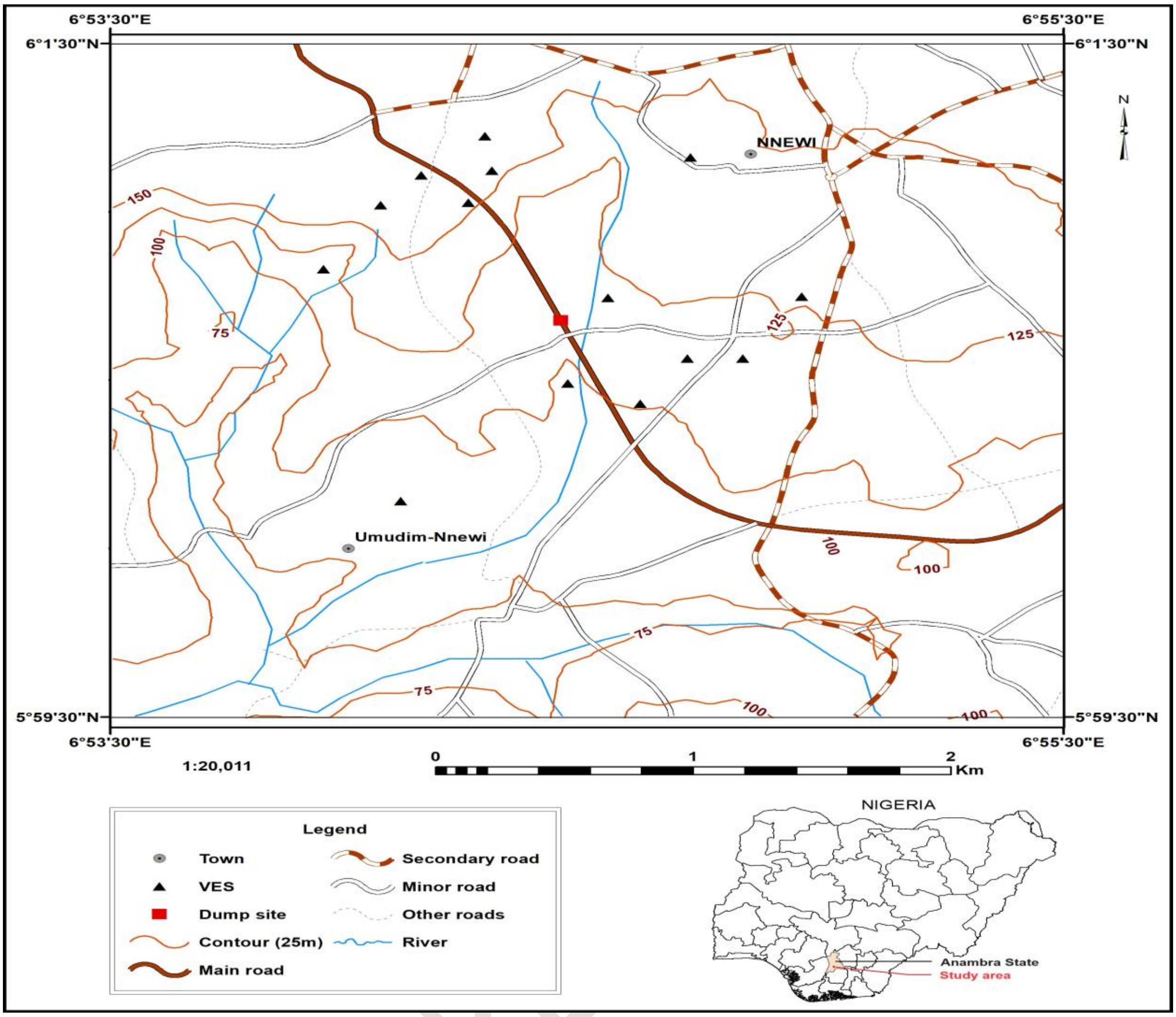


Fig.2: Vertical Electrical Sounding (VES) points distribution in the study area

4.0 Result and Discussion

4.1. Groundwater Potential of the Study Area

The strip logs and curves generated from the VES are shown in figure3. For profile AB' consisting of VES points A to O respectively. The geo-electric sections show a five – layer model with the simulated curves showing type K for A to H. Further, locations I, L, M and N were curve type A, and K and O were curve type Hrespectively.

Also, Table 1 shows thata five-layer geoelectric model was mostly enough to represent the data observed in the field, but occasionally, a six-layer model was used for the interpretation. At all the locations, a low resistivity top layer and base layer were interpreted, with middle layers of average moderate electrical resistivity with occasionally high resistivity units. This was the general trend found in the area except for location C which recorded anomalously very low resistivity (107.42-425.49Ωm) for the entire column of geoelectric units interpreted. This may be because of contaminants or lithologic changes.

The aquiferous units were interpreted as the fourth and fifth layer in a five layer and six layer geoelectric sections respectively.The aquiferous units consist of mostly sand at all the locations with a small percentage being sandy clay. An average resistivity of 1340.25Ωm, average aquifer thickness of 41.75m and average depth to aquifer of 51.25m were observed in the study area figure3 which represents strip logs from the various VES locations.The regional water table ranges from 25.41m to 99.42m. The combination of good aquifer thickness, shallow depth to water table and the aquifer implies good prospect for groundwater. The prospect was also observed by Nfor *et al*., (2007) as the observations are within the values obtained in the present study. Multiple aquifer types exist in the study area which was mostly unconfined and semi-confined aquifers. This means good groundwater recharge to the aquifers exists.

Table 1: Parameters interpreted from VES data

Station ID	Layer No.	App Res (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology	Curve Type
VES A (rms: 8.6%)	6					K
	1	870.3	1.91	0	Top layer/weathered sediments	
	2	1168.64	3.61	1.91	Sandy Clay	
	3	2291.64	21.74	5.52	Clayey Sand	
	4	4888.93	22.47	27.25	Sand	
	5	3491.89	64.98	49.73	Water-Saturated Sand	
	6	1394.52	Undetermined	114.7	Clayey Sand	
VES B (rms: 22.6%)	5					K
	1	174.05	1.32	0	Top layer/weathered sediments	
	2	3236.35	7.58	1.32	Clayey Sand	
	3	5547	52.03	8.9	Sand	
	4	1265.83	40.2	60.93	Water-Saturated Sand	
	5	5593.9	Undetermined	101.17	Sand	
VES C (rms: 4.4%) 5						K
	5					
	1	107.42	1.5	0	Top layer/weathered sediments	
	2	425.49	4.31	1.5	Sand	
	3	394.44	19.6	5.82	Clayey Sand	
	4	359.55	23.12	25.41	Water-Saturated Sand	
	5	145.45	Undetermined	48.54	Clay	K
VES D (rms: 25.2%)	5					
	1	342.21	1.2	0	Top layer/weathered sediments	
	2	1692.46	7.96	1.2	Clayey Sand	
	3	5099.12	30.65	9.16	Dry Sand	
	4	4807.3	31.9	39.81	Water-Saturated Sand	
	5	3961.01	Undetermined	71.73	Sand	K
VES E (rms: 13.4%)	5					
	1	1276.54	1.35	0	Top layer/weathered sediments	
	2	4290.83	3.45	1.35	Clayey Sand	
	3	10832.66	35.01	4.8	Sand	
	4	2962.54	108.83	39.81	Water-Saturated Sand	
VES F (rms: 25.3%)	5				Sandy Clay	K
	1	238.01	1.68	0		
	2	1012.71	13.1	1.68	Top layer/weathered sediments	
	3	4456.51	25.5	14.78	Clayey Sand	
	4	2804.77	31.87	40.28	Dry Sand	
	5	4308.93	Undetermined	72.15	Water-Saturated Sand	
VES G (rms: 4.7%)	6					K
	1	154.93	1.71	0	Top layer/weathered sediments	

	2	1430.19	3.94	1.71	Sand	
	3	1185.38	18.89	5.65	Clayey Sand	
	4	1382.83	49.74	24.54	Dry Sand	
	5	1281.93	26.3	74.28	Water-Saturated Sand	
	6	987.45	Undetermined	100.58	Sandy Clay	
VES H (rms: 33.9%)	6					K
	1	420.15	1.3	0	Top layer/weathered sediments	
	2	1582.23	4.79	1.3	Sand	
	3	1168.53	33.95	6.09	Clayey Sand	
	4	270.05	38.2	40.04	Sandy Clay	
	5	151.06	24.08	78.28	Water-Saturated Sandy Clay	
	6	69.92	Undetermined	102.36	Clay	
VES I (rms: 31.9%)	5					A
	1	1087.84	1.57	0	Top layer/weathered sediments	
	2	24688.34	7.28	1.57	Sand	
	3	10832.66	18.41	8.85	Clayey Sand	
	4	168.9	47.46	27.25	Water-Saturated Sandy Clay	
	5	629.5	Undetermined	74.72	Clayey Sand	
VES J (rms: 18.1%)	6					K
	1	1454.47	1.51	0	Top layer/weathered sediments	
	2	2106.61	4.41	1.51	Sand	
	3	664.77	9.03	5.92	Sandy Clay	
	4	4930.26	60.2	14.95	Sand	
	5	2622.09	26	75.15	Water-Saturated Sand	
	6	1986.04	Undetermined	101.17	Clayey Sand	
VES K (rms: 22.1%)	5					H
	1	140.72	1.26	0	Top layer/weathered sediments	
	2	3520.61	7.7	1.26	Sand	
	3	3155.63	66.6	8.95	Clayey Sand	
	4	2600.1	24.4	75.59	Water-Saturated Sand	
	5	3927.8	Undetermined	100	Sand	
VES L (rms: 29.4%)	5					A
	1	103.01	1.54	0	Top layer/weathered sediments	
	2	7966.72	7.89	1.54	Sand	
	3	3671.97	30.84	9.43	Clayey Sand	
	4	2106.61	59.1	40.28	Water-Saturated Sandy Sand	
	5	800.03	Undetermined	99.42	Clay	
VES M (rms: 19.1%)	5					A
	1	213.34	1.5	0	Top layer/weathered sediments	
	2	2578.31	7.83	1.5	Sand	
	3	1841.12	40.65	9.32	Clayey Sand	
	4	1504.29	48.3	49.97	Water-Saturated Sandy Sand	
	5	1110.97	Undetermined	98.27	Sand	
VES N (rms: 18.9%)	5					A
	1	401.14	1.38	0	Top layer/weathered sediments	
	2	2666.61	7.07	1.38	Sand	
	3	2291.64	41.6	8.45	Clayey Sand	
	4	626.72	96.8	50.04	Water-Saturated Sand	
	5	1083.27	Undetermined	146.83	Clayey Sand	
VES O (rms:	6					H
	1	576.12	1.26	0	Top layer/weathered	

14.7%)					sediments	
	2	3182.31	4.81	1.26	Sand	
	3	1721.2	19.2	6.06	Clayey Sand	
	4	5142.23	74.15	25.27	Sand	
	5	2876.51	58.15	99.42	Water-Saturated Sand	
	6	1004.22	Undetermined	157.57	Clayey Sand	

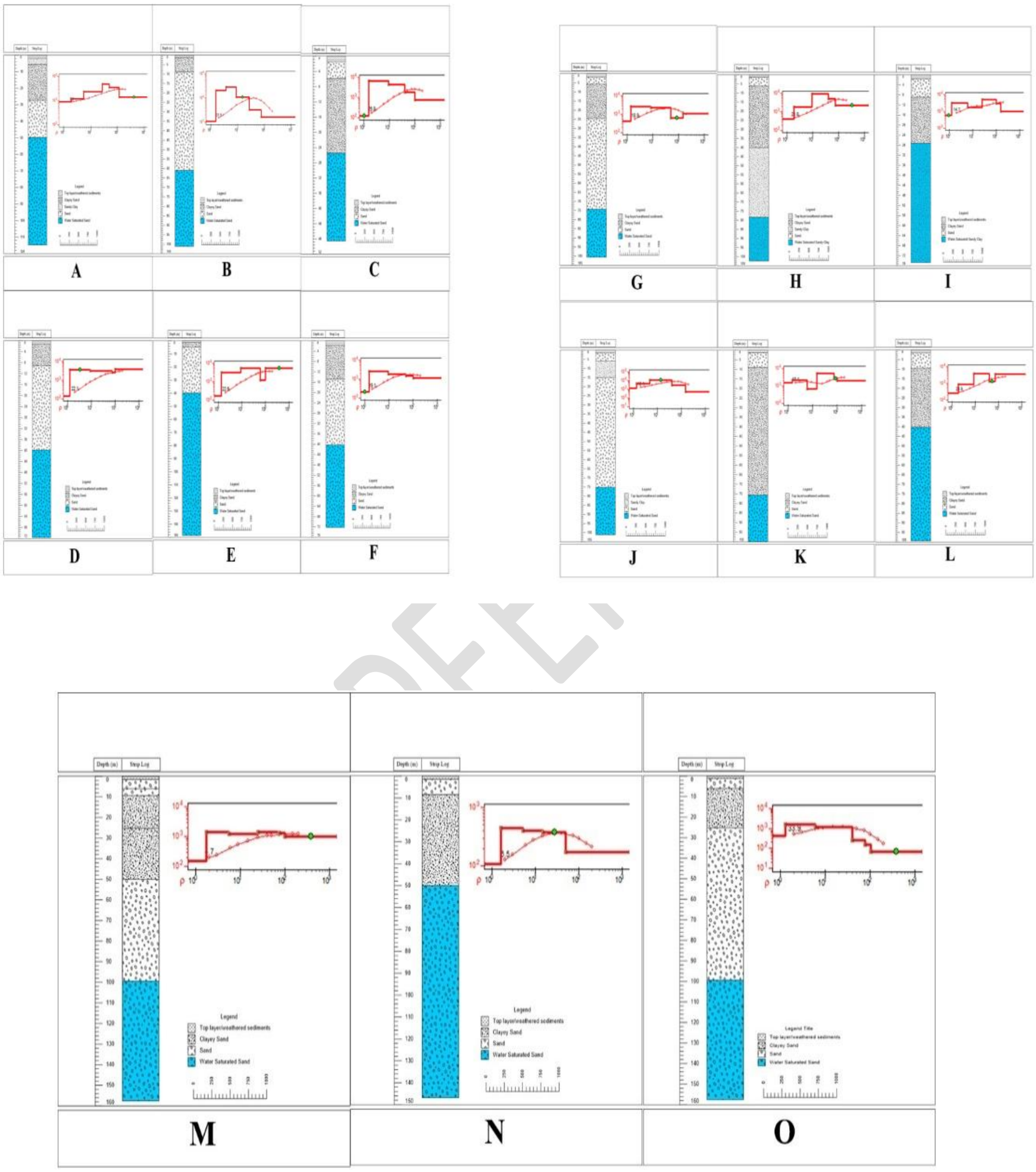


Fig.3: Strip Logs and corresponding VES curves A-O correspond to the different stations.

The map of the spatial distribution of the aquifer thickness and depth to the aquifer is shown in figure 4. From the distribution it was observed that depth to aquifer increased towards the northern parts of the study area and decreased towards the southern parts. However, the southwestern parts recorded the lowest depths. It was observed that elevation influenced the depth to the aquifer and depth to water table. The northern parts of the study area have higher elevations than the other parts (Igbozurike, 1995). The aquifer thickness showed increased thickness towards the southwestern parts of the study though in a small portion of the north-central part high aquifer thickness was also observed. This implies that good potential exists in the study area especially in southwestern parts.

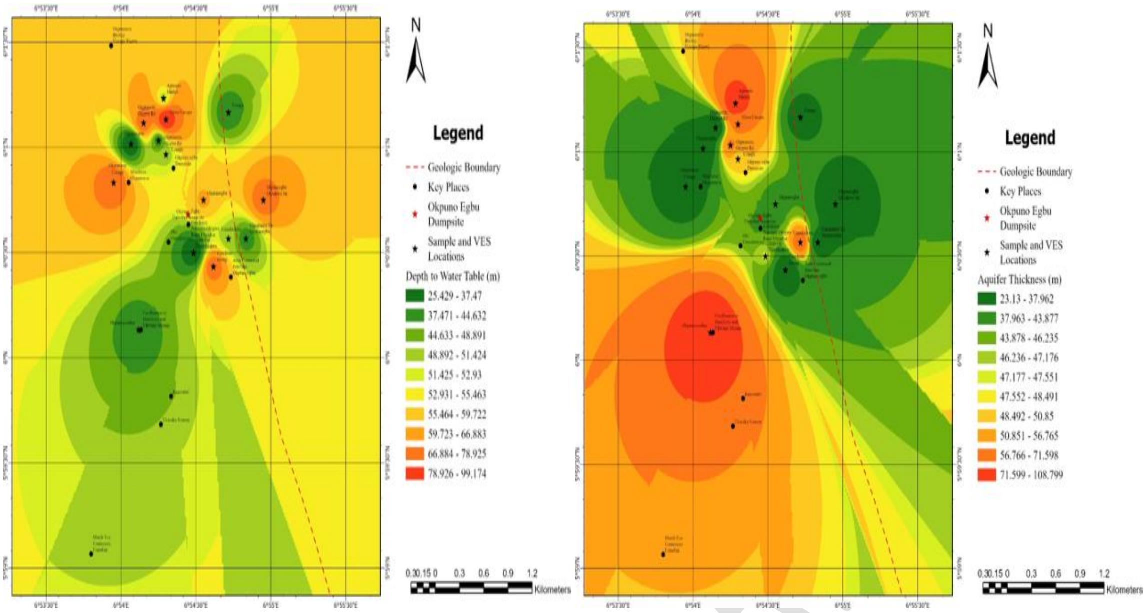


Fig.4: Map of the variation of the regional water table (a) and the variation in the aquifer thickness (b) in the study area.

4.2. Characterization of the Aquifer Properties using Secondary data

The hydraulic properties of the aquifer such as hydraulic conductivity (k) and transmissivity (T) were estimated and are recorded in Table 2.The values of K obtained from the present study range from 0.1227 to 3.0931m/day which is indicative of clean sand to silty sand according to Freeze and Cherry (1979). The T values range from 3.9139 to 79.3152m^2/day. These values are indicative of aquifer materials with good potential for groundwater development and good groundwater recharge.The present result is similar to the result of Nfor et al (2007) and Ifeanyichukwu et al (2021) in Nnewi town. Their study was on a regional scale. However, the present research recorded high values in the study area may be as result of local variations in geology.

Table 2: Dar-Zarrouk and Aquifer Properties; S, T, hydraulic conductivity (K) and transmissivity (T') estimated from VES curve.

Station ID	Hydraulic Conductivity K (m/day)	Transmissivity T (m^2/day)	Average overburden longitudinal conductance S (Ωm)	Transverse resistance (Ωm^2)	Aquifer Thickness (b) (m)	Aquifer Depth (m)	Aquifer Resistivity ρ (Ωm)
A	0.1650	10.7136	0.00484	2.3×10^5	64.98	49.73	3491.89
B	0.4260	17.1072	0.00644	5.1×10^4	40.20	60.93	1265.83
C	1.3824	31.8816	0.0246	8.3×10^3	23.12	25.41	359.55
D	0.1227	3.9139	0.00474	1.5×10^5	31.9	39.81	4807.30
E	0.1927	20.9952	0.00170	3.2×10^5	108.83	39.81	2962.54
F	0.2030	6.46272	0.00857	8.9×10^4	31.87	40.28	2804.77
G	0.4208	11.0592	0.00164	3.4×10^4	26.30	74.28	1281.93
H	3.0931	74.4768	0.00442	3.6×10^3	24.08	78.28	151.06
I	0.2791	132.1920	0.00115	8.0×10^3	47.46	27.25	168.9
J	0.2160	5.6160	0.00723	6.8×10^4	26.00	75.15	2622.09
K	0.2177	5.3136	0.00108	6.3×10^4	24.40	75.59	2600.10
L	0.2652	15.6384	0.00811	1.3×10^5	59.10	40.28	2106.61
M	0.3629	17.5392	0.00107	7.3×10^4	48.30	49.97	1504.29
N	0.8208	79.3152	0.00808	6.1×10^4	96.80	50.04	626.72
O	0.1987	11.4912	0.00732	1.7×10^5	58.15	99.42	2876.51

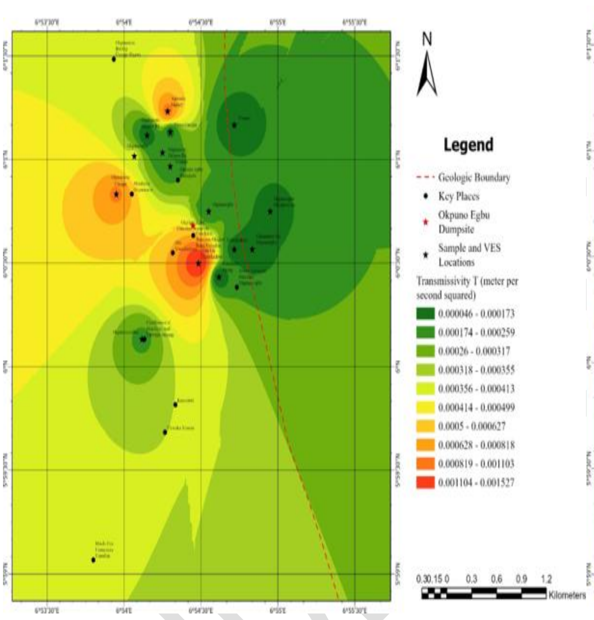
4.3. Characterization of the Aquifer Vulnerability

The values for the Dar-Zarrouk parameters S and T' are recorded in Table 2. Their spatial distributions are shown in figure5. The S, K and T' in the present study are positively correlated. This positive correlation was previously observed by Henriet (1976). The protective capacity of the overburden materials were characterized using the ratings proposed by Ogungbemi et al (2013). The rating is shown in Table 3. The values obtained for S ranges from 0.00107 to 0.0246Ωm which is less than 0.1Ωm and hence rated as poor.

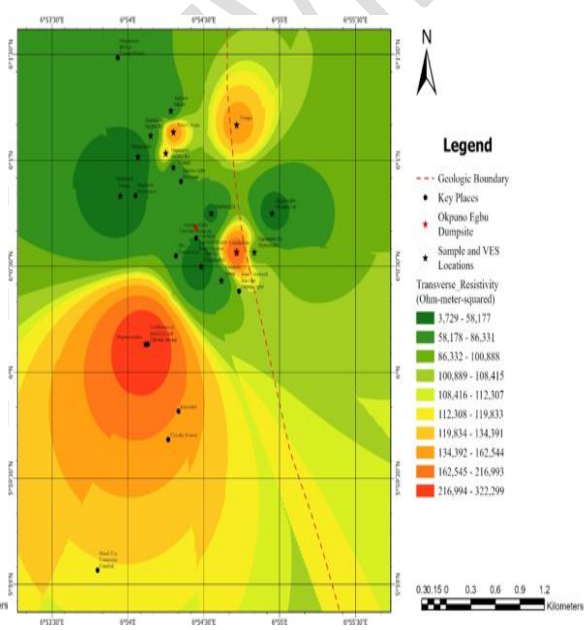
Table3: Longitudinal Conductance/Protective Capacity Rating (Ogungbemi et al. 2013)

Longitudinal Unit Conductance S (mhos)	Aquifer Protective Capacity (APC) rating
>10	Excellent
5-10	Very Good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
<0.1	Poor

The aquifer vulnerability maps (Fig. 5) indicate that the values for the aquifer hydraulic properties K and T and the Dar-Zarrouk parameters S and T’ were increasing towards the western parts of the study area. The highest values for T, K and S were observed in the north-western part while the highest vale for T’ was observed in the southwestern part of the study area respectively.Additionally, these values imply that those parts of the study area are underlain by highly conductive and transmissive geologic materials. Thus, implying that the overburden offer very low protective capacity to the underlying aquiferous rock units in the area. So, even in places where good low resistive rock layers indicative of clayey lithology has been observed, the thickness of the units is not large enough to offer better protection to underlying aquifers from infiltrating contaminated water and the clay content is not large enough to hinder permeability. Also, it was observed that some area where the thickness of the overburdenis large enough, the geology consists of mostly sand which is both porous and permeable. Therefore, the results indicate that two very important factors, thickness of the overburden and lithology greatly affect the protective capacity of overburden rocks in the study area. Hence, the groundwater potential is very good especially in the western parts of the study area. Also, aquifers in the western parts are vulnerable to groundwater pollution from pollutants infiltrating the groundwater zone from the surface.



(a)



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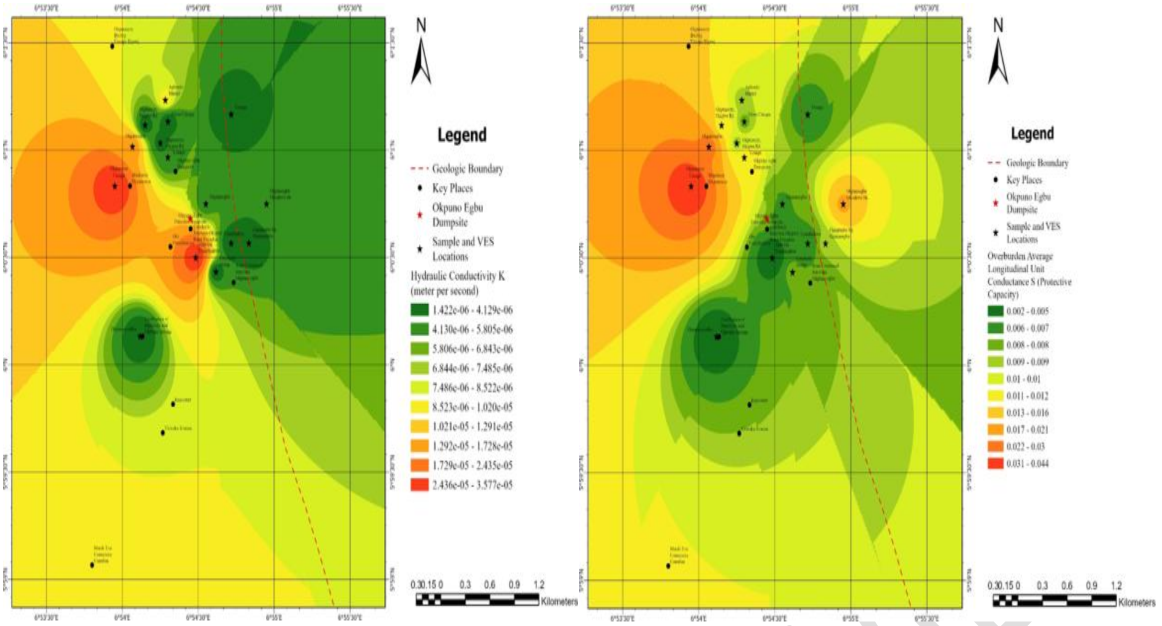

(c) (d)

Fig.5: Aquifer vulnerability map showing distribution of (a) transmissivity, (b) transverse resistance, (c) hydraulic conductivity and (d) longitudinal conductance in the study area

5. Conclusion.

Electrical resistivity method using VES and Schlumberger electrode array was carried out in fifteen locations (A-O). The data obtained was used to determine primary data such as aquifer depth, thickness, resistivity of the aquiferous unit, the curve types and the geoelectric units. The secondary data determined include the aquifer hydraulic properties such as K and T and Dar-Zarrouk parameters S and T'. The average aquifer thickness and depth to aquifer were 41.75m and51.25m respectively. The K and T values range from0.1227 to 3.0931m/dayand 3.9139 to 79.3152m^2/day respectively.These values indicate good prospect for groundwater development. Also the S values range from 0.00107 to 0.0246Ωm with the protective capacity being rate as poor. Thus, good groundwater potential exists in the study and also the aquifers especially in the western parts are vulnerable to pollution from surface infiltration because of the poor protective capacity.

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