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

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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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. An electrical resistivity survey using vertical electrical sounding (VES) employing a Schlumberger electrode array was conducted in fifteen locations (A-0). Also, the data generated was used to interpret the aquifer thickness which ranged from 23.12-108.83m and the depth to the water table ranged from 25.41-99.42m. Additionally, the aquifer properties such as hydraulic conductivity (0.1227 to 3.0931m/day) and transmissivity (3.9139 to 79.3152m2/day) and the Dar-Zarrouk parameters longitudinal conductance (0.00107 to 0.0246Ωm) and transverse resistance (3.6 x 103 to 2.3 x 105Ωm2) were obtained. The VES curves identified were mostly K with some A and H types. At least 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, resulting in good prospects for groundwater development with a potential increase towards the western parts of the study area. Finally, the protective capacity was

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rated as poor indicating 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 industrialization and consequent population growth and urbanization, surface water bodies are increasingly being endangered by wastes from anthropogenic activities. Groundwater has become a viable alternative to surface water. It is deemed to be of good quality, less polluted and less vulnerable to contamination [1,2]. Although, where aquifers are in hydraulic continuity with the ground surface, groundwater could be vulnerable to pollution from surface sources [3,4]. The ability of the earth's subsurface to retard and filter the percolating fluids is a measure of its aquifer protective capacity. The aquifer overburden has been variously referred to as the protective layer of the aquifer [4,5]. Also, it has been widely accepted that the hydraulic conductivity of a subsurface material decreases with increasing resistivity (Aderemi and Bamiro, 2021; Fatoba *et al.,* 2014). According to Alao and Dogara, (2018), the assessment of groundwater protective capacity against any surface contamination is a function of both the hydraulic and longitudinal conductivities. Indexing areas that have potential groundwater vulnerability will facilitate better groundwater management [5]. Further, it has been noted that thick aquifer cover and low hydraulic conductivity result in lower aquifer susceptibility to pollution [6]. Therefore, areas with low aquifer vulnerability levels generally have low hydraulic values [7]. The threat to an aquifer will generally increase if the hydrologic system does not have a good protective layer [7]. Thus in areas with high levels of aquifer vulnerability, groundwater pollution must be considerably managed.

Groundwater is readily available in humid areas of the world. Therefore, groundwater exploration and exploitation to evaluate quantity and quality has become very essential. In recent times both the quantity and quality of water have steadily decreased due to poor management and poor waste management, especially in developing countries such as Nigeria [8].

Groundwater occurs in porous and permeable geologic units termed aquifers, which allow water to transmit in significant quantities of water under ordinary hydraulic gradients [9]. Different geologic materials are classified according to their capability to store and transmit water as an 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 [1]. The properties can be calculated from particle size distribution curves, pumping test analysis and geophysical methods. 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).

Therefore, the need to sustain groundwater development has increased the incorporation of appropriate geophysical and geological methods in the search for water [10,11]. The resistivity method maps subsurface conditions based on rock resistivity parameters [12]. The method has been widely used in hydrological and aquifer susceptibility research [10,13,4], Bayewu et al., 2019, [3]. Vertical electrical sounding (VES) has been variously applied in the characterisation of aquifer protective capacity and hence evaluation of groundwater vulnerability to pollution [14,15] determination of aquifer parameters [16], Nfor *et* *al,* 2007) among others. Also, many researchers used different approaches in identifying groundwater vulnerability. The different methods include the aquifer vulnerability index (AVI) [17], DRASTIC [18] and the Dar-Zarrouk parameters (Nwosu *et al.,* 2021, [19]. The Schlumberger array has been proved to be the method of choice because of the ease of application, low cost and capability [20]. It equally has good vertical resolution in providing a clear view of subsurface conditions [21].

Hence, the present study will assess the aquifer vulnerability and groundwater potential of the study area using vertical electrical sounding (VES) with Schlumberger configuration. It will employ the aquifer properties and the Dar-Zarrouk parameters which have proven successful in another area in the interpretations of results.

The study area 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 area is stratigraphically located in the Niger Delta basin [22] 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 [23]. 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 are believed to be related to the mega-tectonic structural pattern correlated with the breakup of the Gondwanaland during the Late Jurassic to Early Cretaceous [24] 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 [22] The study area is underlain by the Oligocene-Miocene Ogwashi-Asaba Formation [25] (Fig. 1).

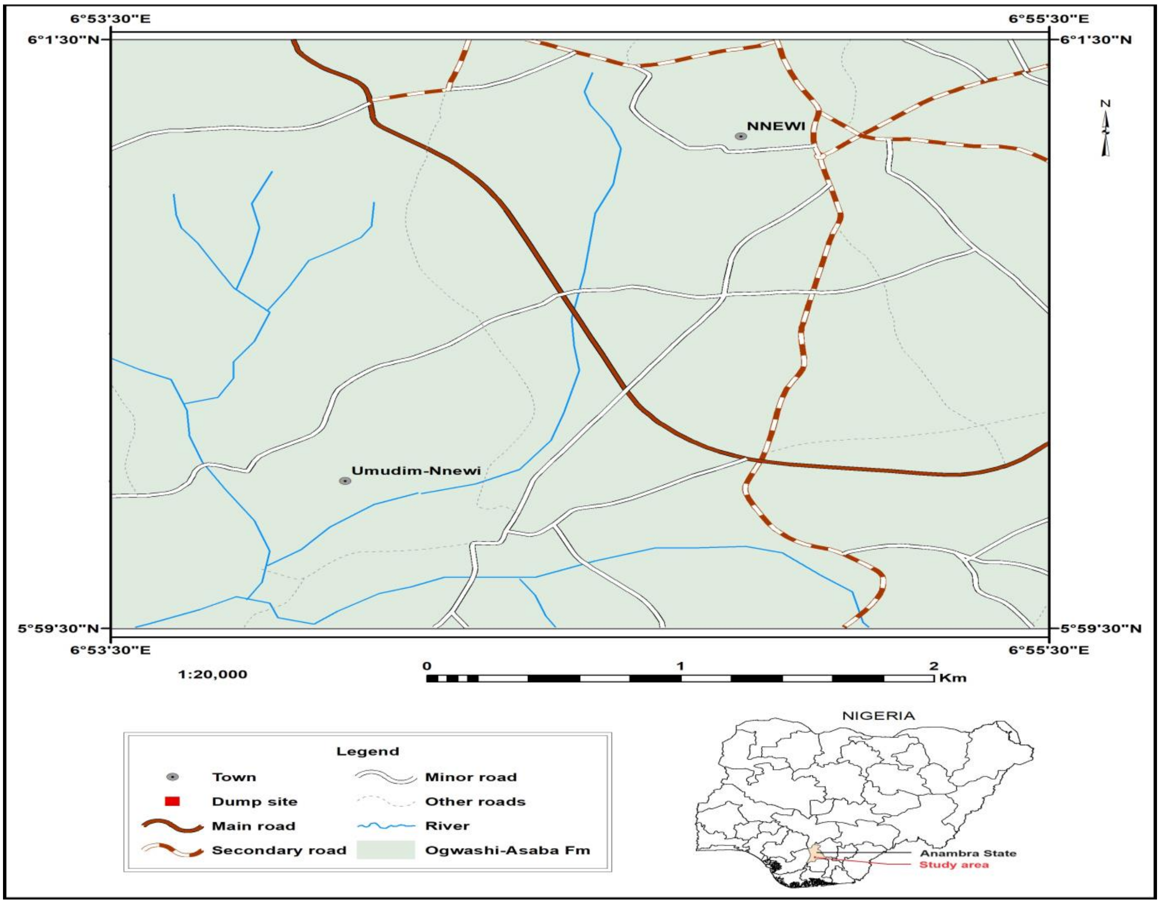


Fig. 1. Geologic, accessibility and drainage map of the study area

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 research alluded to the regional transmissivity and depth to drilled depth. Therefore, it has become imperative to integrate the use of geophysics and Dar-Zarrouk parameters 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.

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 on parts of Uruagu and Umudim areas 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 [26]. There are two major seasons the wet (April to October) and dry (November to March) seasons [27] The wet season generally influences 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. The procedure is known to generate reliable subsurface stratigraphic contrasts. The 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 layers. The apparent resistivity values obtained from equation 1 were plotted on a bi-logarithmic graph against the half-current electrode separation spacing. The curves generated were smoothened to remove the effects of lateral inhomogeneity and other forms of noisy signatures [28,29].

The apparent resistivity was computed using the equation 1;

$$pa = \pi\left(\frac{\left(\frac{AB}{2}\right)2-\left(\frac{MN}{2}\right)2}{MN}\right)\frac{\Delta v}{l} \qquad 1$$

Where ρ_a the apparent resistivity and π is $\frac{22}{7}$

From the plots, qualitative deductions, such as the resistivity of the first or top layer, the depth of each layer, and the curve types were generated. 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 [30]. The ZOND computer software was employed for carrying out the iteration and inversion processes. The aquifer properties were estimated using the equation as given by Heigold et al (1979) (equations 2 and 3):

$$K = 386.40R_{rw}^{-0.93283} \qquad 2$$

Where K is the hydraulic conductivity and R_{rw} is the aquifer resistivity.

The transmissivity values were calculated using (Todd, 1980):

$$T = Kh \qquad 3$$

Where T is transmissivity, K is hydraulic conductivity and h is saturated aquifer thickness. The results provide a general idea of the water-producing capabilities of aquifers from surficial electrical methods.

The aquifer's protective capacity or vulnerability was determined using the Dar Zarrouk and aquifer parameters. The parameters were estimated from electrical resistivity measurement. Also, aquifer vulnerability maps were produced using Arc GIS. The workflow is presented in Fig 3.

The Dar-Zarrouk parameters were originally developed and advanced by Maillet [31]. The Dar-Zarrouk parameters were applied to determine the aquifer protective capacity and groundwater potential [19,16]. The Dar-Zarouk parameters are determined 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 [32].

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 [33]. Transmissivity is the product of the saturated aquifer thickness (b) and the hydraulic conductivity (K), (T = Kb).

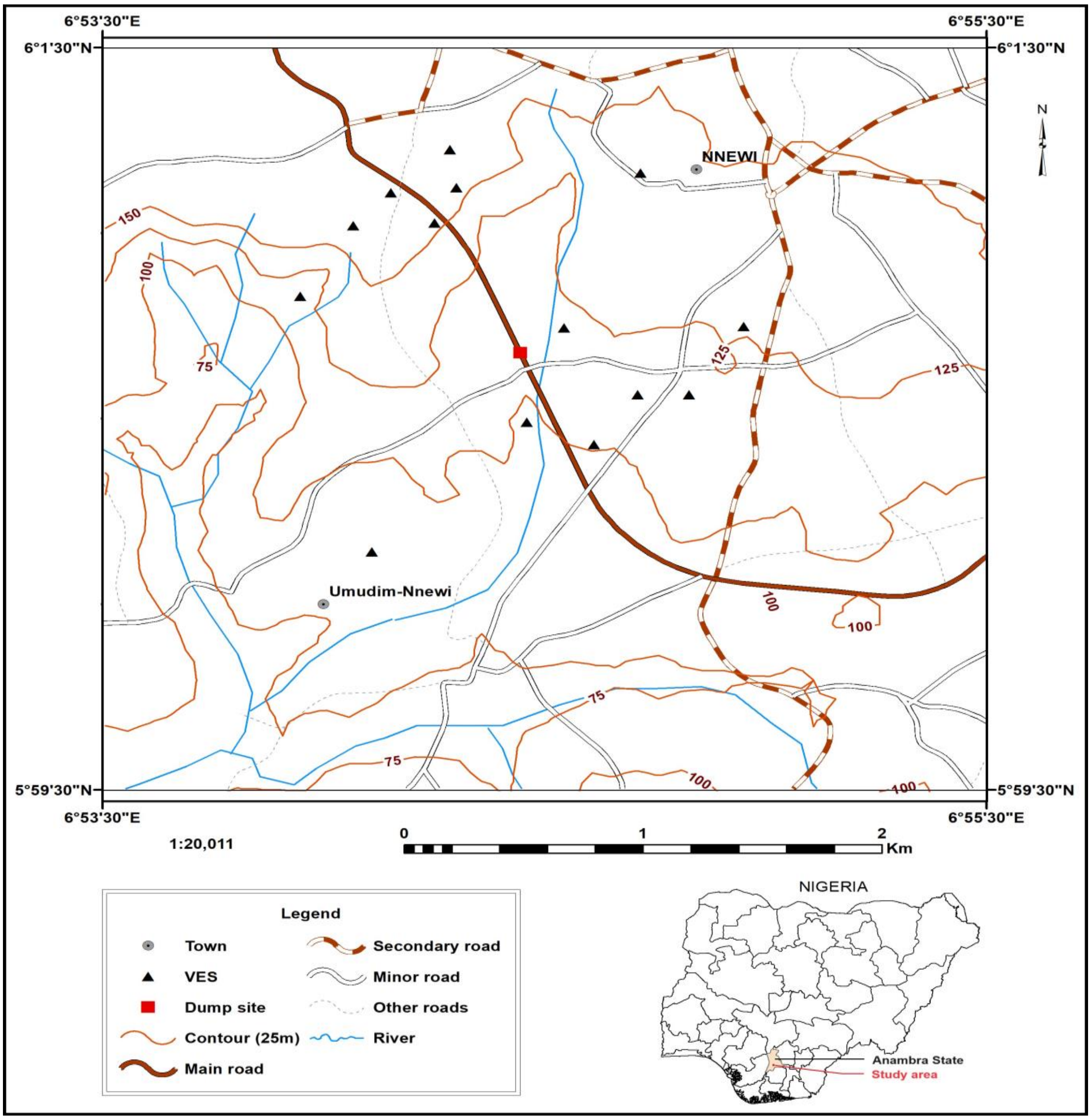


Fig. 2. Vertical Electrical Sounding (VES) points distribution in the study area

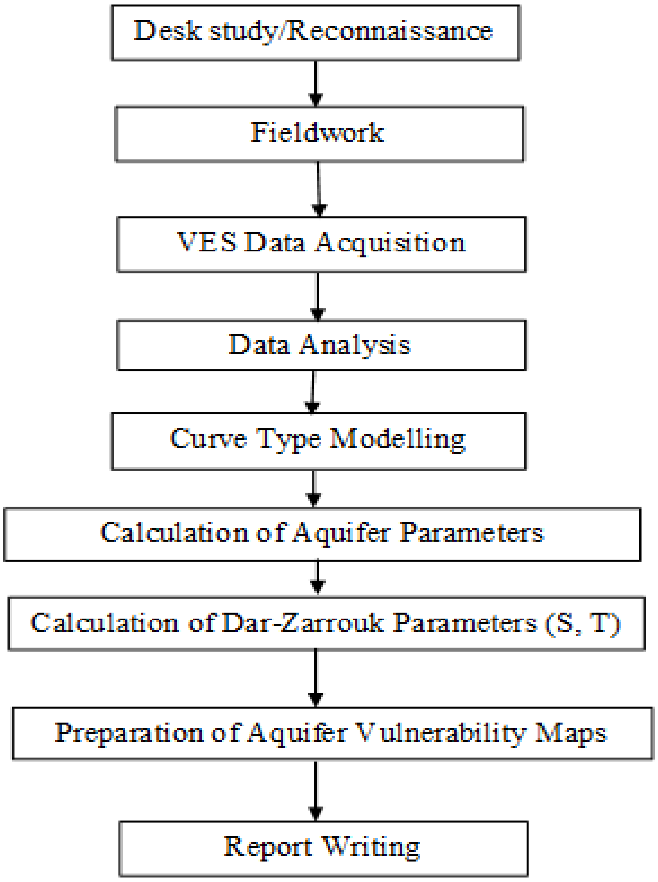


Fig. 3. The methodology of the research is summarized by the workflow

4. RESULTS AND DISCUSSION

4.1 Groundwater Potential of the Study Area

The strip logs and curves generated from the VES are shown in Figure 4. For profile AB' consisting of VES points A to O respectively. The geo-electric sections show a five – six six-layer model. The simulated curves show types K (A to H), A (I, L, M and O), and H (K and O) respectively, a conclusion consistent with the observations of Fajiana [34].

However, Table 1 shows that a 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. The middle layers were of average moderate electrical resistivity with occasionally high resistivity units. The-only exception was location C which recorded anomalously very low resistivity (107.42-425.49Ωm) for the entire column of geoelectric units interpreted. The variation may be because of the presence of contaminants or lithologic changes.

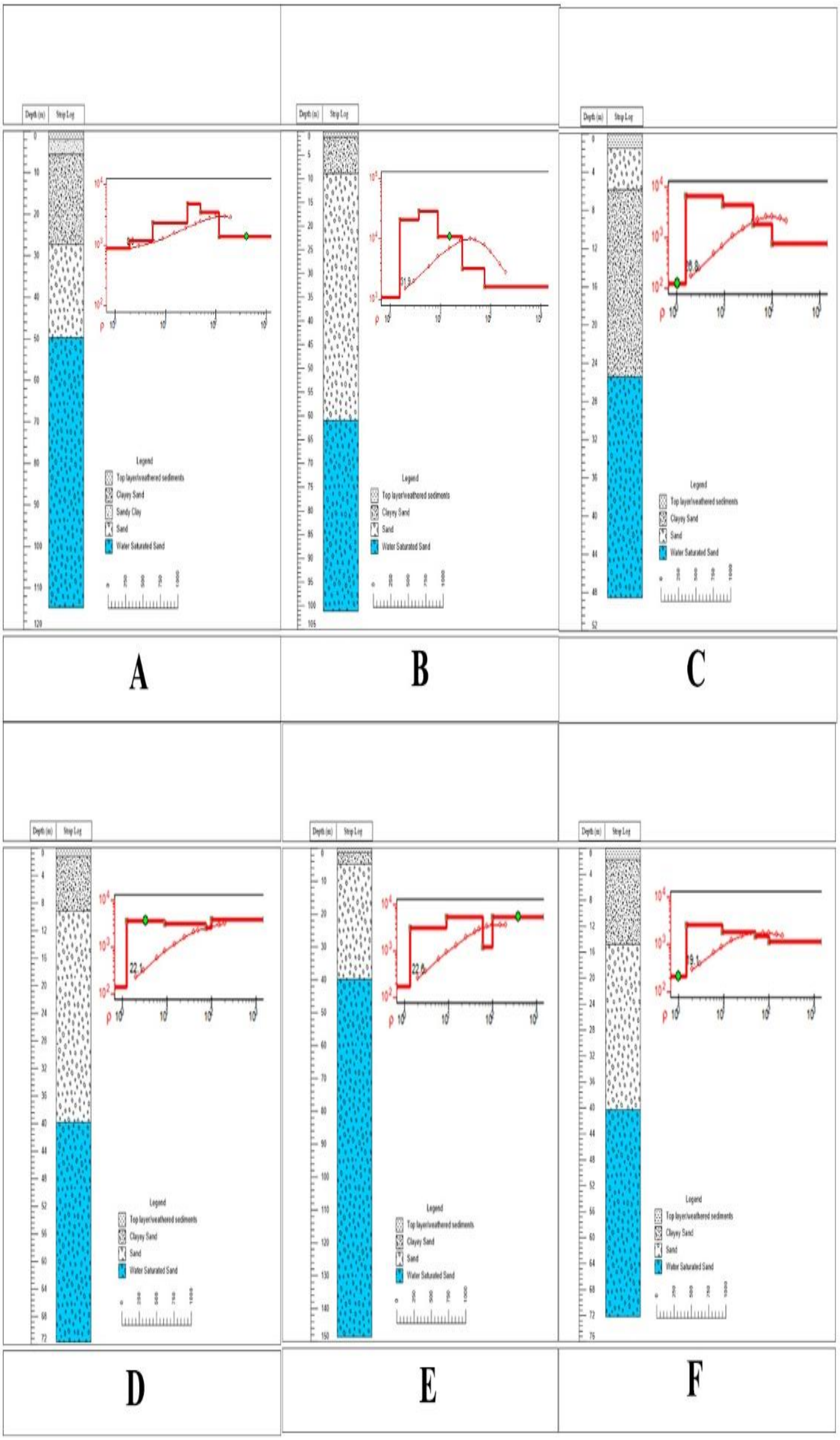
The aquiferous units were interpreted as the fourth and fifth layers in a five-layer and six-layer geoelectric sections respectively. The aquiferous units consist of mostly sand at all the locations with a small percentage being sandy clay. So an average, resistivity of 1340.25Ωm, aquifer thickness of 41.75m and depth to aquifer of 51.25m were observed in the study area Fig 4. The water table ranges from 25.41m to 99.42m. Therefore, the combination of good aquifer thickness, shallow depth to the water table and the aquifer indicate good prospects for groundwater. The prospects are in a manner similar to that reported by Nfor *et al*. (2007). Multiple aquifer types–mostly unconfined and semi-confined exist which is consistent with the result reported by George et al.,[35]. The aquifer types indicate the possibility of good groundwater recharge.

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	
VES E (rms: 13.4%)	5	3961.01	Undetermined	71.73	Sand	K
	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	

Station ID	Layer No.	App Res (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology	Curve Type
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	

Station ID	**Layer No.**	**App Res (Ωm)**	**Thickness (m)**	**Depth (m)**	**Inferred Lithology**	**Curve Type**
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: 14.7%)	6					H
	1	576.12	1.26	0	Top layer/weathered 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	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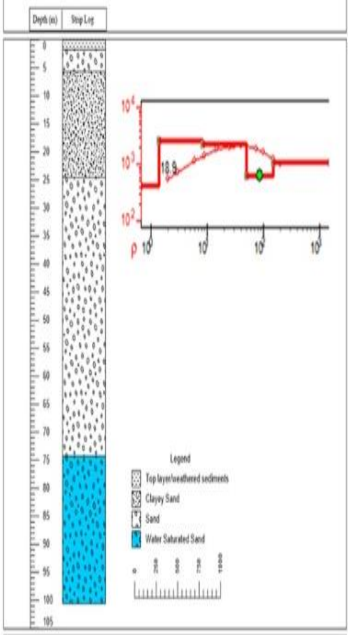
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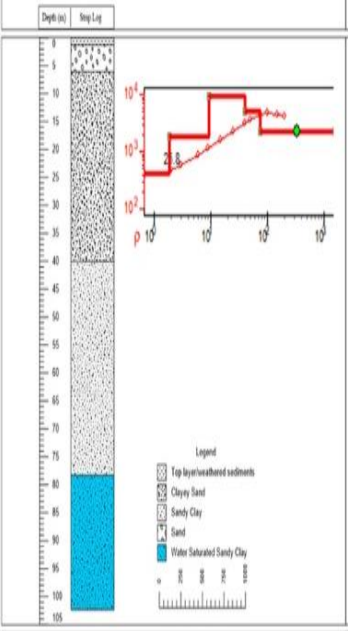
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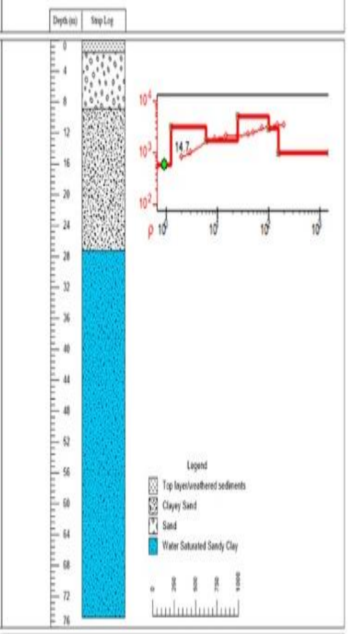
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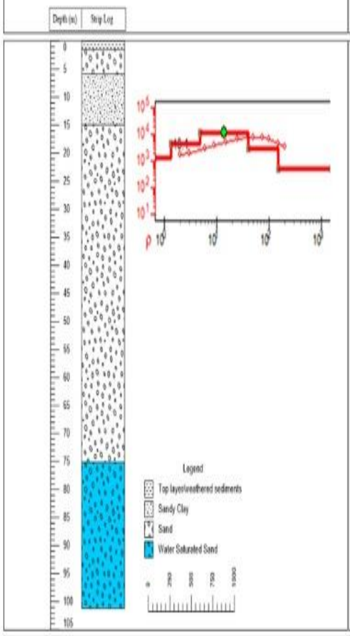
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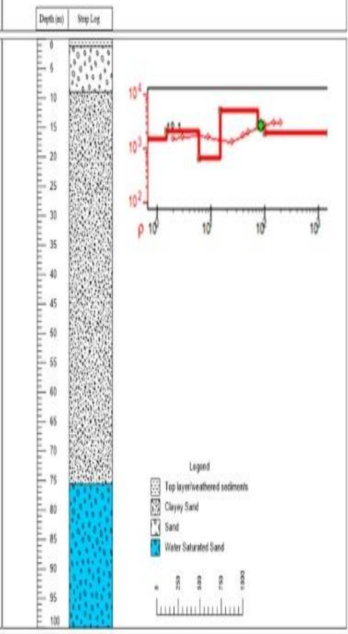
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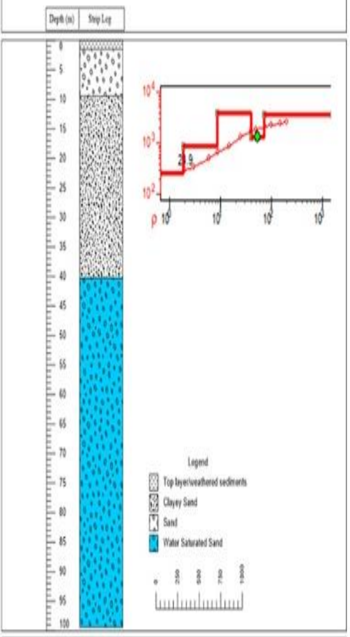
Sand
Water Saturated Sand

K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Water Saturated Sand

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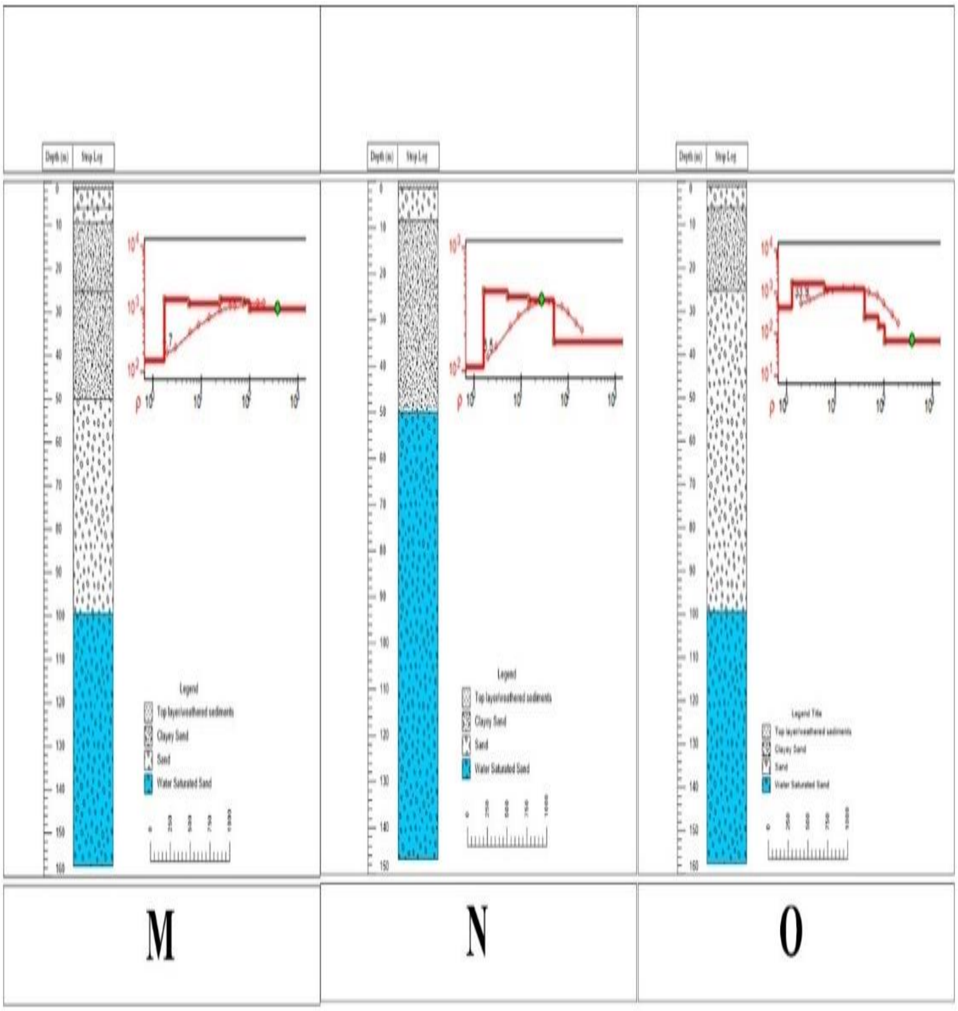


Fig. 4. Strip Logs and corresponding VES curves A-O correspond to the different stations

The map of the spatial distribution of the aquifer thickness and depth to the aquifer is shown in Figure 5. From the distribution, it was observed that the depth of the 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 of the aquifer and the depth of the water table. The northern parts of the study area have higher elevations than the other parts as reported by Igbozurike [27]. The aquifer thickness increased towards the southwestern parts of the study though in a small portion of the north-central part high aquifer thickness was also observed. The results indicate that good potential for groundwater development exists in the study area, especially in the southwestern parts. Good aquifer potential with relation to aquifer thickness and depth was previously reported by Anakwuba et al. [10].

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. The results are indicative of silty sand to clean sand according to Freeze and Cherry [1]. The T values range from 3.9139 to 79.3152m^2/day. The values depict aquifer materials with good potential for groundwater development and good groundwater recharge. Similar results were obtained by Nfor *et al.,* (2007) and Ifeanyichukwu et al.,[36]. Their study was on a regional scale. However, the present research recorded high values in the study area which may be a result of local variations in geology.

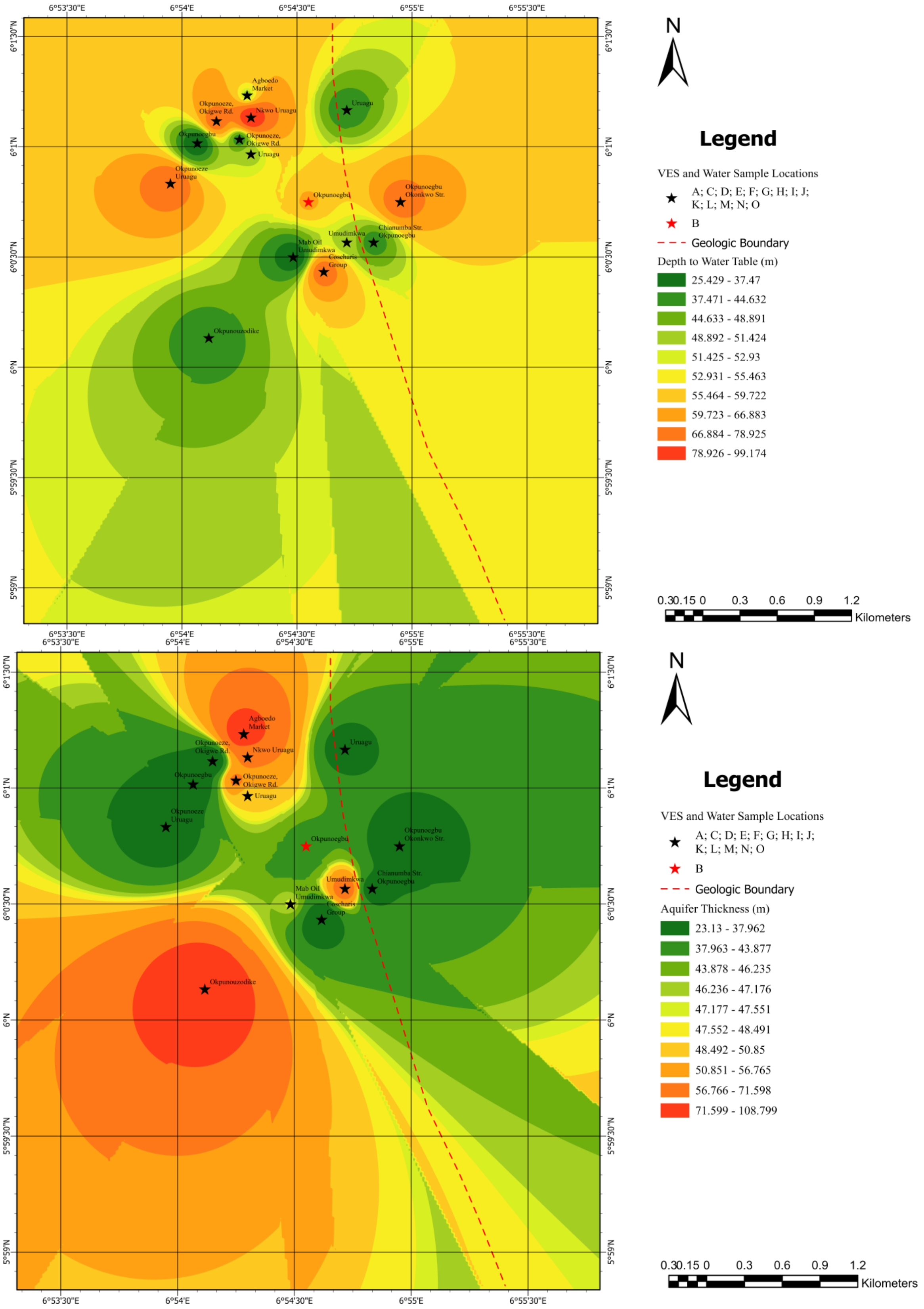


Fig. 5. Spatial distribution of (a) water table and (b) aquifer thickness in the study area

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 x 10^5	64.98	49.73	3491.89
B	0.4260	17.1072	0.00644	5.1 x 10^4	40.20	60.93	1265.83
C	1.3824	31.8816	0.0246	8.3 x 10^3	23.12	25.41	359.55
D	0.1227	3.9139	0.00474	1.5 x 10^5	31.9	39.81	4807.30
E	0.1927	20.9952	0.00170	3.2 x 10^5	108.83	39.81	2962.54
F	0.2030	6.46272	0.00857	8.9 x 10^4	31.87	40.28	2804.77
G	0.4208	11.0592	0.00164	3.4 x 10^4	26.30	74.28	1281.93
H	3.0931	74.4768	0.00442	3.6 x 10^3	24.08	78.28	151.06
I	0.2791	132.1920	0.00115	8.0 x 10^3	47.46	27.25	168.9
J	0.2160	5.6160	0.00723	6.8 x 10^4	26.00	75.15	2622.09
K	0.2177	5.3136	0.00108	6.3 x 10^4	24.40	75.59	2600.10
L	0.2652	15.6384	0.00811	1.3 x 10^5	59.10	40.28	2106.61
M	0.3629	17.5392	0.00107	7.3 x 10^4	48.30	49.97	1504.29
N	0.8208	79.3152	0.00808	6.1 x 10^4	96.80	50.04	626.72
O	0.1987	11.4912	0.00732	1.7 x 10^5	58.15	99.42	2876.51

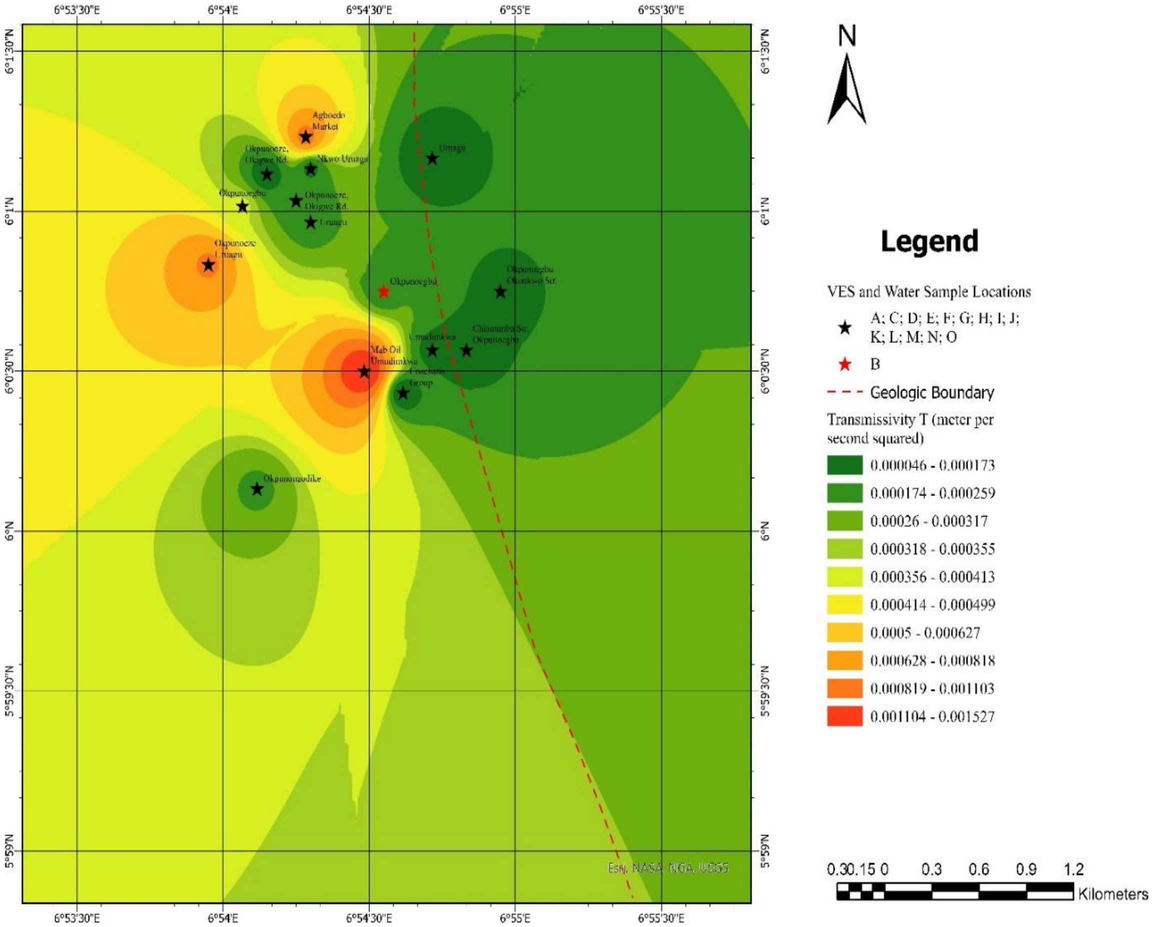
4.3 Characterization of the Aquifer Vulnerability

The values for the Dar-Zarrouk parameters S and T' are recorded in Table 2. The spatial distributions of the parameters are shown in Figure 5. The results of the distribution of S, K and T' in the present study show the same trend. a Similar trend was previously observed by Henriet [19], Nwosu et al., [32], and Obiora et al.,[4]. The protective capacity of the overburden materials was characterized using the ratings proposed by Ogungbemi et al., [37]. The rating is shown in Table 3. The values obtained for S range from 0.00107 to 0.0246Ωm which is less than 0.1Ωm and hence rated as poor.

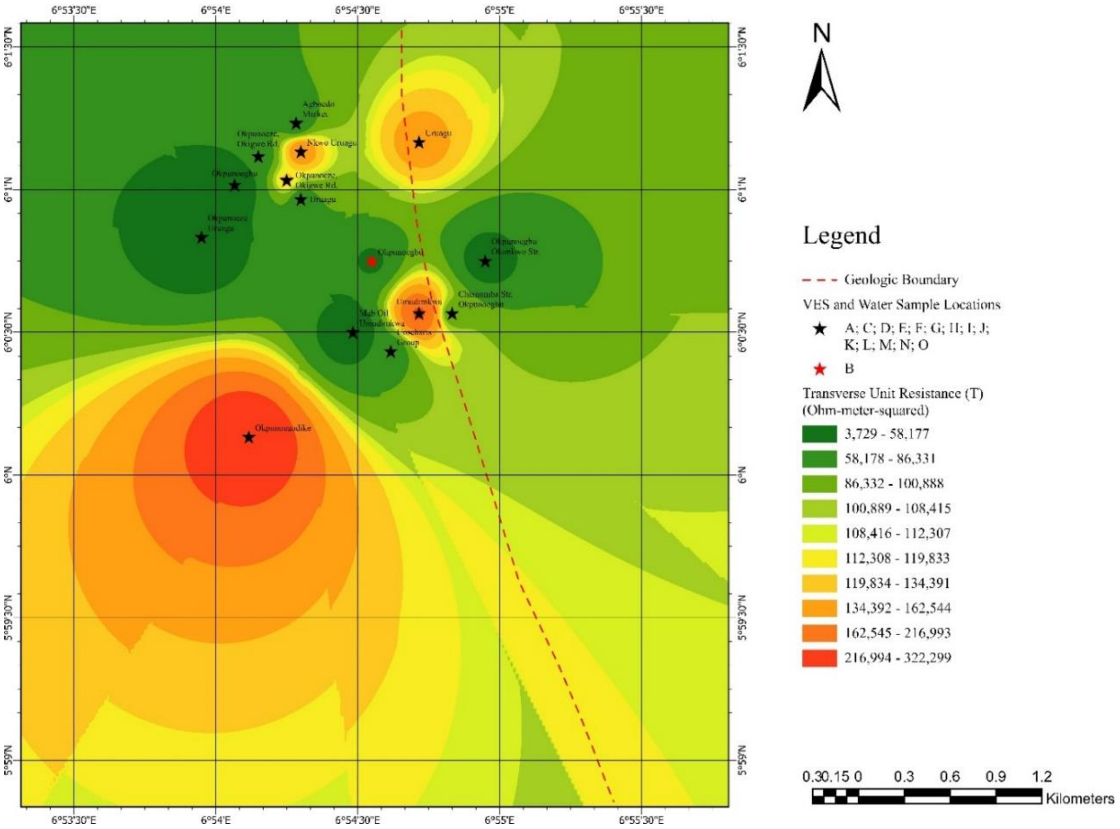
The aquifer vulnerability maps (Fig. 6) indicate that the values for the aquifer hydraulic properties and the Dar-Zarrouk parameters were increasing towards the western parts of the study area. The highest values for T, K and S were observed in the north-western part-Similarly, the highest vale for T' was observed in the southwestern part of the study area.

Table 3. Longitudinal Conductance/Protective Capacity Rating [37]

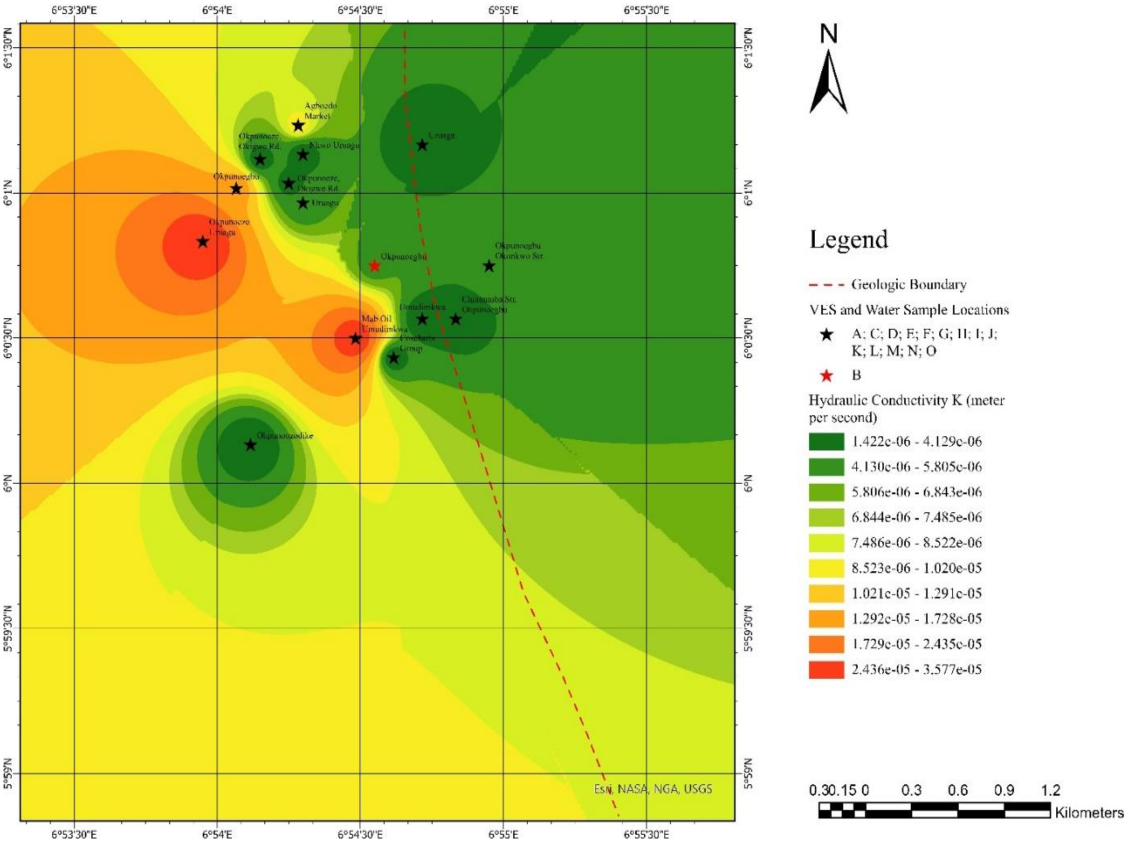
Longitudinal Unit Conductance S (mhos)	Aquifer Protective Capacity (APC) rating
>10	Excellent
5-10	Very Good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
<0.1	Poor



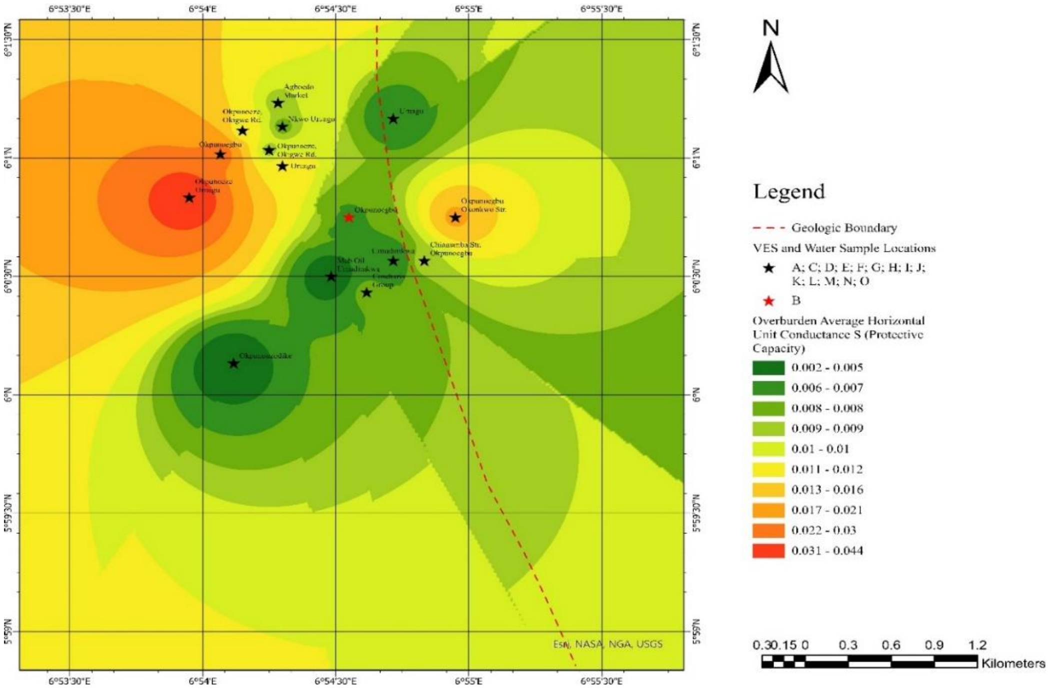
(a)


6°53'30"E
6°54'E
6°54'30"E
6°55'E
6°55'30"E
6°1'30"N
6°1'N
6°0'30"N
6°N
5°59'30"N
5°59'N
Agbaedo Market
Okpunoeze Obigwe Rd.
Nkwo Umagu
Umagu
Okpunoegbu
Okpunoeze Obigwe Rd.
Umagu
Okpunoeze Umagu
Okpunoegbu
Okpunoegbu Okonkwo Str.
Umudimkwa
Chinnamba Str. Okpunoegbu
Mab Oil Umudimkwa
Cosoharn Group
Okpunoozodike
N
Legend
Geologic Boundary
VES and Water Sample Locations
A; C; D; E; F; G; H; I; J; K; L; M; N; O
B
Transverse Unit Resistance (T) (Ohm-meter-squared)
3,729 - 58,177
58,178 - 86,331
86,332 - 100,888
100,889 - 108,415
108,416 - 112,307
112,308 - 119,833
119,834 - 134,391
134,392 - 162,544
162,545 - 216,993
216,994 - 322,299
0.30.15 0 0.3 0.6 0.9 1.2
Kilometers

(b)


6°53'30"E
6°54'E
6°54'30"E
6°55'E
6°55'30"E
6°1'30"N
6°1'N
6°0'30"N
6°N
5°59'30"N
5°59'N
Agbaedo Market
Okpunoeze Obigwe Rd.
Nkwo Umagu
Umagu
Okpunoegbu
Okpunoeze Obigwe Rd.
Umagu
Okpunoeze Umagu
Okpunoegbu
Okpunoegbu Okonkwo Str.
Umudimkwa
Chinnamba Str. Okpunoegbu
Mab Oil Umudimkwa
Cosoharn Group
Okpunoozodike
Esri, NASA, NGA, USGS
N
Legend
Geologic Boundary
VES and Water Sample Locations
A; C; D; E; F; G; H; I; J; K; L; M; N; O
B
Hydraulic Conductivity K (meter per second)
1.422e-06 - 4.129e-06
4.130e-06 - 5.805e-06
5.806e-06 - 6.843e-06
6.844e-06 - 7.485e-06
7.486e-06 - 8.522e-06
8.523e-06 - 1.020e-05
1.021e-05 - 1.291e-05
1.292e-05 - 1.728e-05
1.729e-05 - 2.435e-05
2.436e-05 - 3.577e-05
0.30.15 0 0.3 0.6 0.9 1.2
Kilometers

(c)



(d)

Fig. 6. Aquifer vulnerability map showing distribution of (a) transmissivity, (b) transverse resistance, (c) hydraulic conductivity and (d) longitudinal conductance in the study area

Additionally, the values obtained indicate that the study area is underlain by highly conductive and transmissive geologic materials. Thus, the overburden offers very low protection to the underlying aquiferous units which is consistent with the report of Nugraha et al.,[7]. However, in areas underlain by clayey lithology, the thickness is not large enough to offer the necessary protection to the aquifers. Thus, infiltrating contaminated water flows into the groundwater system. Equally, it was observed that areas underlain by sand have good overburden thickness, but the problem is that sand is porous, permeable and has good K values. The vulnerability of aquifers to pollution because of high values of K was previously reported by Obiora et al., [4] and Stempvoort et al. [5]. Therefore, the results indicate that factors such, as the thickness of the overburden, lithology, K and S greatly affect the protective capacity of of aquifers in the study area. Hence, the groundwater potential is very good and aquifers are vulnerable to pollution from infiltrating surface pollutants [38].

5. CONCLUSION

The 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, aquifer resistivity, 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 and 51.25m respectively. The K and T values range from 0.1227 to 3.0931m/day and 3.9139 to 79.3152m^2/day respectively which indicate silty sand to clean sand. These values indicate good prospects for groundwater development and indicating good potential. Also, the S values range from 0.00107 to 0.0246Ωm which resulted in the protective capacity being rated as poor and the aquifer vulnerable to pollution. Five to six-layer geoelectric units were identified with the aquifer as the fourth and fifth layers respectively. Mostly, curves K, H and A were identified. 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. Furthermore, areas with high aquifer vulnerability have high hydraulic conductivity.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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