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Assessment of Aquifer Protective Capacity, Against the Surface Contamination. A Case Study of Kaduna Industrial Village, 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

Geo-electric soundings was carried out in 22 different locations at Kaduna Refinery Petrochemical Corporation (KRPC) and White Oil and Gas Layout, Mahuta, Kaduna. The aquifer protective capacity and Hydraulic characteristics of the study area was computed from the Geoelectric parameters using Dar-Zarrouk and hydrological parameters. The interpreted data were presented in tabular form, Geoelectric/geology soil profiles and contoured maps. The results show that the study area aquifer is relatively protected with an average value of 0.5 mhos with an indication of infiltration of contaminant in some location. The hydraulic parameter values also show that the study area aquifer has the capacity to produce water non-stopping if the wells are sited based the geophysical investigation. The computed hydraulic characteristics and transmissivity of the area has an average value of 5.5 m/day and 6.1 m^2/hour, which implies that, the study area has the capacity to transmit groundwater through a distance of 5.5 m in 24-hour and can covers 6.1 m^2 in one hour.

Keywords: Protective capacity; hydraulic characteristics; transmissivity; Dar-Zarrouk parameters.

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1. INTRODUCTION

Electrical resistivity surveys have been used for many decades in hydro geological, mining and geotechnical investigations. In recent time, it has been used for environmental surveys and is becoming more promising in all kinds of subsurface exploration [1]. Groundwater resource plays a vital and fundamental role in any nation development irrespective of their technology advancement, economic growth, and social condition. Unfortunately, it is often unappreciated and ignored in many parts of the world, most especially under developed and developing nations [2], noted that, there is a strong interaction and relationship between human activities and water quality in any settlement. Consequently, the environmental pollution is not unconnected to anthropogenic activities emanating from the growth of waste disposals, oil and gas, agrochemicals, industries and technological advancement. However, the earth subsurface has since identified as a natural medium that filter the contaminated fluids infiltrating the earth but may fail if the earth's subsurface is highly porous. The ability of the earth's subsurface to retard and filter the percolating fluids is a measure of its aquifer protective capacity which according to [2,3,4,5], unanimously agreed that the higher the resistivity of subsurface material, the lower its hydraulic conductivity and vice versa. For instance, clay soil is relatively impermeable, and sandy soil is relatively permeable, which implies, the sandy soil has a poor aquifer protective capacity because it can provide an infiltration path for the pollutants to enter the aquifers. The impact of these contaminations over the years on soil and groundwater is becoming more worrisome and its devastating effects on humans and the ecosystem cannot be overemphasized [5,6,7]. Most groundwater of the areas close to industrial area are usually contaminated and becomes unfit for its intended purpose. The study area is well known as industrial area in the City of Kaduna, Nigeria. The noticeable industries in the area include Kaduna Refinery Production Company (KRPC), Reagent Gas Company, White Oil and Gas Company and many other gas companies which has led to rapid growth of the area in terms of population and industry development. With these rapid growths in population, urbanization and industrialization, groundwater resources may have become vulnerable to depletion, contamination and quality degradation. According to [2], the assessment of groundwater protective capacity against any surface contamination is a function of both the hydraulic and longitudinal conductivity. The study area is undoubtedly one of the industrial nerve Centre in Kaduna City in which most industrial activities revolve. Hence, the heavy contaminants from industries can easily break any weakly protective cover provided by the soil layer, and infiltrate the groundwater via the soil and contaminate it, thereby rendering it unfit for consumption [2]. This study seeks to assess the aquifer protective capacity of the study area based on the above trend of events in order to advise government and individuals adequately to avert likely future disaster occurrence.

2. SITE GEOLOGY AND DESCRIPTION

Fig. 1 shows the relief of the terrane under study which lies within the geographical coordinates of latitude and longitude of 10.4326N to 10.429N and 7.4902E to 7.4965E respectively with an average height of 615 m above the sea level.

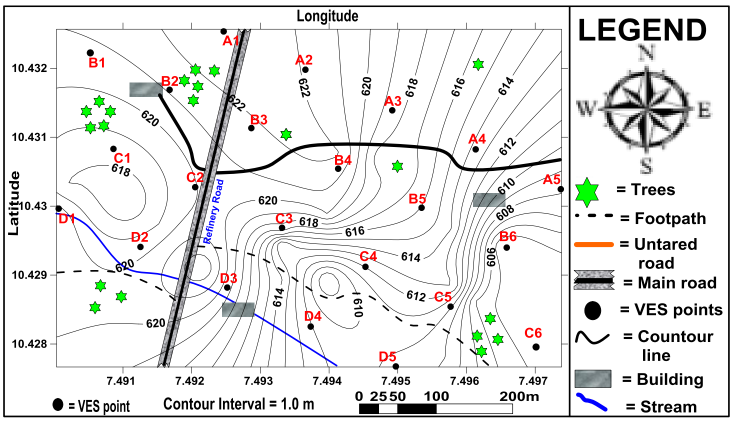

Fig. 1. Map of the Study Area showing VES stations and Profile Locations

The terrane is underlain by precambian rocks typical of the Norther basement complex of Nigeria [6,8]. Though, the literatures review for this work show that the fractured basement and water yielding capacities of wells drilled in the area and its environs are always vary [1,6,7,9,10]. The area rocks are usually capped by consolidated laterites, quartzites, sandstones and silty sand especially at the surface but the laterites have been weathered into lateritic nodules mixed with sandy clays and silty soil over time. The bioclimatic nature of the environment has affected the deep chemical weathering and fluvial erosion, which metamorphous the high undulating plains into subdued interfluves [1].

3. MATERIALS AND METHOD

The subsurface resistivity distribution across the study area were acquired from twenty-two (22) vertical electrical sound (VES) points by Schlumberger array with maximum spread of 200m. It is based on the principle of Ohm's law [6,8]. This is the fundamental physical law used in resistivity surveys that governs the flow of current in the ground. According to Ohm's Law:

$$V = IR \tag{1}$$

The subsurface materials response to the current flow through the ground. That is:

$$\rho_a = \frac{RA}{l} = \frac{2\pi\Delta V}{I\left[\left(\frac{1}{r_A} - \frac{1}{r_B}\right) - \left(\frac{1}{R_A} - \frac{1}{R_B}\right)\right]} \tag{2}$$

Where R is resistivity ($i.e\ R = \Delta V/I$), and K is geometrical factor which depends on the arrangement of the four electrodes [8] and be defined from Fig. 2, as:

$$K = \frac{2\pi}{\left[\left(\frac{1}{r_A} - \frac{1}{r_B}\right) - \left(\frac{1}{R_A} - \frac{1}{R_B}\right)\right]} \tag{3}$$

$$\Rightarrow \rho_a = RK \tag{4}$$

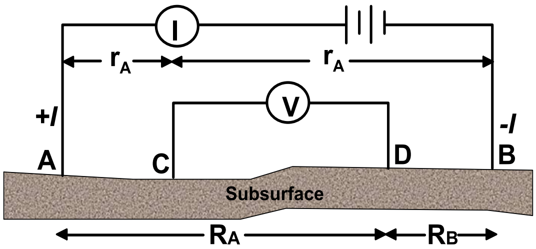

Fig. 2. Schlumberger Configuration

3.1 The Dar Zarrouk Parameters

Further derivatives like Dar Zarrouk [DZ] parameters can be used to estimate the aquifer protective capacity [2]. The basic parameters used to define Geoelectric layer are its layer thickness (h_a) and apparent resistivity (ρ_a). For a sequence of a horizontal homogeneous and isotropic layers of resistivity (ρ_a) and thickness, (h), the DZ parameters (longitudinal conductance, S_L and transverse resistance, R_T) are expressed in Equation (5) and (6) respectively:

$$S_L = h_a/\rho_a \tag{5}$$

$$R_T = h_a.\rho_a \tag{6}$$

Where:

R_T is transverse resistance
S_L is longitudinal conductance.
ρ_a is resistivity of the overburden layer.
h_a is thickness of the overburden layer

The parameters R_T and S_L are terms called the "Dar-Zarrouk parameters' [3]. High S_L and R_T values usually indicate relatively thick succession and should be a focus in terms of groundwater potential [2].

3.2 Aquifer Protective Capacity

Aquifer protective capacity was obtained from Dar-zarrouk parameters, (S_L and R_T), since the earth acts as a natural filter to the infiltrating fluid and its ability to resist fluid is a measure of its protective capacity [1], [4]. That is, the protective capacity (P_c) is defined as:

$$P_c = \sum \frac{h_a}{\rho_a}\left(\sum S_L\right) \tag{7}$$

Table 1. Protective capacity rating [3,4]

Protective Capacity (mhos)	Rating
< 0.1	Poor
0.1 – 0.19	Weak
0.2 – 0.69	Moderate
0.7 – 4.9	Good
5 – 10	Very good
> 10	Excellent

3.3 Hydraulic Conductivity

The most variable and important parameters used to estimate the contaminant travel time is hydraulic conductivity [10]. Studies have shown that the most reliable means to obtain hydraulic conductivity is through aquifer pumping tests and the aquifers yield is low, a slug tests are conducted [3]. However, where these data are not available, hydraulic conductivity could be estimated. Consequently, the relationship between the layer resistance and the hydraulic conductivity can be expressed by:

$$\begin{cases} K = \frac{1}{9750000}\rho_a{}^{1.195}\ (\mathrm{m/sec}) \\ K = \frac{3600}{9750000}\rho_a{}^{1.195}\ (\mathrm{m/hour}) \\ K = \frac{86400}{9750000}\rho_a{}^{1.195}\ (\mathrm{m/day}) \end{cases} \quad (8)$$

Transmissivity (T) describes the rate at which groundwater is transmitted through a unit width of an aquifer with a unit hydraulic gradient [3,10]. Transmissivity is a measure of the quantity of water that the aquifer can transmit horizontally and it can be expressed as:

$$T = Kh_a \quad (9)$$

Where, K is the hydraulic conductivity and T is aquifer transmissivity. Thus; it can be admitted that the transmissivity of an aquifer is directly proportional to its transverse resistance.

4. DATA PROCESSING

The data acquired were interpreted by the computer software *Res ID version 1.00.07 Beta* and its model parameters after interpreted quantitatively and qualitatively for VES point **A2** along profile **A** (Fig. 3).

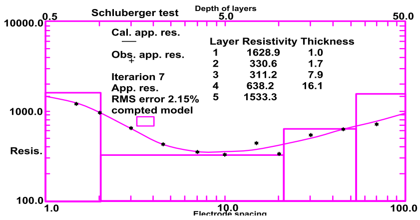

Fig. 3. Typical resistivity curves of VES A2

5. RESULTS AND DISCUSSION

A. Geoelectric/geology Section

The geoelectric and geologic section describes the earth's subsurface electrical properties and soil formation of a sequence of layered rocks [7]. The quantitative and qualitative treatment of the VES provided geo-electrical information characterized by the values of layer resistivity and its thickness. The interpreted field data of the 22 VES stations along profiles A, B C and D were used to prepare the Geoelectric and geologic section of the study area as shown in Fig. 4(a-d), which shows that the study area is underlain by three to four layers comprises of lateritic topsoil, indurated laterite/clay/silty/sand, weathered or fractured layer and the fresh basement. The top layer is highly resistive with an average thickness of 2.0 m. The main aquifer unit of the study area is depicted in blue colour which occupied the second layer (for three layers) and the third layer (for four layers) as shown in Fig. 4(a-d). The aquifer resistivity ranges from 53 Ωm to 638 Ωm with an average thickness of 22.0 m as shown in Fig. 4(a-d) and Table 2.

B. Protective Capacity of the Study Area

The protective capacity of the study area was evaluated from the Geoelectric top layer resistivity using Dar-Zarrouk and hydrological parameters in equations 5–9 to compute the Longitudinal Conductance, Transverse Resistance, Hydraulic Conductivity, Transmissivity and Protective Capacity presented Table 2. From the table, the study area aquifer is relatively protected with an average value of 0.5 mhos. The hydraulic parameter values also show that the study area aquifer has the capacity to produce water non-stopping if the well is sited based the geophysical investigation. The computer hydraulic characteristics and transmissivity of the area has an average value of 5.5 m/day and 6.1 m^2/hour. This implies that, the study area has the capacity to transmit groundwater through a distance of 5.5 m in 24-hour (one day) and can covers 6.1 m^2 in one hour.

C. Transverse Resistance and Transmissivity

Fig. 5 exploits the transverse resistance of the study area, which ranges from 673 Ωm^2 to 20755 Ωm^2 (Table 2). The high transverse resistance value shows that the area aquifer may likely have high transmissivity with prominent and quantifiable groundwater potential, covers about 64% of the study area (Figs. 5 & 6). However, there are indication of poor aquifer potential covers about 36% of the study area.

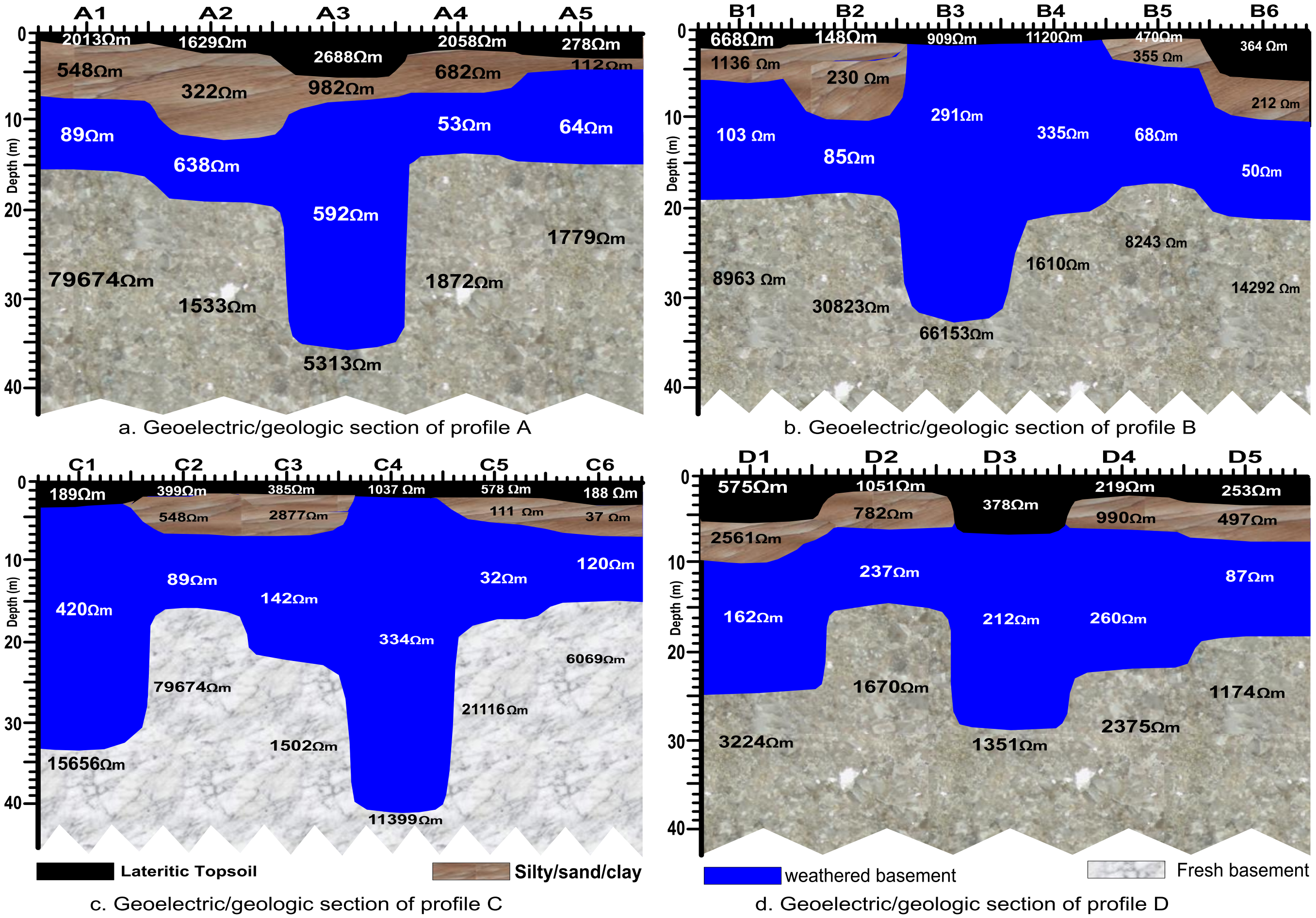

Fig. 4. Geoelectric/geologic section across all the Profiles of the study area

Table 2. The Summary of Computed Dar-zarrouk Parameters and the Hydraulic Characteristics Estimated from the Geoelectric Parameters across all the 22-VES stations of the study area

SN	VES Pts	Aquifer Resistivity ρ(Ωm)	Aquifer Thickness d(m)	Transvers resistance R(Ωm^2)	Longitudinal conductivity S(Ω^{-1})	Protective Capacity P_C(mhos)	Hydraulic conductivity K(m/day)	Transm-issivity T(m^2/h)
1	A1	89.0	15.0	1335.0	0.1685	0.57	1.892	1.183
2	A2	638.0	26.7	17034.6	0.0419	0.14	19.92	22.16
3	A3	593.0	35.0	20755.0	0.0590	0.20	18.25	26.62
4	A4	53.0	12.7	673.1	0.2396	0.81	1.019	0.539
5	A5	63.0	13.9	875.7	0.2206	0.75	1.252	0.726
6	B1	103.0	18.2	1874.6	0.1767	0.60	2.253	1.709
7	B2	84.0	17.9	1503.6	0.2131	0.72	1.766	1.317
8	B3	290.0	31.6	9164.0	0.1090	0.37	7.764	10.22
9	B4	335.0	19.2	6432.0	0.0573	0.19	9.224	7.380
10	B5	63.0	16.5	1039.5	0.2619	0.89	1.252	0.861
11	B6	50.0	19.9	995.0	0.3980	1.35	0.950	0.788
12	C1	420.0	33.3	13986.0	0.0793	0.27	12.08	16.77
13	C2	89.0	15.0	1335.0	0.1686	0.57	1.893	1.183
14	C3	141.0	22.5	3172.5	0.1596	0.54	3.280	3.075
15	C4	334.0	41.4	13827.6	0.1240	0.42	9.191	15.85
16	C5	90.0	16.6	1494.0	0.1844	0.63	1.918	1.326
17	C6	120.0	14.3	1716.0	0.1192	0.41	2.705	1.611
18	D1	162.0	23.0	3726.0	0.1420	0.48	3.872	3.710
19	D2	237.0	14.0	3318.0	0.0591	0.20	6.100	3.558
20	D3	211.0	27.0	5697.0	0.1280	0.43	5.309	5.972
21	D4	260.0	21.4	5564.0	0.0823	0.28	6.814	6.075
22	D5	86.0	17.0	1462.0	0.1977	0.67	1.817	1.287
Average		**205**	**21.5**	**5317**	**0.15**	**0.52**	**5.5**	**6.1**

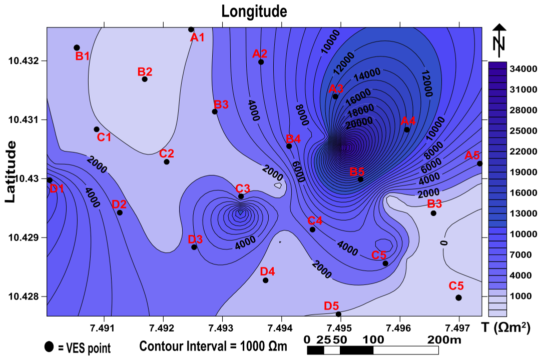

Fig. 5. Transverse resistance of the study area

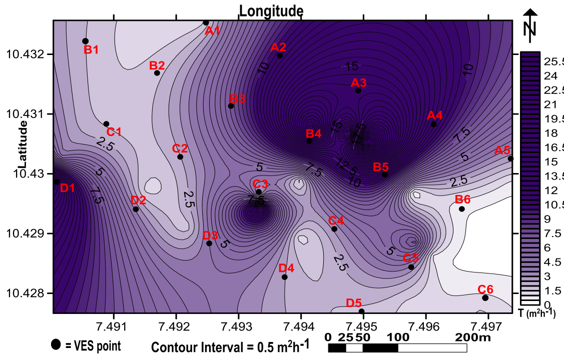

Fig. 6. Transmissivity Map of the study area

D. Longitudinal conductance and Aquifer Protective Capacity of the Study Area

Figs. 7 & 8 shows the longitudinal conductance (S_L) and aquifer protective capacity (P_c) computed and evaluated form Dar-Zarrouk parameters (Table 1 & 2) rating [9]. The result shows a strong correlation the longitudinal conductance and aquifer protective capacity, (Fig. 9). While S_L ranges from $0.04\Omega^{-1}$ to $0.4\Omega^{-1}$, P_c ranges from 0.14 mhos to 1.35 mhos. The high impervious clayey overburden is characterized by relatively high longitudinal conductance that protect the underling aquifer. Figs. 7 & 8 showing aquifer protective capacity of the study area is likely under attack and prone to subsurface contamination due to high area covers by weak protective capacity. This covers about 41% of the total study area with only 59% saved from subsurface contamination. This implies that, the aquifer in these locations are unprotected and vulnerable to contamination from infiltration of Leachate and oil spillage.

E. Hydraulic Conductivity (K) of the Area

Fig. 10 exploits the rate at which the ground transmits groundwater within the earth subsurface. This section is an important factors to be considered while allocating land for industries because the contaminant travel time determines how saved or unsaved the groundwater resources can be [3]. A highly conductive could be an advantage to aquifer recharging but dangerous to the aquifer protective capacity. Fig. 10 reveals that the study area is moderately conductive, which implies that the terrane has the capacity to produce groundwater continuously. Hence, the pollution source like solid waste, sewages, disposal and fuel storage tanks are more likely to discharge below the ground surface thereby infiltrating aquifer protective cover provided by the soil layer. Thus, indiscriminate disposal of wastes should be discourage religiously.

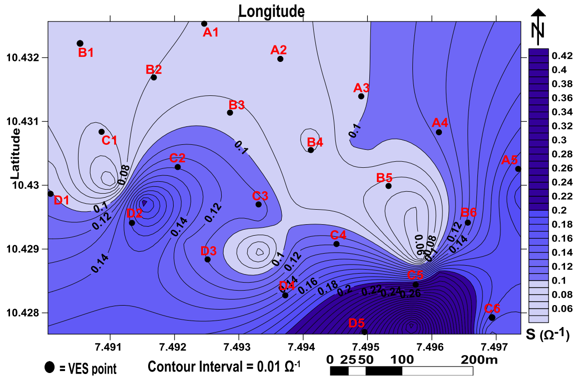

Fig. 7. Longitudinal conductance of the area

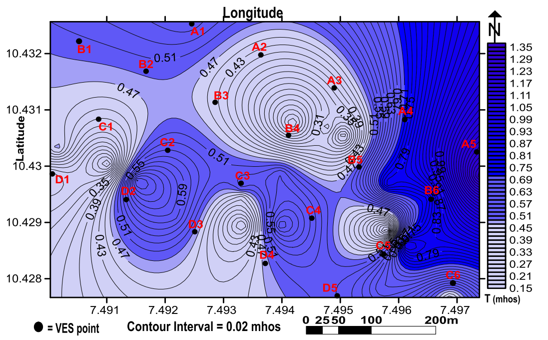

Fig. 8. Protective Capacity of the study area

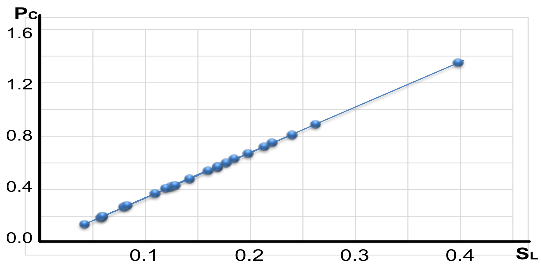

Fig. 9. Relationship between S_L and P_c

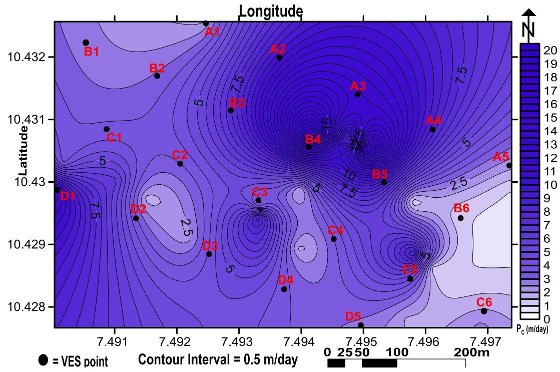

Fig. 10. Hydraulic conductivity of the area

6. CONCLUSION

Geo-electric survey carried out along twenty-two (22) VES stations across four profiles which characterize the subsurface conditions of the study area. The results revealed that the study area is underlain with three to four geological layers. The aquifer unit has an average resistivity and thickness of 205 Ωm and 22.0 m respectively. The geoelectic parameters were used to compute the geoelectic/geology profile, the longitudinal conductance, the transverse resistance, the aquifer protective capacity, the hydraulic conductivity and the transmissivity of the study area. All these parameters were used to evaluate the groundwater potential and its vulnerability to the subsurface contamination. The interpreted data were presented in tables and figures with an interesting results which show that the study area aquifer is relatively protected with an average value of 0.5 mhos. The hydraulic parameter values also show that the study area aquifer has the capacity to produce water non-stopping if the wells are sited based the geophysical investigation and suggestions. However, there are indications that some part of the study area have been contaminated due to its high hydraulic conductivity and weak protective capacity. The computed hydraulic characteristics and transmissivity of the area shows that the study area has the capacity to transmit groundwater through a distance of 5.5 m in 24-hour and can covers 6.1 m^2 in one hour. Consequently, the study therefore recommended that:

- Vulnerable zones (A2, A3, B3, B4, C1, C5 & D4) where the aquifer protective capacity is weak as shown in Fig. 8, should either be avoided for borehole siting or borehole sited in the region should be sunk deep down to at least a depth of 31m
- Good zones (depicted with blue colour in Fig. 8) where aquifer protective capacity is highly protective capacity from surface contamination. These regions covered a significant part of the study area of about 64%.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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The work was carried out in collaboration with all authors and approved the final manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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