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Determination of Groundwater Vulnerability to Surface Contamination Using Dar-Zarrouk Parameters Within Olujoda and Environs

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ABSTRACT

Electrical resistivity investigation was carried out at Olujoda Environ, Ekiti state, Southwestern Nigeria. The aim of this study is to determine the geoelectrical parameters presenting the lithological units and depth to the shallow aquifer, and also to calculate the Dar -zarrouk parameters so as to delineate the hydraulic characteristics of each aquifer from the surface geophysics. Sixteen (16) VES were conducted using Schlumberger array with a maximum half current electrode (AB/2) of 50m. Data were interpreted using partial curve matching technique and assisted 1-D forward modeling with WINRESIST software. The qualitative interpretation revealed AH curves ($\ell_1 > \ell_2 < \ell_3 < \ell_4$), KH curves ($\rho 1 < \rho 2 > \rho 3 < \rho 4$), QH curves ($\ell_1 > \ell_2 < \ell_3 < \ell_4$) and QK curves ($\ell_1 < \ell_2 < \ell_3 < \ell_4$). The geoelectric section generated from the results of the VES revealed four geo-electric layers; these include lateritic topsoil with resistivity ranging from 58-230Ωm, sand clay formation with resistivity values vary from 38 to 514Ωm, weathered basement with resistivity varying from 54 to 455Ωm and fresh basement with resistivity valued between 115 and 1797Ωm. Overburden thickness ranges from 8 to 17m. The hydraulic characteristics of the aquifer estimated from the geoelectric parameters reveal that the aquifer has protective capacities values between 0.0226 and 0.3054 mhos, transverse resistivity ranges from 54.2927-432.843Ωm^2, transmissivity values vary from 8.382 to 136.91m ^{2}/day, reflection coefficient values ranges between 0.270 to 0.472 and hydraulic conductivity ranges from 1.28-9.36 m/day. The results show that the aquifer is characterized by high porosity having weak protective capacities (Fatoba, *et al*., 2014) of overburden layers indicating that it is highly vulnerable to surface contamination. The area has low to intermediate transmissivity values except for VES 2 with moderate value according to the standard for transmissivity classification by Kransy 1993, and moderate hydraulic conductivity values indicating that the aquifer can transmit water at a rate that will suffice for the need of the community in the study area. This study helps in the determination of the hydraulic properties of the aquifer in the study area and its vulnerability to surface contamination.

Keywords. Vulnerability,hydraulic-properties,transverse-resistivity,geoelectric-section, Dar-zarrouk-parameters

1. Introduction

Groundwater as one of the main sources of potable water supply for domestic, industrial and agricultural uses is gaining more and more importance in Nigeria owning to the ever increasing demand for water supplies, especially in areas with inadequate surface water supplies but has been under intense pressure of degradation and contamination due to urbanization, Industrial, agricultural related activities and saline water intrusion from the ocean.

Already, ten percent of the world's population is affected by chronic water scarcity and this is likely to rise to one-third by about 2025 (Coker, 2012). Groundwater is said to be contaminated when it is unfit for the intended purpose and therefore constitute a nuisance to the user. High increases in industrial development, urbanization and agricultural production have resulted in freshwater shortages in many parts of the world. As a result of this increasing demand for portable water for these various purposes, there is need to have a planned and optimal utilization of water resources. Aquifer parameter is necessary for the management of groundwater resource. The parameters necessary for the description of the dynamics of aquifer, include, geometry of the pore space, geometry of the rock particles, secondary geologic processes such as faulting and folding and secondary deposition These parameters jointly affect the rate and pattern of

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groundwater flow (Udoinyang and Igboekwu, 2012).

The common method of determining the hydraulic characteristics (Hydraulic conductivity, Transmissivity, Porosity, specific yield and protective capacity) is by carrying out pumping tests on the boreholes of the area. However, the hydraulic characteristics can also be alternatively estimated from geoelectric parameters at an area where pumping test data are not available. Since the late 1960's surface geolectrictric measurements have been used to determine aquifer characteristics and its protective capacity. Ungemach et.al. (1969) correlated transmissivities determined from the results of six pumping tests in the Rhinc aquifer with transverse resistance.

Physical characteristics of aquifers such as hydraulic conductivity and transmissivity that control groundwater flow and transport are very important properties and are usually estimated for groundwater flow model calibration. The aquifer vulnerability index is a method for assessing the vulnerability of aquifers to surface contaminants which is calculated by the protective capacity of the overburden layers. In the assessment of aquifer vulnerability to potential contamination, the depth to the aquifer and the types of geologic materials above them are considered.

2. Geology of the study area

Ekiti State lies between latitudes 7°15′ 00″ – 8° 5′N and longitudes 4°44′ – 5°45′E covering approximately 6 353 km2 (Akinola et. Al., 2017). The undulating topography of the terrain which stands between 180-425 m above the mean sea level is consequent on the occurrence of several erosion-dissected residual hills (Figure 1). These residual hills (mainly granite, charnockite, quartzite and pegmatite) are of variable sizes and shapes. These hills are concentrated in the west and central part of Ekiti State, while a few others are scattered towards the north. The lush and luxuriant vegetal signature of the area reflects a combination of fertile soils and a humid tropical climate. Ekiti area experiences two seasons- rainy and dry seasons. The rainy season extends between April and October while the dry season is between November and March. With an annual rainfall between 1250 mm to 1900 mm and an average of 1500 mm, precipitation is highest between June to August each year. The rains decrease both in frequency and intensity from September to the end of the raining season. The temperature fluctuates between 25.5°C and 28.3°C with a relative humidity of 60–80 % most months of the year. Climatic variation exerts great influence on stability of rocks precipitating intense weathering and erosion. Located between West Africa and Congo Cratons lies the Nigeria basement which has been reactivated by Pan-African orogenic events (Akande, 1991; Woakes et al., 1987; Odeyemi, 1981). This domain forms part of N-S trending orogenic belt which extends from Hoggar Massif of Algeria into the Brazilian orogen of South America (Grant, 1970, 1978; Bertrand &

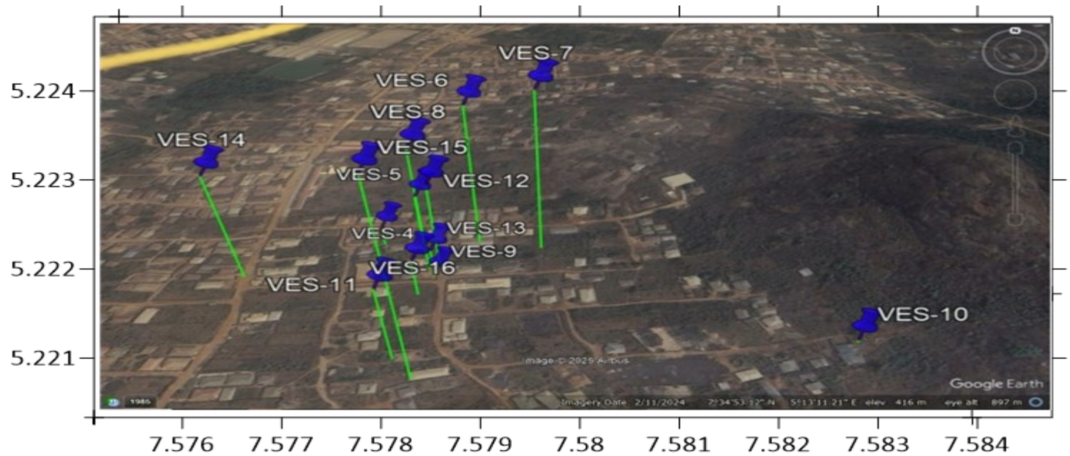

Figure 1: Basemap of the study area showing VES locations

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Davison, 1981; Caby, 1989; Black and Liégeois, 1993; Castaing et al. 1994; de Wit et al. 2008; Goodenough et al. 2014; Adetunji et al. 2016). In addition to migmatite-gneiss quartzite complex and the schist belts which constitute older lithologic units, concomitant deep-sited granitoids common to other Pan-African countries also outcrop prominently in Nigeria.Rock types seen in the study area include Migmatite, Chamokite, Pegmatite and Granite, with sand-like presence of laterite recorded on the topsoil.

3. Methodology

3.1. Dar-Zarrouk Parameters

Dar-Zarrouk parameters consist of the transverse resistance and longitudinal conductance. Niwas and Singhal (1981) show that the Dar-Zarrouk parameters for the horizontal, homogenous and isotropic layer could be obtained as follows:

Transverse Resistance:

$R_T = \sum hi \times pi$

Longitudinal Conductance:

The longitudinal conductance (S_L) gives a measure of the impermeability of a layer.

$S_L = \sum hi/pi$

where:

ρ is the layer resistivity in Ωm.

h is the layer thickness in m.

R_T is the transverse resistance in Ωm^2.

S_L is the longitudinal conductance in mhos.

3.2. Protective Capacity

The values of the longitudinal conductance were used in evaluating the protective capacity of the aquifer. Mogaji et al (2007)., states that the earth medium act as a natural filter to percolating fluid and that its ability to retard fluid is a measure of its protective capacity.

$Pc = \sum hi/pi(\sum S_L$ of the overburden layers).

where: P_c = Protective capacity in mhos.

P_i = Resistivity of the overburden layer.

h_i = thickness of the overburden layer.

S_L = longitudinal conductance.

3.3. Hydraulic Conductivity

The hydraulic conductance is directly proportional to the layer resistivity (Kosinski and Kelly, 1981). Therefore, the region with low resistivity value in the study area which is assumed to be the interface of salt water intrusion will automatically have low hydraulic conductivity. Hilmi S. Salem (1999) says that hydraulic conductivity is proportional to Permeability. Thus, the portion of the aquifer with high hydraulic conductivity would be highly permeable to fluid flow and easy circulation of contaminant. In a porous aquifer, the relationship between the hydraulic conductivity and layer resistance is given by the equation below (Johansen, 1977):

K (in m/s) = $10^{-5} \times 97.5^{-1} \times p^{1.195}$

K (in m/day) = 60 x 60 x 24 x [K in (m/s)]

3.4. Porosity and Formation Factor

Archie's experiments revealed that the formation factor could be related to the porosity of an aquifer by the formula below.

$F = a/\Phi m$

Thus, $\Phi = [a/F]\ 1/m$

Senthil Kumar et al. (2001) relate the formation factor to the hydraulic conductivity by the formula below:

$F = [k/a]^{1/m}$

Where:

F is the formation factor

K is the hydraulic conductivity (m/day)

Φ is the aquifer porosity

a = 0.62 {Tortousity factor for unconsolidated sands}; m = 2.15 {Cementation exponent}.

4. Results and Discussion

The VES data interpretation (**Figure 2**) delineated three to four major geoelectric units comprising the topsoil, sandy clay or clayey sand layer, weathered formation and fresh basement. The topsoil resistivity values topsoil with resistivity ranging from 58-230Ωm, sand clay formation with resistivity values varies from 38 to 514Ωm, weathered basement with resistivity varying from 54 to 455Ωm and fresh basement with resistivity valued between 115 and 1797Ωm. Thickness values of the weathered layer range from 5.1 to 15.4m.

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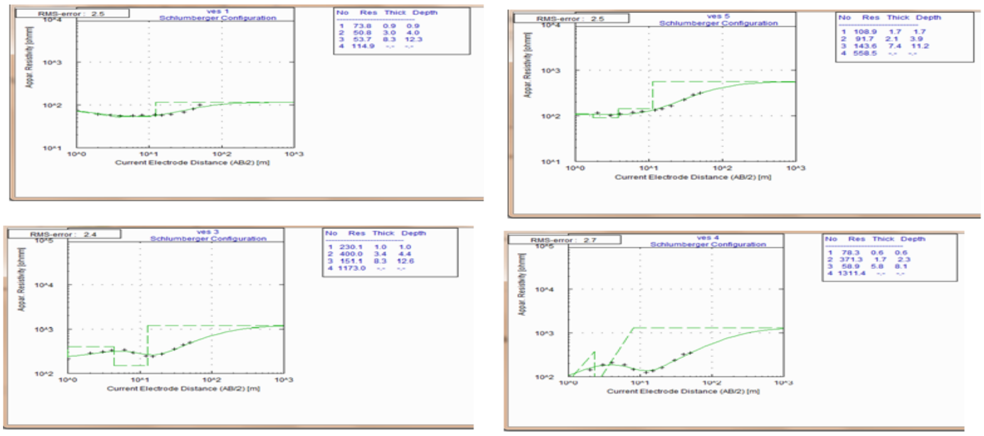

Figure 2: Selected VES Curves across the study area

The results of the interpretation of the sounding curves are presented in table below **(Table.1)**. After interpretation of all the 16 VES points, 2 of the curves are characterized by AH curve type, 6 by QH, 6 by KH, and 2 by QK where $\ell_1 > \ell_2 < \ell_3 < \ell_4$, $\ell_1 > \ell_2 < \ell_3 < \ell_4$, $\ell_1 < \ell_2 > \ell_3 < \ell_4$, $\ell_1 < \ell_2 < \ell_3 < \ell_4$ respectively.

4.1. Overburden Thickness

The overburden is considered in this study to be the materials above the fresh basement at each VES location. The interpreted depths to the basement beneath all the VES stations were plotted and contoured as overburden thickness map with classifications (**Figure 3**) with values ranging from 8 to 17m.Generally, we discover that appreciable overburden in this area have a greater effect in characterizing or determining of groundwater vulnerability.

Table 1: Showing Types of Sounding Curves for Each VES Station)

VES STATIONS	SOUNDING CURVE	CHARACTERIS-TICS	NUMBER OF LAYERS	OVERBURDEN THICKNESS(m)
1	AH	$\ell_1 > \ell_2 < \ell_3 < \ell_4$	4	12
2	QH	$\ell_1 > \ell_2 < \ell_3 < \ell_4$	4	17
3	AH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	13
4	KH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	8
5	QH	$\ell_1 > \ell_2 < \ell_3 < \ell_4$	4	11
6	QK	$\ell_1 < \ell_2 < \ell_3 < \ell_4$	4	10
7	QH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	13
8	QH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	12
9	KH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	8
10	KH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	9
11	QH	$\ell_1 < \ell_2 < \ell_3 < \ell_4$	4	14
12	QK	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	9
13	KH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	8
14	KH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	9
15	QH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	10
16	KH	$\ell_1 < \ell_2 > \ell_3 < \ell_4$	4	10

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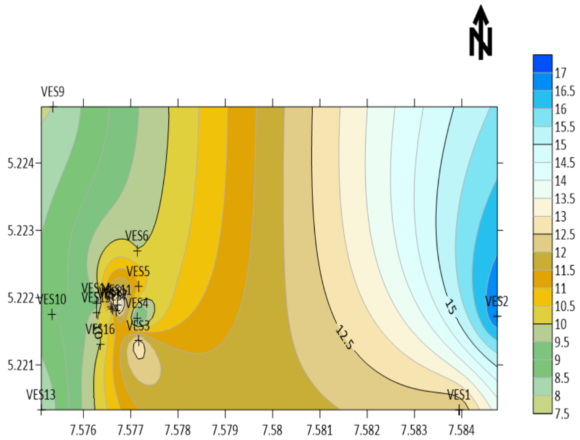

Figure 3: Olujoda Overburden thickness map

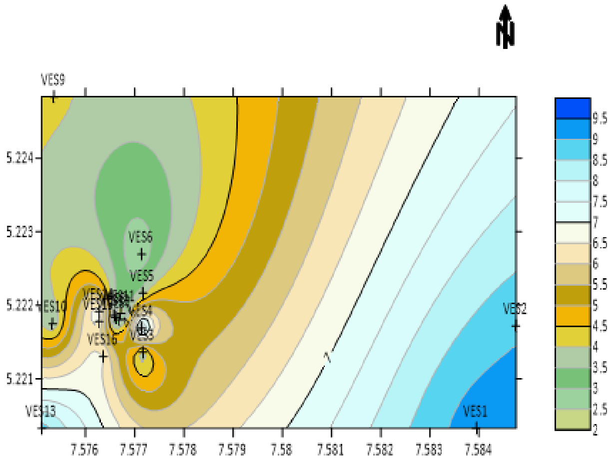

Figure 4: Olujoda hydraulic Aquifer Map

Evaluation of Aquifer Protective Capacity

Aquifer protective capacity (APC) is the ability of the overlying layers of rock (i.e., the overburden) above the aquifer unit to impede, slow-down, filter and contains percolating ground surface contaminating fluids and run-offs. The second order geoelectric parameter – longitudinal conductance (which is a Dar Zarrouk parameter) was evaluated from the first-order parameters (thickness and resistivity) of the geoelectric layers which were used in the classification of the APC of the area. Highly impervious materials such as clay and shale usually have high longitudinal conductance values (resulting from their low resistivity values) while pervious materials such as sand and gravels have low longitudinal conductance values (resulting from their high resistivity values). While high longitudinal conductance value corresponds to excellent and good APC, low longitudinal conductance values are associated with poor and weak APC. The rating of Protective capacity of an aquifer was described by Oladapo and Akintorinwa (2007) as expressed in Table 3.

Olujoda hydraulic Aquifer Characteristics

The hydraulic characteristics of the aquifer estimated from the geoelectric parameters reveal that the longitudinal conductance values calculated to acquire aquifer protective capacity values ranges between 0.0226 and 0.3054 mhos, transverse resistivity ranges from 54.2927-432.843Ωm^2, transmissivity values vary from 8.382 to 136.91 m 2 /day, reflection coefficient values range between 0.270 to 0.472 and hydraulic conductivity ranges from 1.28-9.36 m/day. The results show that the aquifer is characterized by high porosity having weak protective capacities (Fatoba, *et al*., 2014) of overburden layers indicating that it is highly vulnerable to surface contamination. The area has low to intermediate transmissivity values except for VES-2 and VES-1 **(Figure 4)** with moderate value according to the standard for transmissivity classification by Kransy 1993, and moderate hydraulic conductivity values indicating that the aquifer can transmit water at a rate that will suffice for the need of the community in the study area.

Olujoda Aquifer Protective Capacity

Figure 5 presents the aquifer protective capacity map around Olujoda. Western part of Otofure from the north to the south vary in protective rating from 2 to 6.5 mhos indicating moderate to good rating.In the South Eastern part of Olujoda, the protective capacity ranges from 0.2 to 0.4 mhos [Figure 5] which indicates good protective capacity rating.According to the rating of Protective capacity of an aquifer whcich was described by Oladapo and Akintorinwa (2007) in **Table 3 ;** VES 3, VES 5, VES 6, VES 7, VES 8, VES 9, VES 10, VES 11, VES 12 all show poor aquifer protective capacity values, VES 4, VES

Table 2. Dar-zarrouk parameters and the Hydraulic characteristics estimated from the geoeletric parameters of the aquifer.

VES Number	Resistivity	Reflection coefficient	Conductivity	Longitudinal conductance	Protective capacity	Longitudinal resistivity	Transvers Resistivity	Coefficient anisotropy	Transverse Resistance	Hydraulic conductivity	Transmissivity
1	74 51 54 115	0.184	0.014 0.011 0.019	0.0126 0.033 0.1577	0.2033	60.502	54.2927	0.95	66.6 153 448.2	9.36	77.69
2	106 38 57 355	0.472	0.009 0.026 0.018	0.0126 0.0156 0.2772	0.3054	56.975	60.2874	1.03	148.4 22.8 877.8	8.89	136.91
3	230 400 151 1173	-0.270	0.004 0.003 0.007	0.004 0.0102 0.0581	0.0723	174.274	225.659	1.14	230 1360 1253.3	3.59	29.79
4	78 371 59 1311	-0.653	0.013 0.003 0.007	0.078 0.0051 0.0986	0.1817	44.579	125.889	1.68	46.8 630.7 342.2	8.61	49.94
3	109 92 144 559	0.085	0.009 0.011 0.007	0.0153 0.0231 0.0518	0.0518	142.857	195.149	1.17	185.3 193.2 1065.6	3.75	27.75
6	65 132 205 537	-0.345	0.015 0.008 0.005	0.015 0.0128 0.039	0.0668	155.689	180.308	1.08	65.0 211.2 1599	2.69	20.98
7	59 174 155 325	-0.494	0.017 0.006 0.006	0.0136 0.0072 0.0612	0.082	148.781	150.574	1.01	47.2 208.8 1581	3.49	35.59
8	65 269 149 685	-0.611	0.015 0.004 0.007	0.012 0.0048 0.0714	0.0882	138.322	155.295	1.06	52 322.8 1519.8	3.63	37.03
9	89 473 128 1797	-0.683	0.011 0.002 0.008	0..0066 0.0054 0.0408	0.0528	159.091	236.107	1.22	53.4 1277.1 652.8	4.18	21.32
10	143 380 152 843	-0.453	0.007 0.003 0.007	0.0049 0.0075 0.0399	0.0523	170.172	215.337	1.12	100.1 950 866.4	3.56	20.29
11	146 333 345 1126	-0.390	0.007 0.003 0.003	0.0042 0.0012 0.0396	0.045	315.556	336.254	1.03	87.6 133.2 4554	1.66	21.91
12	120 514 455 1033	-0.621	0.008 0.002 0.002	0.0064 0.0024 0.0138	0.0226	393.805	432.843	1.05	96 616.8 3139.5	1.28	8.832
13	58 315 58 1263	-0.689	0.017 0.003 0.017	0.0119 0.0027 0.102	0.1166	65.1801	88.4342	1.16	40.6 283.5 348	8.75	52.5
14	101 230 74 144	-0.390	0.009 0.004 0.014	0.0072 0.004 0.1064	0.1176	79.9320	92.8934	1.08	80.8 230 562.4	6.97	52.97
15	71 90 81 665	-0.118	0.014 0.011 0.012	0.0112 0.0473 0.0624	0.1209	85.1944	83.1068	0.99	56.8 378 421.2	6.41	33.33
16	90 192 79 871	-0.362	0.011 0.005 0.013	0.011 0.0085 0.1001	0.1196	86.9565	98.5289	1.06	90 326.4 608.3	6.56	50.512

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Table 3: Protective Capacity Rating (Oladapo and Akintorinwa (2007)

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

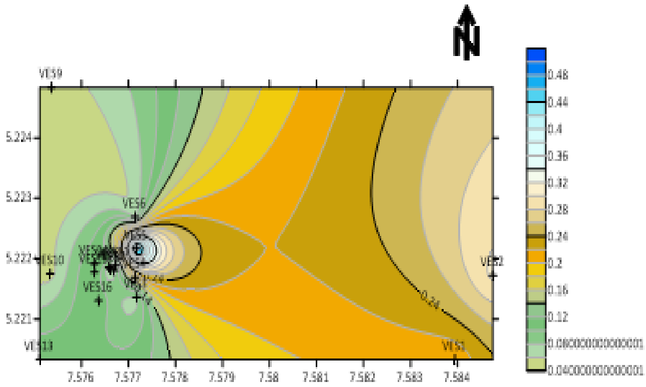

Figure 5: Olujoda protective capacity map

2 show moderate values, which is just 12.5% of the whole VES points surveyed.

4.2. Olujoda Total Longitudinal Unit Conductance Evaluation

The total longitudinal unit conductance values have been utilized severally in the evaluation of overburden protective capacities over hydrogeologic structures (Oladapo and Omotola 2015; Okiongbo et al., 2011; Atakpo and Ayolabi, 2008; Braga et al., 2006). Aquifer protective capacity values within the study area range from 0.0226 to 0.3054mhos. The aquifer protective capacity map shown in **Figure 6** shows that the hydrogeologic structures underneath areas of VES 1 and VES 2 (northwest through to southeastern parts) have overlying materials consisting of moderate to good protective capacity rating (0.1 - 2.7 mhos). The northeastern and southwestern flanks of the area are weakly protected (0.01-0.1 mhos) from contaminant infiltration.

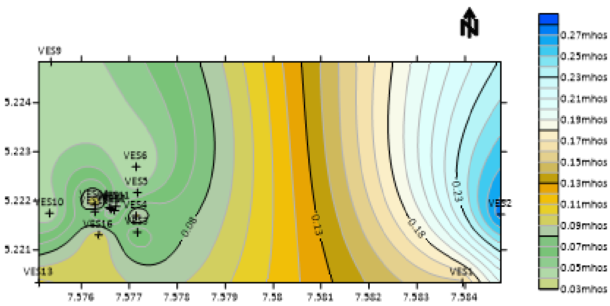

Figure 6: Olujoda Total Longitudinal Unit Conductance Map

5. Conclusion

This study applied Dar–Zarrouk parameters—namely longitudinal conductance and transverse resistance—to evaluate groundwater vulnerability to surface contamination within Olujoda and its surrounding communities. The integration of geoelectrical sounding data with these hydrogeophysical indicators provided a reliable framework for characterizing subsurface protective capacity and identifying zones most susceptible to pollution. The results revealed significant spatial variations in aquifer protection levels, reflecting differences in overburden thickness, clay content, and lithological composition. Areas with low longitudinal conductance and low transverse resistance were classified as highly vulnerable, indicating weak protective layers and enhanced risk of contaminant migration from the surface into the groundwater system. Conversely, zones showing high protective capacity corresponded to thick clayey overburden, which provides natural attenuation against infiltration of pollutants.

Due to growing urbanization and farming activity around Olujoda area and its suburbs, which has the high possibility of contaminating the regional aquifer with the leachates they have generated over the years, an assessment of the aquifer vulnerability using Longitudinal Unit Conductance, S - a Dar-Zarrouk parameter was carried out in the study are with a view to prevent the exploitation and consumption of contaminated groundwater in the localities. Sixteen VES data were acquired across the study area. The VES results in the

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area delineate four major geoelectric layers which are indicative of the topsoil, sand, Basement, and Fresh basement. The control VES(9&10) delineate four geoelectric layers which are only topsoil and sand units (with varying degree of moisture content). Generally, the results from the study area show that the aquifer is characterized by high porosity having weak protective capacities (Fatoba, *et al*., 2014) of overburden layers indicating that it is highly vulnerable to surface contamination. There are traces of leachate occurrence at a depth from 2.9 to 4 m along VES2,3,4, and 4, respectively.

Overall, the findings show that groundwater resources within Olujoda and environs range from moderately protected to highly vulnerable, depending on local subsurface conditions. This underscores the need for targeted groundwater management strategies, land-use regulation, and pollution-control measures, particularly in areas where the aquifer is poorly confined. The study also confirms the usefulness of Dar–Zarrouk parameters as a cost-effective and efficient tool for groundwater vulnerability assessment in crystalline basement terrains. It is recommended that the identified high-risk zones be prioritized for continuous monitoring, environmental sanitation improvement, and the siting of boreholes away from potential contamination sources. Future work may incorporate hydrochemical analysis, GIS-based vulnerability modeling, and long-term monitoring to further improve understanding of contaminant pathways and strengthen groundwater protection efforts in the region.

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