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ARTICLE

Assessment of the Protective Capacity of Vadoze Zone over Aquifer Systems Using Secondary Geoelectrical Parameters: A Case Study of Kaltungo Area North East, Nigeria

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ABSTRACT

An assessment of the protective capacity of the vadose zone overlying the aquifer systems in the Kaltungo area was carried out to determine its influence on groundwater quality. Applying the schlumberger array with a maximum electrode spread AB/2 = 100m through VES, thirty water well points were surveyed using Omega terrameter (PIOSO1) resistivity meter. The field data was first subjected to manual interpretation through curve marching and then digitized modeled curves using computer software. The interpreted data revealed that the area is characterized by eleven different curve types representing three to five geo electrical layers. In order to assess the protective capacity of the vadoze zone over the aquifer systems, the longitudinal conductance (S) and transverse resistance (T) (secondary geoelectric parameters) were computed from the primary data using the Dar Zarouk formula. The values of S obtained range from 0.0018 to 0.4056 ohms with a mean value of 0.0135 ohms while the values of T range from 0.55 ohms to 1195.68 ohms with a mean value of 39.84 ohms. The values of S and T obtained reveal that 90% of probed points has poor protective capacity, 10 % has moderate protective capacity and 83 % has high transmissivity, 17 % has intermediate transmissivity. The T and S values are skewed towards poorly protective capacity thus making groundwater in the area highly vulnerable to contamination from the surface. To achieve good groundwater quality in the area, proper completion of newly constructed wells should install protective casing through the entire vadose zone.

1. Introduction

Groundwater remains the most readily available alternative source of supply to humanity especially in areas with limited access to surface water. Aquifer systems in geological complex terrain like crystalline basement vary in nature and extent depending on the bed rock and its degree of weathering. The quality of water from such aquifer systems is determined by a number of factors such as the thickness and composition of the materials in the overburden (vadose zone), the depth of occurrence and the nature of human activities in the area. An effective groundwater protection is given by protective layers of the vadose zone with sufficient thickness and

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low hydraulic conductivity [18,26].

Surface geophysical measurements provide an alternative approach for estimation of some of the aquifer properties [2]. In the past 3 decades severl investigators have studied the relations between aquifer parameters and geoelectric properties [4,10,13,16,19,23,24].

In this study 30 VES were conducted at preselected stations employing Schlumberger array. The points were selected based on their proximity to existing production wells with the aim of assessing the protective capacity of the vadose zone to the underlying aquifers systems. The background to this study was conceived from the fact that variations in resistivity of subsurface materials is due to variation in the geology and their characteristic compositions. Transverse resistance (T) and longitudinal conductance (S) (Dar Zarouk Parameters) of the vadose zone for the study area were computed from measured field resistivity data and used to assess the protective capacity of the vadose zone over the aquifer systems.

Geology of the Study Area

The study area is part of the Gombe sub-basin of the upper Benue Trough and is geographically located between latitude $9^0 45^1$ and $9^0 50^1$N, Longitude$11^0 15^{11}$ and $11^0 20^1$E. The geology of the area is characterized by crystalline basement rocks mainly coarse porphyritic granite, medium grain granite and biotite granite as well as the intrusion of pegmatite and basalt. The sedimentary succession is defined by Cretaceous sediments of the Bima sandstone. (Figure 1). Comprehensive geology of this sub-basin has been discussed in the works of Benkhelil et'al [5], Zaborski et al [27], Mboringong et al [17].

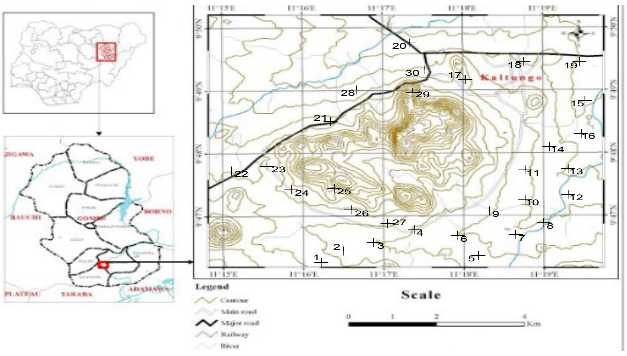

Figure 1. Location map of the study area showing VES points

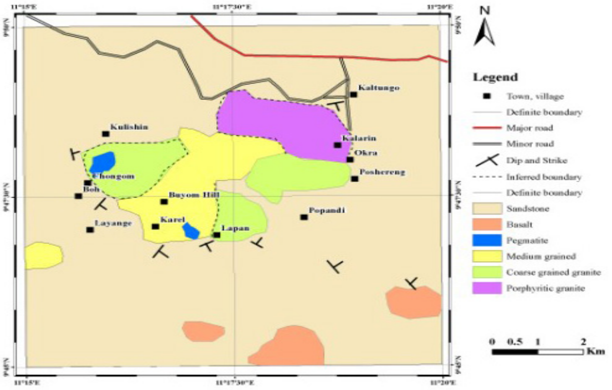

Figure 2. Geologic Map of the study area (Modified from Sa'ad and Baba [25])

2. Materials and Methods

2.1 Theoretical Basis

An effective groundwater protection is given by protective layers (vadose zone) with sufficient thickness and low hydraulic conductivity leading to longer residence time of percolating water [18]. Residence time of percolating water into the aquifer through materials with large pore spaces is shorter than that for smaller pore spaces and as a result water moves faster leading to poor natural filtration process.

2.2 Data Acquisition and Processing

The data for this study is of two sets; the field data (primary) and the processed data (secondary geoelectric data). The primary data was generated in the field from investigating thirty probe points using OhmegaTerrameter employing Schlumberger electrode configuration with a maximum spread of 200 m at (AB/2 = 100m). The field data generated in form of apparent resistivity versus electrode spread was interpreted using WINRESIST computer software to give layer resistivity and thickness for each VES point. The interpreted VES results (layer resistivity values and thicknesses) were used to compute the secondary geo-electric parameters, also known as Dar-Zarrouk parameters. These parameters include the Longitudinal Unit Conductance (S) and Transverse Unit Resistance (T).

2.3 Longitudinal Conductance

The longitudinal conductance (S) is the geo-electric parameter used to define target areas of groundwater potential.

$$S = h/\rho a \qquad (1)$$

Where S is the longitudinal conductance, h is thickness

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and ρa is apparent resistivity of the aquiferous layer. For the purpose of this study the resistivity values of the layers overlying the perceived aquiferous zone was used to compute the S values (table 4)

2.4 Transverse Resistance

The transverse resistance (T) is one of the parameters used to define target areas of good groundwater potential. It has a direct relation with transmissivity and the highest T values reflect most likely the highest transmissivity values of the aquifers or aquiferous zones. The transverse resistance (T) is correlated with aquifer transmissivity to establish the functional relationship of the vadose zone and the underlying aquifer in terms of hydraulic communication. This parameter has been used in this study to evaluate the capacity of the top soil (vadose zone) overlying the aquifer system so as to determine its ability to allow infiltrating water to the aquifer. The assumption is that when geologic materials have high transmissivity, the tendency is for them to permit high infiltration into the underlying aquifer systems. The values of T for each VES points were computed using the formula below.

$$T = h.\rho a \qquad (2)$$

Where T is the transverse resistance, h is thickness and ρa is apparent resistivity of the aquiferous layer

2.5 Vadoze Zone Protective Caoacity

Vadoze zone protective capacity (VZPC) is the capacity of the overburden unit to impede and filter percolating ground surface polluting liquid into the aquiferous unit. This concept was derived from Henriet's 1976 relationship that "the protective capacity of the overburden (vadose zone) is proportional to its longitudinal conductance S which in terms of aquifer protection gets a dimension of time (infiltration time)". The second order geo-electric parameter (Dar Zarrouk parameter) was evaluated from the primary/first order parameters (using equation 1) (thickness and resistivity) of the geo-electric subsurface layers which were used in the classification of the protective capacity of the vadoze zone over the aquifer systems of the area. According to Oladapo [20] the protective capacity of the vadose zone over an aquifer can be classified based on total unit conductance ($\sum S$); Excellent ($S> 5$), very good ($5 \leq S<10$), good ($0.7 \leq S<5$), moderate ($0.2 \leq S<0.7$), weak ($0.1 \leq S<0.2$) and poor ($S<0.1$).

As the hydraulic conductivity is directly proportional to the resistivity [13] and the product of the resistivity for its thickness, it is defined as being the transverse resistance (T), on a purely empirical basis and it can be admitted that the transmissivity of an aquifer is directly proportional to its transverse resistance [12]. Clay layer corresponds to low resistivities and low hydraulic conductivities, and vice versa, hence, the protective capacity of the overburden could be considered as being proportional to the ratio of thickness to resistivity - longitudinal conductance (S). In the present study, layers found above the potential aquifers have generally been considered as the vadose zone and as such their transmissivities (T) have been computed using equation 2 above. Adopting Culled 1982 classification the T values were categorized as follows: Very high transmissivity magnitude ($T \geq 1000$), High transmissivity magnitude ($100 \leq T<1000$), intermediate transmissivity magnitude ($10 \leq T<100$), Low transmissivity magnitude ($1 \leq T<10$), very low transmissivity magnitude ($0.1 \leq T<1$) and imperceptible transmissivity magnitude ($T< 0.1$)

3. Result and Discussion

Table 1. Result of Interpretation of VES Curves from the Study area

VES No.	Layers No.	R(Ω)	Layer Thickness (m)	Inferred Lithology	Curves Types and % error	Inferred Aquifer
1	1. 2. 3. 4.	150 17.4 7188 31.3	2.92 3.25 8 -	- Top soil -Weathered basement - Fractured basement Fresh basement	HK	Aquifer
2	1. 2. 3. 4.	149 110 31.6 21097	1.55 10 15.6 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	QH	Aquifer
3	1. 2. 3.	49.2 376 27.7	5.25 13 -	- Top soil -Weathered basement - Fresh basement	H	Aquifer
4	1. 2. 3. 4.	86.1 26.1 104 425	1.48 1.23 8.29	- Top soil -Weathered basement - Fractured basement - Fresh basement	HA	Aquifer

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5	1. 2. 3.	163 388 90.7	3.84 18 -	Top soil -Weathered basement - Fresh basement	K	Aquifer
6	1. 2. 3. 4.	37.3 55.6 237 15.5	6.93 5.39 6.68 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	AH	Aquifer
7	1. 2. 3. 4.	99.1 55.4 16.6 10749	5 13 17.4 -	- Top soil -Weathered Basement - Fractured Basement - Fresh Basement	QH	Aquifer
8	1. 2. 3. 4.	24.8 4.26 3324 37	2.06 2.96 5.52 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	HA	Aquifer
9	1. 2. 3. 4.	171 399 153 0.862	1.57 0.66 40.7	- Top soil -Weathered basement - Fractured basement - Fresh basement	KH	Aquifer
10	1. 2. 3. 4.	3.9 54.3 9.44 95.4	0.142 3.46 2.63 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	HK	Aquifer
11	1. 2. 3.	80.7 26.1 170	5.43 3.58 -	Top soil -Weathered basement - Fresh basement	H	Aquifer
12	1. 2. 3. 4. 5.	251 116 369 18.5 14180	2.46 1.93 4.29 9.46 -	- Top soil - Slightly Weathered basement -Weathered basement - Fractured basement - Fresh basement	HKH	Aquifer
13	1. 2. 3. 4.	89.8 220 14.8 444	2.81 5.63 8.6 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	KH	Aquifer
14	1. 2. 3. 4.	53.8 147 561 94.5	0.323 9.99 9.03 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	HK	Aquifer
15	1. 2. 3. 4. 5.	39.3 62.3 23.5 512 33.9	0.9 1.02 2.18 4.66 -	- Top soil - Slightly Weathered basement -Weathered basement - Fractured basement - Fresh basement	KHK	Aquifer
16	1. 2. 3. 4. 5.	28.1 362 28.3 119 0.434	1.64 1.67 5.86 15.5 -	- Top soil - Slightly Weathered basement -Weathered basement Fractured basement Fresh basement	KHK	Aquifer
17	1. 2. 3.	62.7 10.3 11095	9.78 13.4 -	- Top soil -Weathered basement - Fresh basement	H	Aquifer
18	1. 2. 3. 4.	236 113 9.33 104	0.783 3.38 1.52 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	HK	Aquifer
19	1. 2. 3. 4.	114 29.2 11.5 3307	0.941 11.6 15.6 -	- Top soil -Weathered basement - Fractured basement - Fresh basement	QH	Aquifer

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20	1.	243	0.51	- Top soil	QHA	Aquifer
	2.	105	4.53	- Slightly Weathered basement		
	3.	27.1	4.43	-Weathered basement		
	4.	119	36.6	- Fractured basement		
	5.	6491	-	- Fresh basement		
21	1.	631.1	1.1	- Top soil	HQ	Aquifer
	2.	81.3	14.3	- Weathered basement		
	3.	166.0	70.8	- Fractured basement		
	4.	147.9	-	- Fresh basement		
22	1.	275.7	0.8	- Top soil	H	Aquifer
	2.	103.0	24.3	- Weathered basement		
	3.	2546.6	-	- Fresh basement		
23	1.	403.5	1.8	- Top soil	H	Aquifer
	2.	66.3	14.6	- Weathered basement		
	3.	726.1	-	- Fresh basement		
24	1.	380.5	0.8	- Top soil	HQ	Aquifer
	2.	60.3	3.2	- Weathered basement		
	3.	1069.9	56.4	- Fractured basement		
	4.	789.2	-	- Fresh basement		
25	1.	112.8	10.6	- Top soil	K	Aquifer
	2.	675.2	56.2	- Weathered basement		
	3.	77.8	-	- Fresh basement		
26	1.	200.6	1.6	- Top soil	H	Aquifer
	2.	22.6	4.8	- Weathered basement		
	3.	1003.8	-	- Fresh basement		
27	1.	231.0	3.0	- Top soil	HK	Aquifer
	2.	28.7	10.1	- Weathered basement		
	3.	249.5	49.9	- Fractured basement		
	4.	327.0	-	- Fresh basement		
28	1.	195.3	1.8	- Top soil	HKH	Aquifer
	2.	24.2	3.0	- Slightly weathered		
	3.	401.9	11.0	- Weathered basement		
	4.	23.0	39.5	- Fractured basement		
	5.	32.8	-	- Fresh basement		
29	1.	423.1	1.1	- Top soil	HK	Aquifer
	2.	91.0	5.6	- Weathered basement		
	3.	212.6	28.7	- Fractured basement		
	4.	942.0	-	- Fresh basement		
30	1.	435.7	0.8	- Top soil	H	Aquifer
	2.	89.4	14.2	- Weathered basement		
	3.	3020.6	-	- Fresh basement		

3.1 Geo-Electric Section

The data analysis from the study area shows a three to five layers geo-electric succession (Figure 3 and 4). This succession comprises of the dry topsoil, slightly weathered, weathered basement, fractured basement and Fresh basement. Weathered and fractured zones represented by low and fairly high resistivity units, respectively, are considered to be the potential groundwater bearing zones. Dike el al. [8]

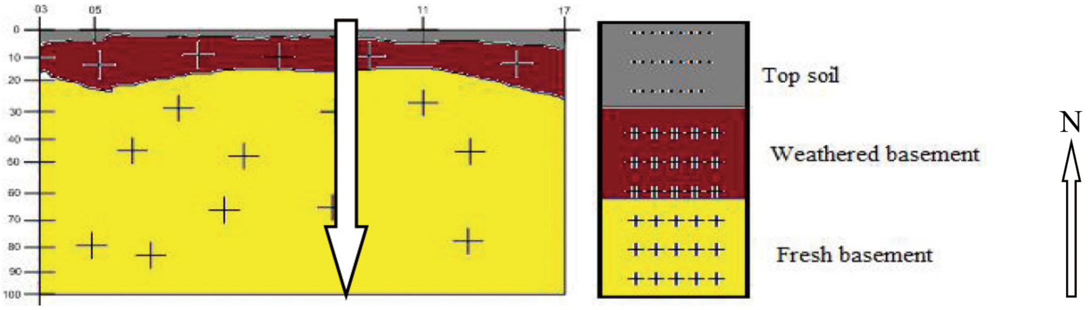

Figure 3. Geo electric Section of Ves 03, 05, 11 and 17 (3 layers)

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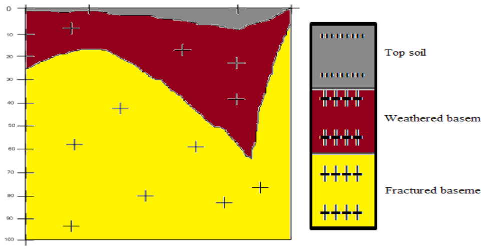
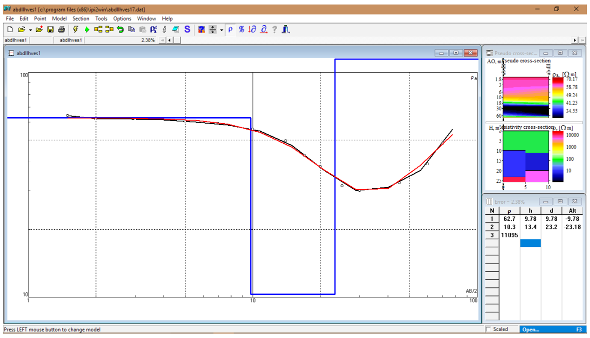


Figure 4. Geo electric Section of Ves 22, 23 25 and 26 (3 layers)



Error = 2.38%

N	ρ	h	d	Alt
1	62.7	9.78	9.78	-9.78
2	10.3	13.4	23.2	-23.18
3	11095			

Figure 5. A three layer type curve

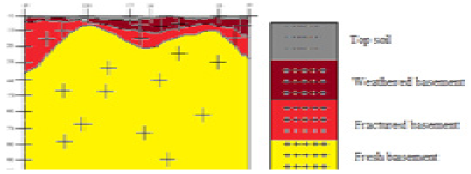


Figure 6. Geo electric Section of Ves 1, 2, 4, 6, 7 and 8 (4 layers)

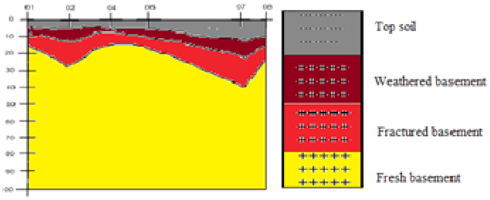
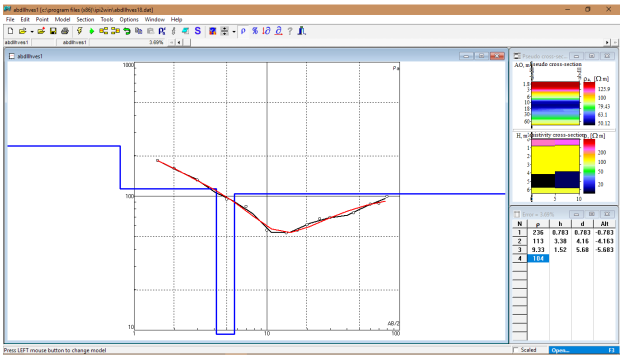


Figure 7. Geo electric Section of Ves 9, 10, 13, 14, 18 and 19 (4 layers)



Error = 3.69%

N	ρ	h	d	Alt
1	236	0.783	0.783	-0.783
2	113	3.38	4.16	-4.163
3	9.33	1.52	5.68	-5.683
4	104			

Figure 8. A four layer type curve

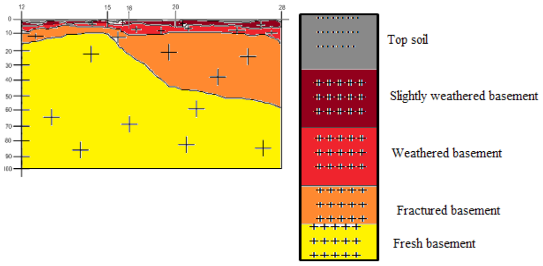
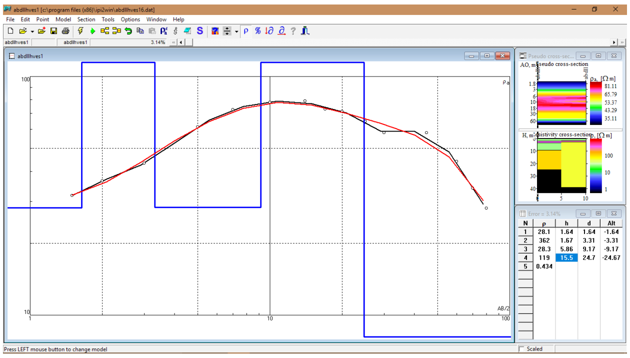


Figure 9. Geo electric Section of Ves 12, 15, 16, 20 and 28 (5 layers)



Error = 3.14%

N	ρ	h	d	Alt
1	28.1	1.64	1.64	-1.64
2	362	1.67	3.31	-3.31
3	28.3	5.86	9.17	-9.17
4	119	15.5	24.7	-24.67
5	0.434			

Figure 10. A five layer Type Curve

Table 2. Evaluation of the Longitudinal Conductance and Transverse Resistance of the Layers Obtained from each VES Location

VES NO	S1Ω	S2 Ω	S3 Ω	S4 Ω	T1 Ω	T2Ω	T3 Ω	T4 Ω
1	0.0197	0.2443	0.0011		444.00	73.95	57504.00	
2	0.0104	0.0909	0.4937		230.95	1100.00	492.96	
3	0.1067	0.0346			258.30	4888.00		
4	0.0172	0.0457	0.0797		127.43	33.09	862.16	
5	0.0236	0.0464			625.92	6984.00		
6	0.1859	0.0969	0.0282		258.64	299.68	1583.16	
7	0.0505	0.2347	1.0482		495.50	720.20	288.84	
8	0.0831	0.6854	0.0017		51.09	12.44	188348.48	
9	0.0092	0.0017	0.2660		268.47	263.34	6227.10	
10	0.0364	0.0637	0.2786		0.55	187.88	24.83	

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11	0.0673	0.1372			438.20	93.44		
12	0.0098	0.0166	0.0166	0.5114	617.46	223.88	1583.01	175.01
13	0.0313	0.0256	0.5838		252.34	1238.60	127.87	
14	0.0060	0.0680	0.0161		17.38	1468.53	5065.83	
15	0.0229	0.0164	0.0928	0.0091	35.37	63.55	51.23	2385.92
16	0.584	0.0046	0.2071	0.1303	46.08	604.54	165.84	1844.50
17	0.1559	1.3009			613.21	139.36		
18	0.0033	0.0299	0.1629		184.79	381.94	14.18	
19	0.0083	0.3973	1.3565		107.27	338.72	179.40	
20	0.0021	0.0431	0.1635	0.3076	123.93	475.65	120.05	4355.40
21	0.0017	0.1759	0.4265		694.21	1162.59	11752.8	
22	0.0029	0.2559			220.56	2502.9		
23	0.0045	0.2202			726.30	967.98		
24	0.0021	0.0531	0.0527		304.4	192.96	60342.36	
25	0.0939	0.0531			1195.68	37946.24		
26	0.0079	0.2124			320.96	108.48		
27	0.0129	0.3519	299.4		693.0	289.87	12450.05	
28	0.0092	0.1239	0.0274	1.7174	351.54	72.6	4420.9	908.5
29	0.0026	0.0615	0.1349		465.41	509.6	6101.62	
30	0.0018	0.1588			348.56	1269.48		

Table 3. Evaluation of the Total Longitudinal Conductance, Total Transverse Resistance and Average Longitudinal Conductance and Average Transverse Resistance each VES Location

VES NO	S	PL	T	Pt
1	0.2651	57.37	58021.95	3814.72
2	0.5950	45.78	1823.91	67.18
3	0.1413	129.16	5146.30	281.99
4	0.1426	77.14	1022.68	92.97
5	0.07	312	7609.92	348.44
6	0.1501	0.06	2141.48	112.71
7	1.3334	26.55	1504.54	42.50
8	0.7702	0.0031	18412.01	1753.52
9	0.2769	155.04	6758.91	157.44
10	0.3787	16.46	213.26	34.21
11	0.2045	44.06	531.64	59.01
12	0.5494	33.02	2599.36	143.29
13	0.6407	26.66	1618.81	94.78
14	0.0901	95.95	6551.74	355.40
15	0.1412	62.04	2536.07	289.51
16	0.4004	61.61	2659.96	107.82
17	1.4568	15.91	752.57	32.47
18	0.1961	28.98	544.91	95.88
19	1.7621	15.97	625.39	22.22
20	0.5163	89.23	5075.03	110.16
21	0.6040	13609.6	142.69	157.88
22	0.2388	2723.46	15.11	108.50
23	0.2247	1694.28	72.99	103.31
24	0.1079	60839.72	559.78	1007.28
25	0.1515	39141.92	436.96	519.27
26	0.2203	429.44	29.05	67.10
27	299.7648	13432.92	0.21	216.31
28	1.8779	5681.01	29.45	102.73
29	0.199	7076.62	177.89	0.01
30	0.1606	1618.04	93.40	107.87

3.2 Protective Capacity Evaluation of the Vadoze Zone

The nature of the materials that overlain the mapped aquifers were evaluated using the layer parameters (i.e. resistivity and thickness), to determine its capacity to prevent infiltration of unwanted fluids into the aquifer. It should be noted that the earth materials act as natural filter to percolating fluids; therefore its ability to retard and filter percolating ground surface polluting fluids is a measure of its protective capacity [22]. That is to say that the geologic materials overlying an aquifer could act as seal in preventing the fluid from percolating into it.

The longitudinal unit conductance (S) values of the overburden materials obtained from the study area, ranges from 0.0018 to 0.4056 ohms (Table 4) with a mean value of 0.0135 ohms. Clayey overburden, which is characterized by relatively high longitudinal conductance, offers protection to the underlying aquifer. According to the classification of Oladapo and Akintorinwa [21], the longitudinal unit conductance (S) values from the study area enabled us to classify the area into poor, (S<0.1), weak, (0.1≤S<0.2), moderate (0.2≤S<0.7) and good, (0.7≤S<5), very good (5≤ S<10) and excellent(S>10) protective capacity zones. Where the conductance is greater than 10 mhos are considered zones of excellent protective capacity. This study has revealed that the overburden materials (vadose zone) in the VES 01, 04, 05, 08, 09,11, 12, 13, 14, 15, 16, 18, 20, 22, 23, 24, 25, 26, 27, 29 and 30 have poor protective capacity while VES 02, 03, 06, 10, 17, 21 and 28 are characterized by weak protective capacity. Furthermore, the VES 07, 19 and 27 are found to have a moderate protective capacity (Table 4, Figure 10). The result revealed that 90% of VES within the study area have poor protective capacity, while 10% have weak to moderate protective capacity.

Table 4. Summary of the vadoze zone protective capacity over the aquifer systems of the study area

VES No	No. of Overburden layers	Lithology	Longitudinal Conductance (∑S)	Protective Capacity
1	1.	- Top soil	0.02	(S<0.1), (Poor)
2	1. 2.	- Top soil - Weathered basement	0.10	(0.1 ≤S < 0.2) (Weak)
3	1.	- Top soil	0.11	(0.1 ≤S < 0.2) (Weak)
4	1. 2.	- Top soil - Weathered basement	0.06	(S<0.1), (Poor)
5	1.	- Top soil	0.02	(S<0.1), (Poor)
6	1.	- Top soil	0.19	(0.1 ≤S < 0.2) (Weak)
7	1. 2.	- Top soil - Weathered basement	0.03	(S<0.1), (Poor)
8	1.	- Top soil	0.08	(S<0.1), (Poor)
9	1. 2.	- Top soil - Weathered basement	0.01	(S<0.1), (Poor)
10	1. 2.	- Top soil - Weathered basement	0.1	(0.1 ≤S < 0.2) (Weak)
11	1.	- Top soil	0.07	(S<0.1), (Poor)
12	1. 2. 3.	- Top soil - Slightly weathered - Weathered basement	0.04	(S<0.1), (Poor)
13	1. 2.	- Top soil - Weathered basement	0.06	(S<0.1), (Poor)
14	1.	- Top soil	0.006	(S<0.1), (Poor)
15	1. 2.	- Top soil - Weathered basement	0.04	(S<0.1), (Poor)
16	1. 2.	- Top soil - Weathered basement	0.06	(S<0.1), (Poor)
17	1.	- Top soil	0.16	(0.1 ≤S < 0.2) (Weak)
18	1. 2.	- Top soil - Weathered basement	0.03	(S<0.1), (Poor)

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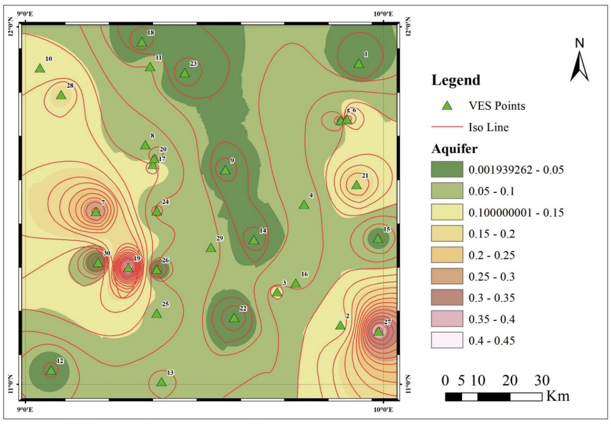
19	1. 2.	- Top soil - Weathered basement	0.4	(0.2≤S<0.7), (Moderate)
20	1. 2.	- Top soil - Weathered basement	0.05	(S<0.1), (Poor)
21	1. 2.	- Top soil - Weathered basement	0.28	(0.1 ≤S < 0.2) (Weak)
22	1.	- Top soil	0.003	(S<0.1),, (Poor)
23	1.	- Top soil	0.005	(S<0.1), (Poor)
24	1. 2.	- Top soil - Weathered basement	0.06	(S<0.1), (Poor)
25	1.	- Top soil	0.09	(S<0.1), (Poor)
26	1.	- Top soil	0.01	(S<0.1), (Poor)
27	1. 2.	- Top soil - Weathered basement	0.36	(0.2 ≤ S < 0.7) (Moderate)
28	1. 2. 3.	- Top soil - Slightly weathered - Weathered basement	0.16	(0.1 ≤S < 0.2) (Weak)
29	1. 2.	- Top soil - Weathered basement	0.06	(S<0.1), (Poor)
30	1.	- Top Soil	0.002	(S<0.1) (Poor)



Legend:

🟨

(0.2 ≤ S < 0.7) Moderate Protective Capacity

⬜

(0.1 ≤S < 0.2) Weak Protective Capacity

🟩

(S<0.1) (Poor) Poor Protective Capacity

Figure 11. Vadoze zone protective capacity Map

3.3 Vadose Zone Transmissivity

The transmissivity values of the Vadoze zone were evaluated using a relationship between transverse resistance and aquifer transmissivity. The transmissivity values obtained within the area of study range from 0.55 to 1195.68 ʹΩ^2 with a mean value of 72.47. The results as presented in (Table 5) and figure 11 show that the vadose zone in the study area majorly offers less protection to the underlying aquifer systems. Generally from the analysis it shows that 80% of the points investigated have High, 3.3% Very High, 13.3% intermediate and 3.3% very low Transmissivity magnitude. The points with high to very high values of T also corresponded with those with poor to weak protective capacity as represented by table 4 and figure 9. These two parameters have thus revealed that the underlying aquifer systems are highly vulnerable to any contaminants emanating from surface activities.

Table 5. Vadoze zone Transmissivity in relation to Transverse Resistance within the VES locations

VES NO	ʹPa of the vadoze zone	Thickness	Transmissivity	Comment
1	150	2.96	444.00	High
2	149	1.55	230.95	High
3	49.2	5.25	258.30	High
4	86.1	1.48	127.43	High
5	163	3.84	625.92	High
6	37.3	6.93	258.64	High
7	99.1	5	495.50	High
8	24.8	2.06	51.09	Intermediate

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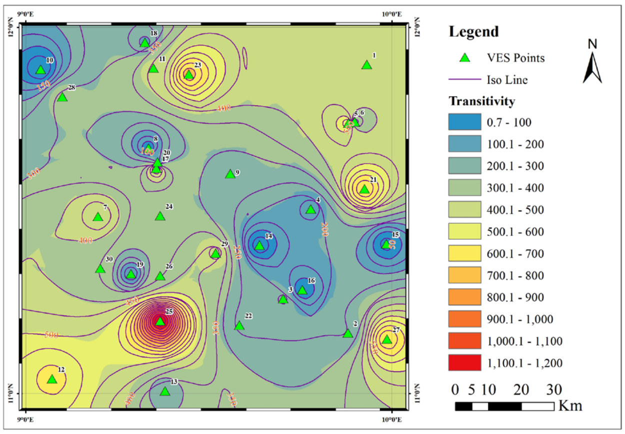
9	171	1.57	268.47	High
10	3.9	0.142	0.55	Very Low
11	80.7	5.43	438.20	High
12	251	2.46	617.46	High
13	89.8	2.81	252.34	High
14	53.8	0.323	17.38	Intermediate
15	39.3	0.9	35.37	Intermediate
16	28.1	1.64	46.08	Intermediate
17	62.7	9.78	613.21	High
18	236	0.78	184.79	High
19	114	0.94	107.27	High
20	243	0.51	123.93	High
21	631.1	1.1	694.21	High
22	275.7	0.8	220.56	High
23	403.5	1.8	726.30	High
24	380.5	0.8	304.40	High
25	112.8	10.6	1195.68	Very High
26	200.6	1.6	320.96	High
27	231.0	3.0	693.00	High
28	195.3	1.8	351.54	High
29	423.1	1.1	465.41	High
30	437.7	0.8	348.56	High



Legend:

🟧

(100≤T<1000) - (T≥1000),
High to very High Transmissivity magnitude

🟩

(10≤T<100),
Intermediate transmissivity magnitude

Figure 12. Vadose Zone Transmissivity Map

4. Conclusion

An assessment of the protective capacity of the vadose zone overlying aquifer systems in kaltungo area was carried out using secondary geo-electric parameters computed from VES data generated from 30 points in the field. The parameters considered here are longitudinal conductance (S) and Transverse Resistance here synonymous with Transmissivity (T) computed based on established relation between geo-electric resistivity and aquifer parameters (Dar Zarouk Parameters) thus;

$$S = h/\rho a \qquad (1)$$

$$T = h.\rho a \qquad (2)$$

The results from the two parameters as presented in tables 4 and 5 revealed that the vadose zone (overburden materials) in the study area offer poor protection to the underlying aquifer systems. The study has confirmed that using geo-electric parameters can be useful in groundwater quality studies. The relation between electrical resistivity, layer thickness and aquifer properties has also been confirmed by this study hence combining geophysical resistivity methods and other groundwater quality vulnerability mapping can form a good basis for groundwater sustainability studies.

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