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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 the 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 (vadoze 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 several 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°45' and 9°50'N, Longitude 11°15' and 11°20'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 Benkhelif et al \[5\], Zaborski et al \[27\], Mboringong et al \[17\].

\[\text{Figure 1. Location map of the study area showing VES points}\]

\[\text{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.

\[
S = \frac{h}{\rho a}
\]

(1)

Where S is the longitudinal conductance, h is thickness
and ρ_a 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.

\[ T = \frac{h\cdot\rho_a}{s} \]  \hspace{1cm} (2)

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

2.5 Vadoze Zone Protective Capacity

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 vadose 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 (ΣS); Excellent (S > 5), very good (5 ≤ S < 10), good (0.7 ≤ S < 5), moderate (0.2 ≤ S < 0.7), weak (0.1 ≤ 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 ≥ 1000), High transmissivity magnitude (100 ≤ T < 1000), intermediate transmissivity magnitude (10 ≤ T < 100), Low transmissivity magnitude (1 ≤ T < 10), very low transmissivity magnitude (0.1 ≤ T < 1) and imperceptible transmissivity magnitude (T < 0.1).

3. Result and Discussion

| VES No. | Layers No. | R(Ω) | Layer Thickness (m) | Inferred Lithology | Curves Types and % error | Inferred Aquifer |
|---------|------------|------|---------------------|--------------------|-------------------------|-----------------|
| 1       | 1. 150     | 2.92 | Top soil - Weathered basement - Fresh basement | -                   | HK                      | Aquifer         |
|         | 2. 17.4    | 3.25 | Top soil - Weathered basement - Fresh basement | -                   | QH                      | Aquifer         |
|         | 3. 7188    | 8    | Top soil - Weathered basement - Fresh basement | -                   | H                       | Aquifer         |
|         | 4. 31.3    | -    | Top soil - Weathered basement - Fresh basement | -                   | HA                      | Aquifer         |

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

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

| Layer | Top Soil | Slightly Weathered Basement | Weathered Basement | Fractured Basement | Fresh Basement | Aquifer |
|-------|----------|----------------------------|-------------------|-------------------|---------------|---------|
| 20    | 243.1    | 105                        | 27.1              | 119               | 6491      | QHA     |
| 21    | 631.1    | 181.3                      | 166.0             | 147.9             | -          | HQ      |
| 22    | 275.7    | 103.0                      | 2546.6            | -                 | -          | H       |
| 23    | 403.5    | 66.3                       | 726.1             | -                 | -          | H       |
| 24    | 380.5    | 603.3                      | 1069.9            | 753.2             | -          | HQ      |
| 25    | 112.8    | 675.2                      | 77.8              | -                 | -          | K       |
| 26    | 200.6    | 22.6                       | 1003.8            | -                 | -          | H       |
| 27    | 231.0    | 28.7                       | 249.5             | 327.0             | -          | HK      |
| 28    | 195.3    | 24.2                       | 401.9             | 23.0              | 32.8       | HKH     |
| 29    | 423.1    | 91.0                       | 212.6             | 942.0             | -          | HK      |
| 30    | 435.7    | 89.4                       | 3020.6            | -                 | -          | H       |

### 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) (Image)]](image-url)
Figure 4. Geo electric Section of Ves 22, 23 25 and 26 (3 layers)

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)

Figure 8. A four layer type curve

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

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 | S1 Ω | S2 Ω | S3 Ω | S4 Ω | T1 Ω | T2 Ω | 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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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     | 0.5163| 89.23 | 5075.03    | 110.16      |
| 28     | 0.5163| 89.23 | 5075.03    | 110.16      |
| 29     | 0.1999| 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 overlie 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)    |
The transmissivity values obtained within the area of study range from 0.55 to 1195.68 Ω² 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 | Pa 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 |
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;

\[
S = \frac{h}{\rho_a} \\
T = h \cdot \rho_a
\]

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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### Table 4: Geo-electric Parameters

| No. | \(S\)  | \(R_a\) | \(T\)  | Category       |
|-----|--------|---------|--------|----------------|
| 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           |

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![Vadose Zone Transmissivity Map](image)

Legend:

- **High to very High Transmissivity magnitude**
  - \((100 \leq T < 1000)\)
  - \((T \geq 1000)\)

- **Intermediate transmissivity magnitude**
  - \((10 \leq T < 100)\)

**Figure 12.** Vadose Zone Transmissivity Map
Benue trough, Nigeria. Journal of Africa earth Sciences, 1989(8): 251-282.

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