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Estimating Aquifer Potential and Protective Capacity Using Dar-Zarrouk Parameters and Geo-Electrical Techniques: A Case Study of the University of Ilorin Permanent Site, South-Western Nigeria.

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Competing Interests.

The authors declare no competing interests.

ABSTRACT

Background: Quality of water plays a vital role in the existence of human lives and the understanding of aquifer parameters is essential for effective groundwater management.

Objectives: The purpose of this research is to analyze the groundwater potential and the vulnerability of the aquifers to pollution at the University of Ilorin, Nigeria community.

Methods: Dar-Zarrouk mathematical parameter was used in this study to calculate the aquifer formation's transmissivity, hydraulic conductivity, and protective capacity and represented in a spatial map.

Results: 90% of the formations of the subsurface material have high to intermediate degrees of fracturing, according to the analysis and interpretation of the hydrogeological media. The hydraulic conductivity (0.2 – 21.4 m/day) and transmissivity (5.4 – 152.2 m^2/day) values indicate that most of the aquifers are of intermediate to high groundwater potentials. The spatial distribution map of reflection coefficient shows very low to high reflection coefficients indicating high to low groundwater potential across the study area. The Coefficient of anisotropy ranged from 0.9 – 3.3 suggesting high to low permeability aquifers. The aquifer formations are made up of weak to intermediate aquifer protective capacity. The calculated porosity values of the aquifer range from 1.79 % to 60.8 % showing negligible (VES 1 and 6) to good porosity quality (VES 5 and 10) of the inferred rock types from the calculated porosity. Thick overburden, weak to moderate aquifer protective capacity, and relatively high hydraulic conductivity and transmissivity make up the aquifer formations.

Conclusion: In conclusion, the study indicates promising groundwater occurrences, offering potential benefits for the University of Ilorin community. However, concerns arise regarding areas with weak aquifer protective capacity, suggesting vulnerability to pollutant infiltration. This research identified areas of possible groundwater viability and weak protective aquifer zones.

Keywords: Dar-Zarrouk Parameters, Aquifer Parameters, Aquifer Protective Capacity, Vertical Electrical Sounding, Geo-electric Section.

1. INTRODUCTION

Transmissivity and hydraulic conductivity are important parameters in understanding the aquifer properties for groundwater resource management. (Ige et. al, 2018). Groundwater exploitation is the major means of water supply for agricultural, industrial, and domestic uses in most parts of the world. An increase in urbanization, industrialization, and agricultural activities has led to groundwater degradation and subsequent pollution of the groundwater aquifer system, this phenomenon is at an alarming rate, and apart from groundwater pollution, these activities also have affected the human ecosystem negatively and this

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calls for attention. When groundwater is contaminated, it is dangerous for humans to use, due to its adverse effect on individuals and the environment.

In Basement Complex terrain, where the search for viable aquifers is difficult due to the peculiarity of the terrain the community relies mainly on surface water for water supplies. As a result, understanding the hydrologic features of the basement aquifer is critical for proper monitoring of basement water. The pumping test technique is popular for testing hydraulic parameters (hydraulic conductivity, transmissivity, porosity, and specific yield). However, in areas where pumping test data are unavailable, hydraulic properties can be calculated using geo-electric parameters (Ige et al., 2018). Surface geo-electrical measurements have been utilized to estimate aquifer properties and protective capacity since the late 1960s. Ungemach et al. (1969) linked transverse resistance with transmissivity determined from six pumping tests in the Rhinc aquifer. Gulraiz and Hassan (2016), Kazakis et al. (2016), Sattar et al. (2016), Ige et al. (2018) and other contemporary authors have all published research on this topic.

Another tool for assessing an aquifer's susceptibility to contaminants on the surface is the aquifer vulnerability. The depth of an aquifer and the sorts of geologic materials above it are crucial factors in determining how vulnerable it is to contamination. The objectives of this study are to characterize the shallow aquifer's subsurface lithology using the geo-electric approach, as well as to infer its hydraulic properties from surface geophysics.

Study Area

The study area is located within 08°30"00' to 08° 40"00' N and 04° 30"00' to 04° 40"00' E" (Fig.1) in the southern part of Ilorin area, Kwara state, Southwestern Nigeria.

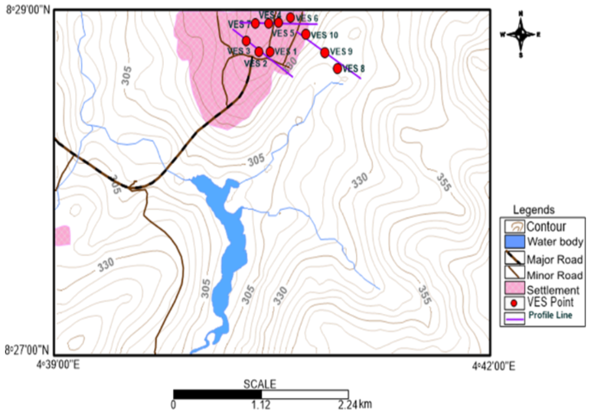

Figure 1: Topographic map of the study area showing the VES stations along three profiles.

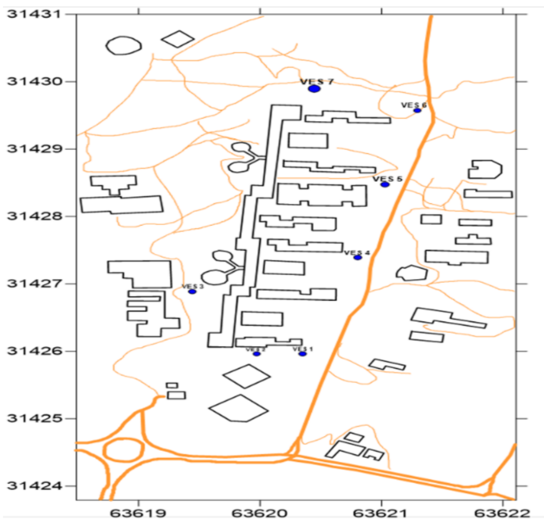

Figure 1.1: Base map of the study area showing the VES stations.

Geology of the Area

The area of interest covers about 2.9 Km² and lies within the Basement Complex terrain of Nigeria. It is underlain by mainly metamorphic rocks and a few granitic rocks consisting of high-grade metamorphic rocks in the form of

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gneisses, migmatite, and granitic suites. The major rock types identified are Migmatite, Migmatite Gneiss, Biotite Granite, Granite Gneiss, and Granite (Fig. 2). Predominant veins of mineralization include, Quartz vein, Pegmatitic vein, Quartzo-feldspathic vein.

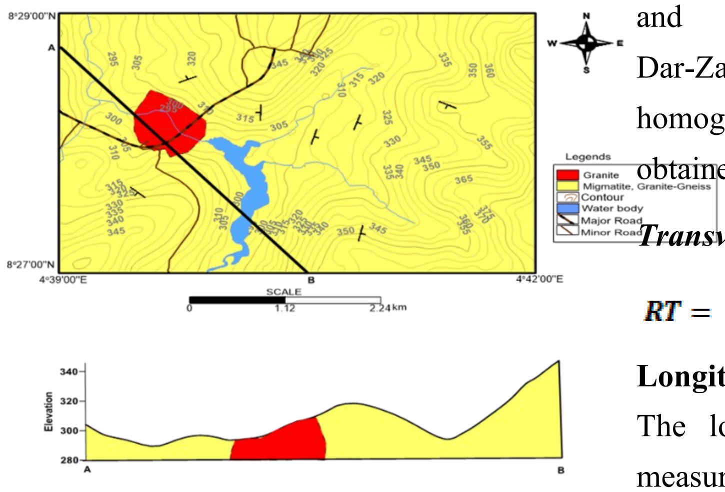

Figure 2: Geological Map of the study area.

Materials and Method

Using the Schlumberger electrode array, ten (10) Vertical Electrical Soundings were conducted in the research area. The potential electrode is held at its initial distance while the current electrode is symmetrically increased until the resistance being measured is too low. The condition AB/2 ≥ 5 (MN/2) was satisfied at all times. MN/2 was given a maximum spread of 5 m, and AB/2 was given a maximum spread of 100 m. To create the sounding curves, the apparent resistivity (Pa) is plotted against the matching half-electrode spacing (AB/2) on a bi-logarithm graph. Partial curve matching and computer-assisted 1-D forward modelling with WINRESIST software were used to understand the sounding curves. The findings were provided in the form of geo-electric sections and pseudo-sections. Isopach and iso-resistivity maps were also created to highlight the variance in overburden thickness and resistivity values.

Dar-Zarrouk Parameters

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

Transverse Resistance:

$$RT = \Sigma hi \; x \, pi \ldots\ldots eqn.1$$

Longitudinal Conductance:

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

$$SL = \frac{\Sigma hi}{pi} \ldots\ldots eqn.2$$

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.

Protective Capacity

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

$$Pc = \frac{\Sigma hi}{pi}$$

$$(\Sigma \; SL \; of \; the \; overburden \; layers)..eqn.3$$

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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.

The rating of the Protective capacity of an aquifer was described by Fatoba *et al*., (2014) as shown in Table 1 below.

Table 1: Rating of Protective Capacity (Fatoba, *et al*., 2014)

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

Hydraulic Conductivity

Layer resistivity is directly proportional to hydraulic conductance (Kosinski and Kelly, 1981). As a result, the section in the research area with a low resistivity value, which is presumed to represent a weathered formation, will have poor hydraulic conductivity. According to Salem (1999), hydraulic conductivity is proportional to permeability. As a result, the area of the aquifer with high hydraulic conductivity would be highly permeable to fluid flow and easily contaminated.

The following equation (Johansen, 1977) describes the relationship between hydraulic conductivity and layer resistance in a porous aquifer:

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

$K\ (m/day) = 386.40\ Rrw^{-0.93283}$

Where Rrw = Aquifer Resistivity Value

Transmissivity of the Aquifer

Transmissivity is an important aquifer attribute that aids in the assessment of rocks as water-conducting geologic media. Aquifer transmissivity (T in m2/day) is calculated as the product of hydraulic conductivity and layer thickness.

$$T = K * h \ldots.. eqn.4$$

Where:

K is the hydraulic conductivity (in m/day)

h is the layer thickness (in m). Aquifer transmissivity values have been classified by Krasny, 1993)

Table 2: Standard for Transmissivity Classification (Kransy, 1993).

Results and Discussion

The most common VES curve types are KH, HK, and A. The predominant top soils are sandy and clayey. The overburden thickness varies between 15 and 30 m. 90 % of the aquifer in the area falls within the moderate to optimum aquifer groundwater potential function, according to Alabi et al. 2016 assessment criteria (Table 2), which indicates that the location may likely be an excellent formation for groundwater investigation.

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Table 2: Aquifer potential as a function of the overburden thickness (Alabi *et al*; 2016)

Overburden thickness(m)	Weighting
<10	2.5
10-20	5
20-30	7.5
>30	10

Reflection Coefficient (R_C)

The reflection Coefficient quantifies the degree of fracturing in the research area. It could also reflect the aquifer formation density. Low reflection coefficient values suggest areas with moderate to high groundwater potential. The regional distribution map of the reflection coefficient (Fig.3) reveals a range of reflection coefficients from very low to very high. VES 1 and VES 9 have negative reflection coefficients (-0.186 and -0.103, respectively), indicating that the reflection coefficient is exceptionally low. VES 10 and 5, on the other hand, have strong positive reflection coefficients (0.702 and 0.707, respectively). Low reflection coefficient values are depicted in light to deep blue on the spatial distribution map, whereas medium to high reflection coefficient values are represented in green, yellow, red, pink, and white.

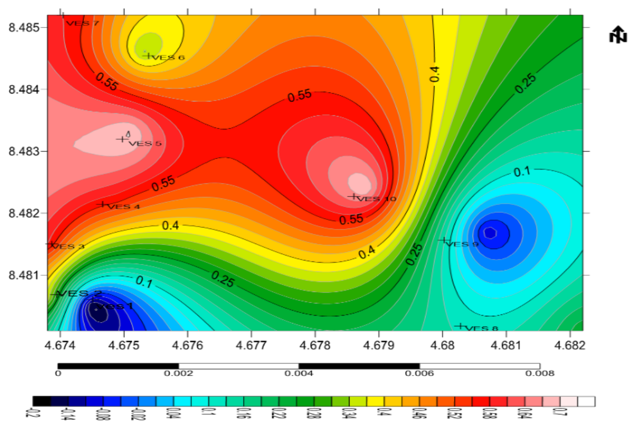

Figure 3: Reflection Coefficient Map

Resistivity Contrast (Fc)

Low resistivity contrast values imply a high groundwater potential. According to Table 3, the resistivity contrast ranged from 0.69 to 5.84, indicating a high to moderate groundwater potential in the area.

Coefficient of Anisotropy (λ)

A low coefficient of anisotropy values suggests a high-density water-filled aquifer, which is commonly calculated for a basement complex, whereas a high coefficient of anisotropy values implies poor porosity and permeability. The obtained coefficients of anisotropy ranged from 0.9 to 3.3 (Table 3). Except for VES 1, VES 4, VES 6, VES 8, and VES 9, the values are relatively high. The geographical distribution map (Fig. 4) depicts areas with low coefficients of anisotropy in dark blue to light blue, dark blue, and light green colors, which correspond to the map's NW-SE region.

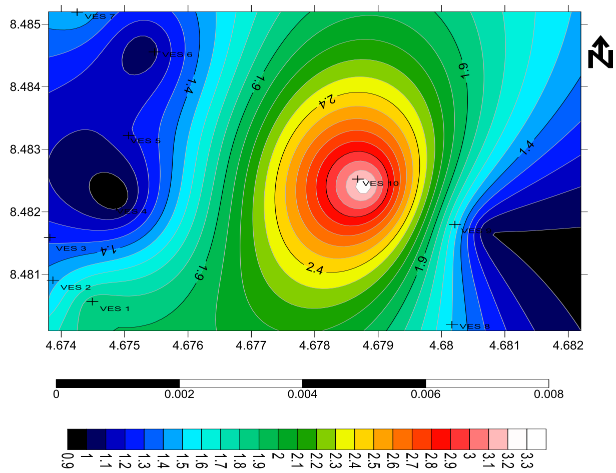

Figure 4: Coefficient of Anisotropy Map

Hydraulic Conductivity

Hydraulic conductivity measures the ease with which water flows in the subsurface. A greater value reflects how easily the water flows.

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Table 3: VES locations and their geo-electrical parameters computed using Dar-Zarrouk parameters.

S/ No	VES Number	Reflection coefficient	Resistivity contrast	Coefficient of Anisotropy	Aquifer Protective capacity	Transmissivity (m^2/day) Tr = kh	Hydraulic Conductivity (m/day)	Aquifer Porosity (%)
1.	VES 1	-0.186	0.69	1.9	0.257	117.89	21.435	1.79
2.	VES 2	0.352	2.08	1.5	0.338	65.719	1.6267	23.63
3.	VES 3	0.582	3.78	1.3	0.345	76.592	2.0479	14.34
4.	VES 4	0.557	3.52	0.9	0.283	152.364	2.0479	14.34
5.	VES 5	0.707	5.84	1.2	0.359	123.0716	1.2520	30.7
6.	VES 6	0.333	1.99	1.0	0.174	73.899	8.694	4.42
7.	VES 7	0.564	3.58	1.5	0.234	44.243	0.966	38.5
8.	VES 8	0.245	1.65	1.0	0.066	31.376	2.2411	17.2
9.	VES 9	-0.103	0.81	1.0	0.16	45.981	2.6275	14.6
10.	VES 10	0.702	5.71	3.3	0.0451	5.4067	0.204	60.8

In aquifer zones with high hydraulic conductivity, high permeability will be seen (Niwas and Singhal, 1981). The hydraulic conductivity values estimated using the Dar-Zarrouk parameter (Table 3) show that the distribution of hydraulic conductivity values at the University of Ilorin area ranges from a minimum of 0.204 m/day to a maximum of 21.435 m/day, which falls within the very low to intermediate range.

Transmissivity Values

The transmissivity ranges from 5.4 to 152.4 m^2/day. According to Kransy's (1993) numerical border classification for transmissivity in Table 4, high transmissivity values equal high groundwater potential. The majority of the study area lies within the intermediate transmissivity band, the aquifer in the area can provide enough water for the university community.

Table 4: Kransy's (1993) numerical border classification for transmissivity

T (m/day)	Designation	Groundwater supply
>1000	Very high	Withdrawal of great regional
100 – 1000	High	Withdrawal of lesser regional
10 – 100	Intermediate	Withdrawal from local water supply (small
1 – 10	Low	Local water supply. For
0.1 – 1.0	Very low	Withdrawal for local water supply with limited use.
<0.1	Impermeable	Water withdrawal is

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Aquifer Protective Capacity

The aquifer protective capacity index values varied from 0.04 to 0.4. According to Fatoba et al. (2014), this falls within the weak to moderate aquifer protection capacity grade (see Table 1). The regional distribution map of the rate of the overburden's protective capacity (Fig. 5) shows that VES 9, 10, and 8 have low aquifer protective capacity, whereas VES 5, 4, 6, 7, 3, and 1 have intermediate protective capacity.

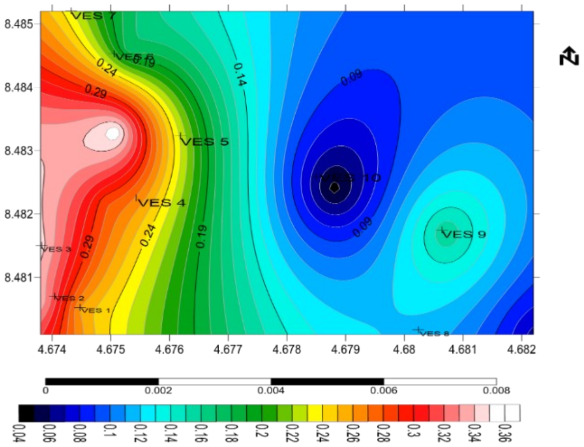

Figure 5: Aquifer Protective Capacity Map.

Porosity factor

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

$$F = \left[\frac{k}{a}\right]\frac{1}{m} \ldots\ldots\ldots\ldots eqn\ 5$$

Where:

F is the formation factor

K is the hydraulic conductivity (m/day)

Φ is the aquifer porosity

a = 0.62 (Tortuosity factor for unconsolidated sands)

m = 2.15 (Cementation exponent)

The calculated porosity shows that the aquifer has a porosity value ranging from 1.79 % - 60.8 % (Table 3). From interpretations, the porosity factor of the weathered layer gives information in correlation with the geology of the area studied with more details about the weathered layer.

According to the numerical boundary for porosity, the porosity values obtained from various Vertical Electrical Sounding (VES) measurements exhibit distinct characteristics indicative of different geological formations or conditions:

1. VES 1: The calculated porosity aligns with the typical range found in unfractured igneous and metamorphic rocks, which tend to have lower porosity due to their crystalline structure.

2. VES 2, 3, 4, 6, 8, and 9: These measurements fall within the porosity range associated with Quartzite, a metamorphic rock predominantly composed of quartz grains known for its relatively low porosity.

3. VES 5: The porosity value corresponds to the range typical of weathered clay, where weathering processes can increase porosity by breaking down rocks into smaller particles.

4. VES 10 and 7: These readings fall within the porosity range typical of unweather clay, which often exhibits higher porosity due to the fine-grained nature of clay minerals and their water-retaining properties.

The variations in porosity among the VES measurements reflect the diverse geological formations present in the surveyed area.

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Understanding these variations is crucial for interpreting subsurface properties, and guiding groundwater exploration. According to the porosity quality boundary, VES 1 and 6 values are negligible. VES 2,3,4,8 and 9 are fair to good while VES 5 and 10 are good to very good.

Geo-electric Sequence

The geo-electric sections in Figs 6 a-c show the fluctuations in resistivity and layer thickness values within the depth penetrated. The profiles were taken in the north-south and west-east directions. The profiles, in general, highlighted the lithology as it changes with depth, as well as the fractured basement within the fresh basement. The thickness of the topsoil varies from 1 to 3 m in profile 1 (Fig. 6a), with varied resistivity. The weathered basement thickness ranges from 3 to 10 m, with resistivity values ranging from 22.2 to 39.7 m. Fresh basement ≥10 m with a resistivity value of 308.4 – 19291 Ωm while the fractured basement is within the fresh basement.

In profile 2 (Fig. 6b), the thickness of the topsoil ranges from 1-2 m with variable resistivity values. The thickness of the weathered basement ranges between 2-12 m with resistivity values ranging from 42.5-122.6 Ωm. The fresh basement is ≥12 with a resistivity value 275.3 – 1042 Ωm. The fractured basement is within the fresh basement but occurs generally above 40 m with resistivity ranging from 204.5 – 634.3 Ωm. Profile 3(Fig. 6c) shows the following geo-electric units: topsoil, weathered basement, fractured and fresh basement. The thickness of the topsoil, weathered and fractured basement ranges from 1-5 m, 5-18 m, and 20 – 50 m respectively. Weathered basement between 5 - 18 m with a resistivity value between 18.9 - 147.1Ωm; fresh basement between 10-50 m, and fractured basement between 20 - 45 m.

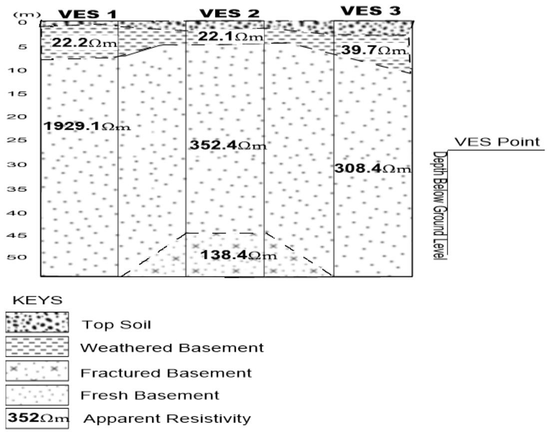

Figure 6a: Geo-electric section for profile 1

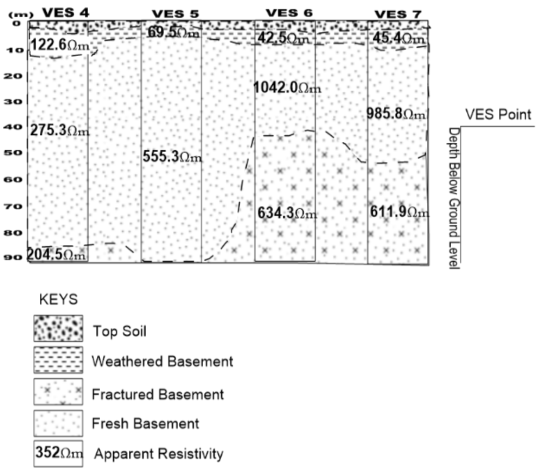

Figure 6b: Geo-electric section for profile 2

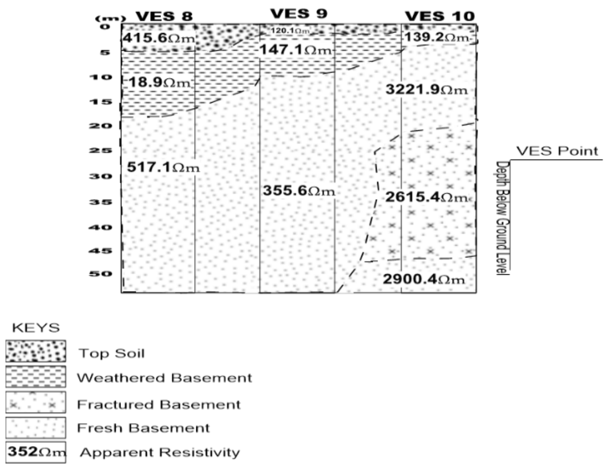

Figure 6c: Geo-electric section for profile 3

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Pseudo-section Interpretation

The soil resistivity from the topsoil to the fresh basement is revealed by the pseudo-section for the geo-electric profiles along the N-S direction (Figure 8a-c).

Profile 1 (Fig. 7a) demonstrates how the resistivity of VES 1 increases with depth. For hydrogeological concerns, the lack of voids or fissures does not favor groundwater occurrence. VES 2 and 3 exhibit a progressive increase in resistivity up to a depth of 48 m, beyond which it decreases, the K-curve represents this formation. Groundwater abstraction is more concentrated at depths of 50 to 80 meters. Depths between 50 and 80 meters are more concentrated for groundwater exploitation, and the resistivity range (120 to 170 meters) reflects a weathered zone ideal for groundwater accumulation.

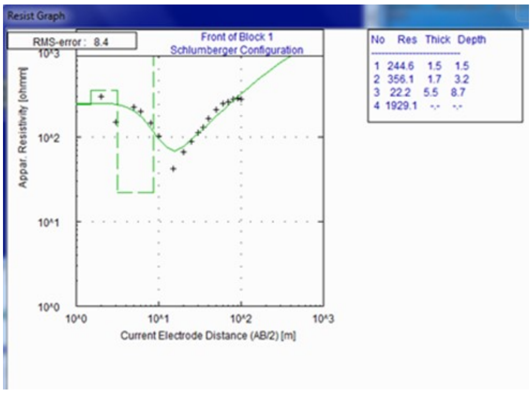

Fig. 7a: VES 1 iterated curve: KH curve type

Profile 2 in Figure 8b shows the change in resistivity value with depth, vertically VES 4-6. The resistivity value increases with depth, with the highest value of 280m for VES 4 but the increasing value in VES 5, and 6, which can be interpreted as moderate yield for groundwater potential; for VES 7 the resistivity value is low but increases with depth, indicating that the area is suitable for hydro-geological purposes. The resistivity value increases from VES 4 to VES 7 at horizontal depth. Because of the low resistivity value, which indicates a weathered or fractured zone, depths of 10m-70m are better suited for groundwater exploitation. This interpretation is of the HA-curve type.

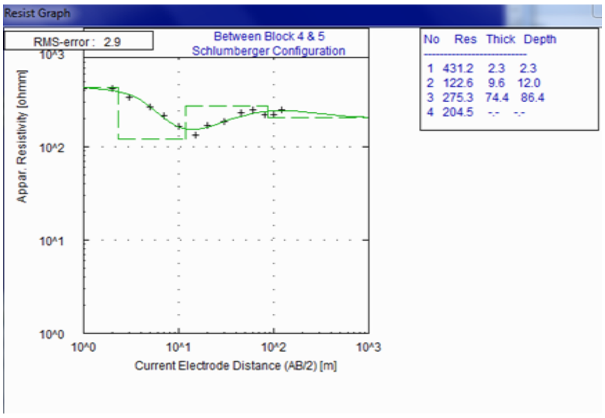

Fig 7b: VES 6: HA-curve type.

In profile 3 (figure 8c), VES 8 demonstrates an increase in resistivity values with depth; VES 9 demonstrates an increase in resistivity values with depth, with 1400Ωm as the lowest resistivity value; and VES 10 demonstrates an increase in resistivity values with depth. Horizontally, resistivity rises from VES 8 to 9 but decreases at VES 10 at 150m depth. This profile is an example of an A-curve.

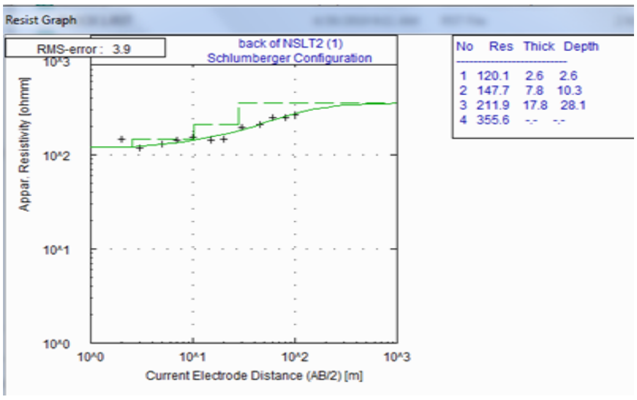

Fig 7c; VES 10: A – curve type.

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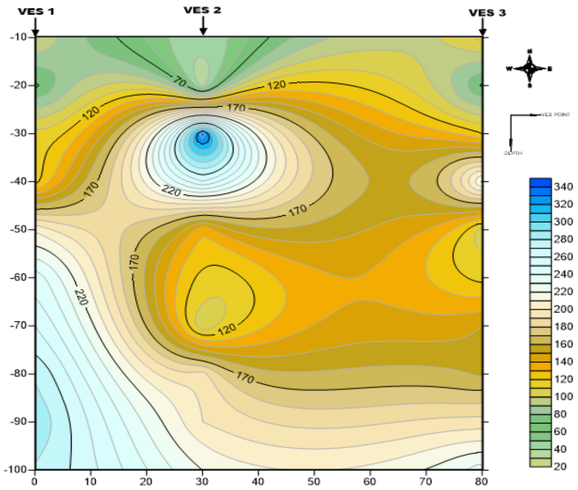

Figure 8a: Pseudo-section for profile 1.

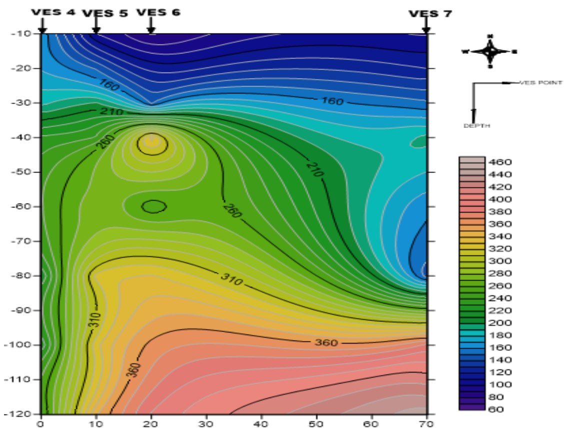

Figure 8b: Pseudo-section for profile 2.

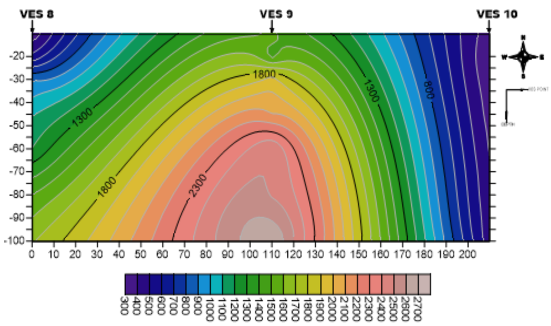

Figure 8b: Pseudo-section for profile 3

Conclusion

The groundwater transmissivity and aquifer protective capacity of the underlying formations at the University of Ilorin in Southwestern Nigeria were assessed. Ten VES data sets were collected and analyzed. The data interpretation, which included quantitative partial curve matching and computer iteration, was carried out with the use of 1-D forward modelling software. The area's curve types include KH-, HK-, and A- curves. Topsoil (sandy/clayey), weathered/fractured basement (the principal aquifer unit for groundwater in the area), and fresh basement are the subsurface lithology. Approximately 90 % of the research region had a moderate to optimum groundwater yield rate. The geo-electric sections and pseudo -sections demonstrated how resistivity and layer thickness varied with depth in the research area. The study found that the reflection coefficient values in the study area ranged from low to high, indicating varying degrees of fracturing. The hydraulic conductivity and transmissivity values revealed that the study area has a high probability of occurrence of groundwater and can serve the university community. The area's aquifer protection capacity ranged from poor to moderate. The findings of this study give critical information for groundwater protection and environmental concerns to be considered in the planning, development, and placement of academic, residential, and commercial buildings within the University of Ilorin's academic and residential region. Management should concentrate on future groundwater development in the study region within zones of moderate/good groundwater protective capacity with considerably thick overburden. Furthermore, the placement of underground sewage septic tanks and waste dumps on campus should be limited to zones with moderate/good groundwater protection capabilities.

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