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Integrating in-situ hydraulic conductivity measurements and vertical electrical sounding for groundwater exploration in fractured shales within Alex Ekwueme Federal University Ndufu Alike (AE-FUNAI), South Eastern Nigeria

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Abstract: An appraisal of the groundwater potential of Alex Ekwueme Federal University Ndufu Alike was carried out by integrating datasets from geology, geographic information system and electrical resistivity survey of the area. The study area is underlain by the Asu River group of Albian age. The Asu River Group in the Southern Benue Trough comprises of Shales, Limestones and Sandstone lenses of the Abakaliki Formation in Abakaliki and Ikwo areas. The shales are generally weathered, fissile, thinly laminated and highly fractured and varies between greyish brown to pinkish red in colour. Twenty (20) Vertical Electrical Sounding data were acquired using SAS 1000 ABEM Terrameter and processed to obtain layer parameters for the study area. A maximum current electrode spacing (AB) of 300 meters was used for data acquisition. Computer aided iterative modelling using IPI2 Win was used to determine layer parameters. In-situ Hydraulic Conductivity measurements at seven parametric locations within the study area were conducted and integrated with Electrical Resistivity measurements to determine aquifer parameters (e.g. Hydraulic conductivity and Transmissivity) in real time. This technique reduces the attendant huge costs associated with pumping tests and timelines required to carry out the technique. Accurate delineation of aquifer parameters and geometries will aid water resource planners and developers on favourable areas to site boreholes in the area. Several correlative cross-sections were generated from the interpreted results and used to assess the groundwater potential of the study area. Results show that the resistivity of the the aquifer ranges from 7.3 Ωm –530 Ωm while depth to water ranges from 11.4 m to 55.3 m. Aquifer thicknesses range from 8.7 m at VES 5 to 36.3 m at VES 6 locations. Hydraulic conductivity ranges from 1.55 m/day at VES 15,18, and 19 locations to 9.8 m/day at VES 3 and 4 locations respectively. Transmissivity varies from 17.48 m^2/day at VES 19 to 98 m^2/day at VES 3 locations respectively. Areas with relatively high transmissivities coupled with good aquifer thicknesses should be the target of water resource planners and developers when proposing sites for drilling productive boreholes within Alex Ekwueme federal University Ndufu Alike.

Keywords: groundwater; shale; hydraulic conductivity; transmissivity; VES

1. Introduction

Shales are portrayed as aquitards on hydrogeology maps and often ignored as a veritable source of water supply to rural, semi urban and urban communities whose geology does not include conventional aquifer materials like Sandstones and Carbonates [1]. Previous research works have shown that 70 million or more people in sub-saharan Africa live in semi-urban and rural communities underlain by low permeability formations like Shales and Mudstones [2–4]. Some of these rural

communities can be found in Ikwo Local Government Area of Ebonyi state, Nigeria, where Alex Ekwueme Federal University Ndufu Alike is located. The area has continued to witness huge influx of both staff, students, entrepreneurs and artisans as a result of the establishment of the University since 2011. Alex Ekwueme Federal University Ndufu Alike and environs is underlain by the Asu River Shales; a Cretaceous Formation of Albian age, deposited within the Southern Benue Trough. Shales in their natural form cannot transmit water effectively but their transmissivity can be enhanced when the Shales are fractured. Fractured Shales can deliver substantial amount of water that can serve a rural community for domestic and Agricultural purposes. Several researchers applied electrical resistivity method to delineate aquifer types and geometry [5–8]. Some more recent works have been done by utilizing geosounding datasets to explore for water in low permeability formations (e.g. Shales and Mudstones) and hard rock terrains [9–11]. In Nigeria, a significant proportion of residents in rural areas lack reliable access to safe water sources. The quality of groundwater holds equal significance to its availability. The drive to grant access to potable water supply and the need to eradicate Guinea worm scourge (*Dracunculus medinensis*) in some of these rural communities propelled the Jimmy Carter Foundation, through collaboration with United Nations International Children Education Fund (UNICEF) and World Health Organization (WHO) to sink several boreholes to provide water to the rural populace [12]. Nigeria is faced with increasing demands for water resources due to high population growth rate and growing prosperity [13]. The advantages of groundwater as a source of supply cannot be overemphasized especially where populations are still largely rural and demand are dispersed over large areas [14]. Groundwater is a dependable and assured resource and can be exploited with greater ease and flexibility. The southern Benue trough is the southwestern part of the Benue depression [15]. It is distinctively characterized by the Abakaliki anticlinorium and the Afikpo syncline and bounded to the west by Anambra basin [16]. The major part of the Ikwo metropolis is underlain by aquicludes and aquitards, except in locations or zones where secondary aquiferous conditions were made possible by syn- and post depositional circumstances [17]. The resistivity of the subsurface material observed is a function of the magnitude of the current, the recorded potential difference and the geometry of the electrode array used [18]. Measurement of resistivity is, in general, a measure of water saturation and pore space connectivity. Resistivity measurements are associated with varying depths relative to the distance between the current and potential electrodes in the survey and can be interpreted qualitatively and quantitatively in terms of a lithologic and/or geohydrologic model of the subsurface [19]. The form of resistivity curve type obtained by sounding over a horizontally stratified medium is a function of the resistivities and thicknesses of the layers as well as the electrode configuration [20]. The objective of this study was to integrate in-situ Hydraulic conductivity measurements with results from the interpretation of electrical resistivity data to map fractures in Shales with the aim of determining favourable sites to drill boreholes within Alex Ekwueme Federal University Ndufu Alike and environs.

2. Location and geology

The study area is underlain by the Asu River Group shales of Albian age [21] and lies between latitude 6°7'10" to 6°8'10"N and 8°8'0' to 8°9'0"E (Figure 1).

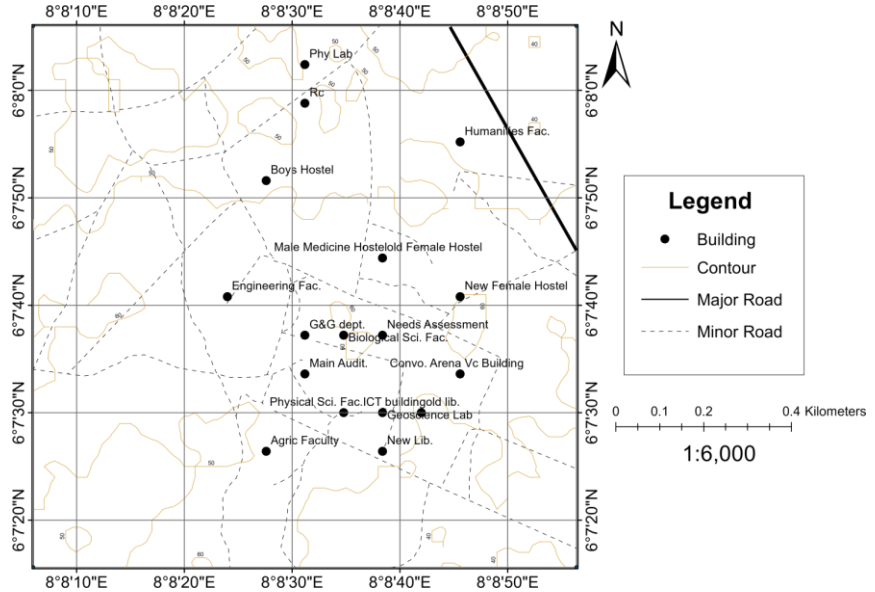


Figure 1. Topographic map of AE-FUNAI.

The Asu River Group (Figure 2) sediments are predominantly shales, and localized occurrences of sandstone, siltstone and limestone intercalations [22]. It was generally believed to have started depositing in the mid-Albian period and continued within the Southern Benue Trough, southeastern Nigeria. Emplaced within the Asu River Group sediments are intermediateto basic intrusive diorites and dolerites and pyroclastics [22–24]. The group has average thickness of about 2000 m and rests unconformably on the Precambrian Basement [25,26] have reported type localities of Asu River sediments at Abakaliki, and Ishiagu areas.

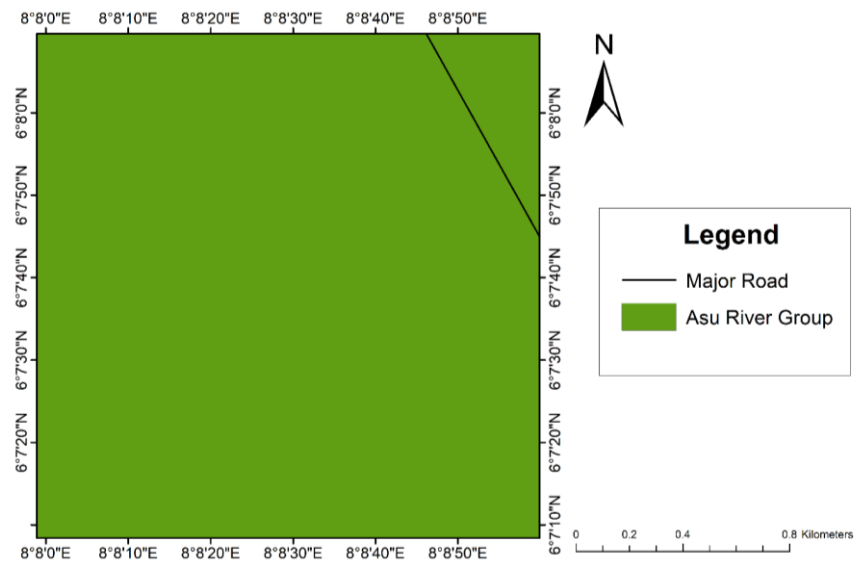


Figure 2. Geologic map of AE-FUNAI.

3. Materials and methods

The equipments/materials used for the present research include ABEM Terrameter, two current electrodes, two potential electrodes, 4 reels of wire, 12V battery, GPS, common salt, measuring tape, hammer, Hand Auger, laptop, Jerry cans of water and measuring tape. The study started with a detailed literature review of past research works in the area and related studies in other areas with similar geology. This was followed by detailed geological studies of the study area. Subsequently, twenty (20) vertical electrical soundings (VES) were acquired using an ABEM SAS 1000 Terrameter with the Schlumberger configuration (**Figure 3**) and a maximum current electrode spacing (AB) of 200 meters. The Schlumberger technique involves the injection of direct current or low frequency alternating current into the earth through a pair of current electrodes and the measurement of the potential difference between another pair of potential electrodes. The method was adopted because it allows the acquisition of numerous data points within a short time. The Schlumberger technique allows a clearer mapping of the subsurface for a given current electrode spacing and the processing and interpretation softwares are readily available. Few soundings were taken near existing boreholes to facilitate comparison between the geologic and geoelectric sections. The data obtained was plotted as a graph of apparent resistivity against half current electrode spacing on a log-log graph sheet to provide insights into the layer resistivities and depths to the interfaces.

The apparent resistivity (ρ_a) for the Schlumberger array is given by

$$\rho = \pi \left[\frac{a^2}{b} - \frac{b}{4} \right]$$

$$K = \frac{2\pi}{\left(\frac{1}{a} - \frac{b}{2} \right) - \left(\frac{1}{a} + \frac{b}{2} \right) - \left(\frac{1}{2} \right) + \left(\frac{b}{2} \right) + \left(\frac{1}{a} - \frac{b}{2} \right)}$$
(1)

$$K = \pi \left(\frac{a^2}{b} - \frac{b}{4} \right) = \left\{ \frac{\left(\frac{AB}{2} \right)^2 - \left(\frac{MN}{2} \right)^2}{MN} \right\} \pi$$
(2)

$$K = \pi \left(\frac{a^2}{b} - \frac{b}{4} \right) \frac{V}{I} \text{ or } \rho = \pi \left(\frac{a^2}{b} - \frac{b}{4} \right) R$$
(3)

Recall $\rho = KR$

where K = Geometric factor which depends on the electrode configuration and R = measured resistance.

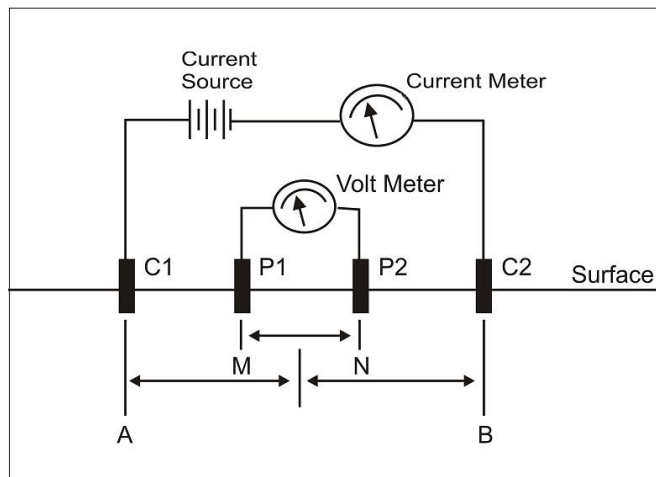


Figure 3. Schematic of the schlumberger array.

3.1. Estimation of aquifer parameters

Hydraulic conductivity and transmissivity are useful aquifer parameters for proper development and management of groundwater resources. Direct determination of hydraulic conductivity from field measurements has proven to be a cost effective technique for the estimation of transmissivity by utilizing the empirical relationship between transmissivity (m²/day), hydraulic conductivity (m/day) and aquifer thickness (m). We measured hydraulic conductivity in the field by substituting several other field parameters into the well known Darcy's equation and used the calculated value to determine transmissivity in areas with known aquifer thickness.

3.2. Hydraulic conductivity

Hydraulic conductivity, K is used to describe the capacity of a porous material to transmit water [27]. Without hydraulic conductivity data, neither simple analytical solutions nor complex computer simulations of groundwater flow are possible.

Darcy formula for hydraulic conductivity (K) is given by

$$K = \frac{QL \times \mu_L \times 1000}{A(P_2 - P_1)} \quad (4)$$

where K = Hydraulic conductivity.

$$QL = \text{flow rate} = \frac{\text{height of water (h)}}{\text{time of water to dry}} = (\text{m/s})$$

$$\mu_L = \text{Viscosity of water (Centipose)}$$

$$A = \text{Cross-sectional (M}^2) = 2\pi r^2 + 2\pi h$$

$$L = \text{Height of section}$$

$$H = \text{height of water}$$

$$P_2 = \text{Atmospheric Pressure (known)}$$

$$P_1 = \text{pressure of water (unknown)}$$

$$P_2 - P_1 = \Delta P \phi \Delta h$$

$$P_2 - P_1 = P_{\text{atm}} - P_w = \phi \Delta h$$

3.3. Determination of hydraulic conductivity in the field

Hydraulic conductivity, often denoted by the symbol K , is a property of porous materials like soil and rock that describes how easily a fluid (usually water) can move through the pore spaces or fractures within the material. A total of seven (7) hydraulic conductivity values were obtained in the field at the various VES locations. Field measurements of hydraulic conductivity were obtained using a simple infiltration test (**Figure 4**). A borehole was created, and three liters of water were poured in. The following parameters were monitored: water level change (height), borehole dimensions (diameter and radius), and time taken for water to infiltrate. Darcy's equation was then used to calculate hydraulic conductivity values at various locations across the study area. The above technique is very challenging because of the geology of the study area which comprises of shales and other low permeability rocks. The low permeability in shales dovetails to longer time for the water poured in the drill holes to drain and this translated to longer waiting time of up to 2 to 3 hours in the field.



Figure 4. In-situ hydraulic conductivity measurement in the field.

3.4. Transmissivity

Transmissivity describes the rate at which water can be transmitted horizontally through an aquifer. (a) water-bearing layer of soil or rock. Transmissivity (T) is calculated by multiplying the average hydraulic conductivity (K) of the aquifer by the thickness. (b) of the saturated zone.

$$\text{Mathematically, } T = K \times b.$$

Where T is the transmissivity (m^2/day), K is the Hydraulic conductivity and b is the aquifer thickness (m).

4. Results and discussion

Figure 5 shows the VES locations superimposed on the geologic map of the area while **Figure 6** shows the lithology log of the borehole at the Male hostel (close to VES 15), Alex Ekwueme Federal University Ndufu Alike. The lithologic succession comprises of top lateritic overburden, Dry clay, Gray shale, Partially fractured shale, fractured Shale section which serves as the aquifer and a non-fractured shale section of indeterminate thickness. **Figure 7** shows sample type curves from the study area. The fractured shale aquifer sections were discriminated from other sections in the curve by their characteristic low resistivities due to fluid filled fractures in secondary porosities.

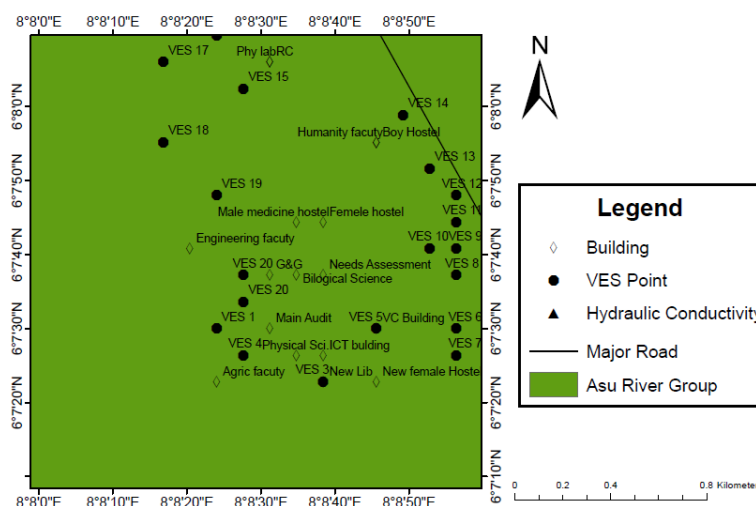


Figure 5. Geologic map of the study area showing the VES points.

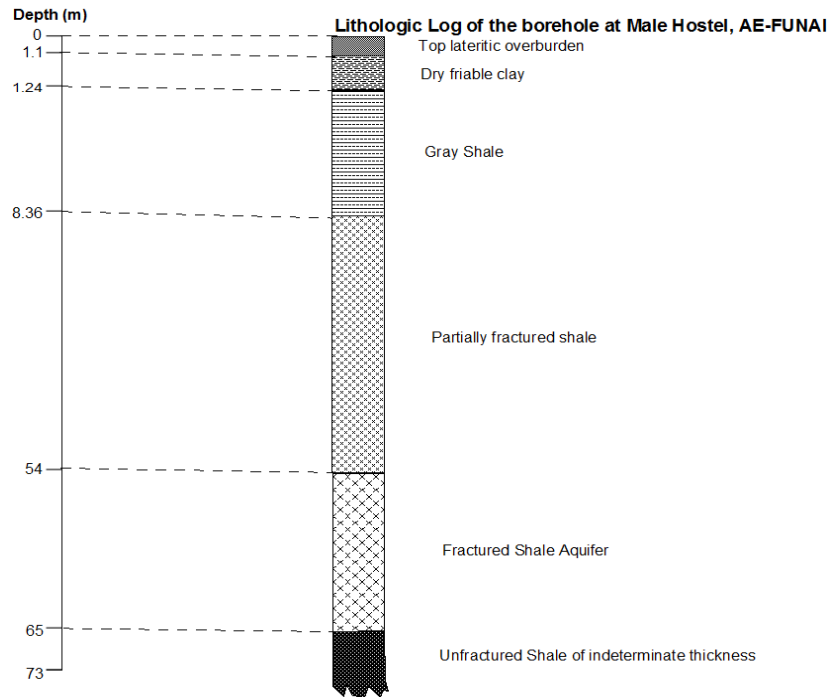


Figure 6. Lithology log of the borehole at the male hostel, AEFUNAI.

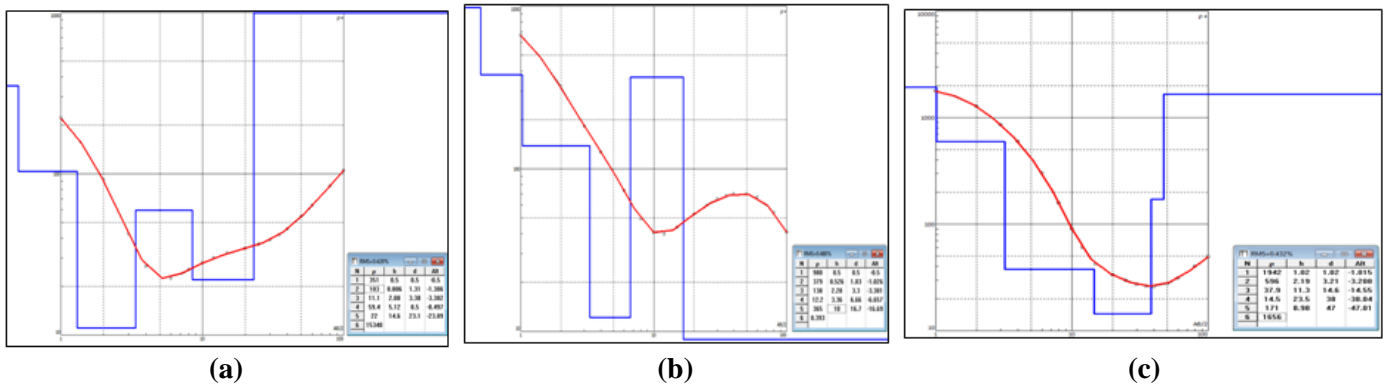


Figure 7. Sample curve types obtained from the study area.

4.1. Hydraulic conductivity

Table 1 shows in-situ hydraulic conductivity values obtained from measurements in the field while **Table 2** shows the derived Hydraulic conductivity values across the study area. Hydraulic conductivity values range from 1.546560 m/day at location 5 to 9.800300 m/day with variations across the vertical electrical sounding (VES) locations. The variations in measured hydraulic conductivity values was attributed to presence of fractures, weathering and mineralogy. The entire study area was sub-divided into three zones (A,B and C) with Hydraulic Conductivity varying from 7.5 to 9.8 m/day in Zone A; 4.5–7.5 m/day in Zone B and 1–4.5 m²/day respectively (**Figure 8**).

Table 1. In-situ hydraulic conductivity (HC) values obtained in the field.

In-situ HC locations/Proximal VES points	Depth of hole (m)	Diameter (m)	Radius (m)	Height of water (m)	Drainage time (sec.)	Hydraulic conductivity (m/s)	Hydraulic conductivity (m/day)
1 (VES 2)	0.50	0.152	0.076	0.30	7200	2.5884×10^{-5}	2.236277
2 (VES 4)	0.60	0.177	0.088	0.35	10800	11.343×10^{-5}	9.800300
3 (VES 7)	0.70	0.160	0.080	0.50	7200	2.541×10^{-5}	2.195424
4 (VES 10)	0.90	0.203	0.101	0.65	5400	2.68×10^{-5}	2.315520
5 (VES 15)	0.70	0.152	0.072	0.50	10800	1.79×10^{-5}	1.546560
6 (VES 17)	0.50	0.120	0.060	0.30	7200	3.368×10^{-5}	2.909954
7 (VES 20)	0.70	0.127	0.064	0.50	10800	3.2432×10^{-5}	2.802120

Table 2. Hydraulic conductivity (HC) values across the study area.

VES points	In-situ HC values (m/day)	Aquifer Resistivity (m)	Aquifer Thickness (m)	Hydraulic conductivity (HC) values at other VES locations (m/day)
1	-	171.00	8.98	2.24
2	2.236	17.70	30.10	2.24
3	-	365.00	10.00	9.80
4	9.800	4.54	8.75	9.80
5	-	59.70	8.70	2.20
6	-	42.30	36.30	2.20
7	2.195	43.80	23.60	2.20
8	-	530.00	11.30	2.20
9	-	16.50	15.00	2.32
10	2.316	10.60	9.57	2.32
11	-	374.00	17.40	2.32
12	-	7.55	12.60	2.80
13	2.802	22.00	14.60	2.80
14	-	41.50	45.60	2.80
15	1.547	85.10	38.10	1.55
16	-	9.60	8.66	2.91
17	2.910	7.30	12.00	2.91
18	-	57.10	14.10	1.55
19	-	8.80	11.30	1.55
20	-	12.80	16.20	2.24

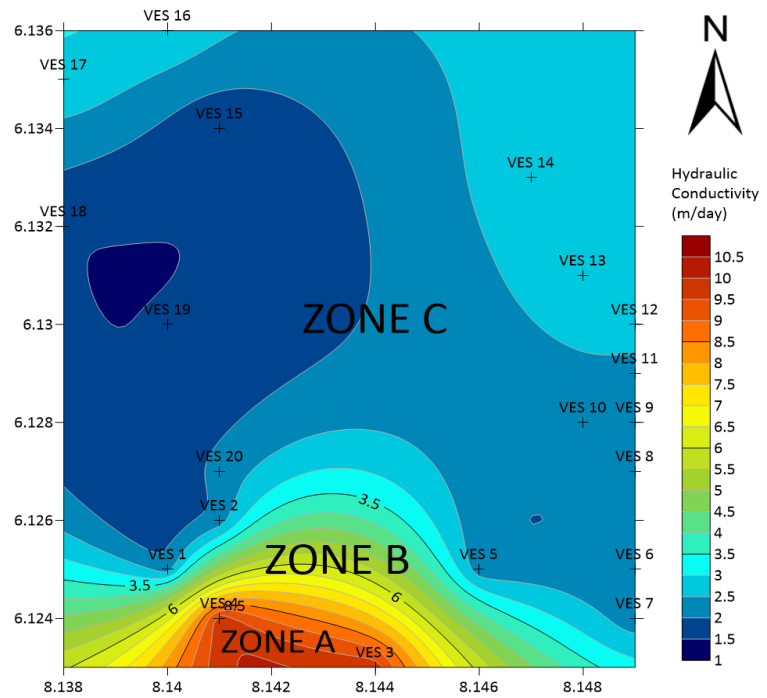


Figure 8. Hydraulic conductivity values across the study area.

4.2. Aquifer thickness across the study area

The thickness of the aquifer in the study area exhibits significant variability, which can be attributed to a combination of geological factors and human activities, particularly construction activities within the campus vicinity. The aquifer thickness ranges from high in certain areas to extremely low in others, reflecting the complex hydrogeological conditions that influence groundwater distribution. Aquifer thickness ranges from 8.66 m at VES 5 to 45.60 m at VES 14 locations respectively (Figure 9).

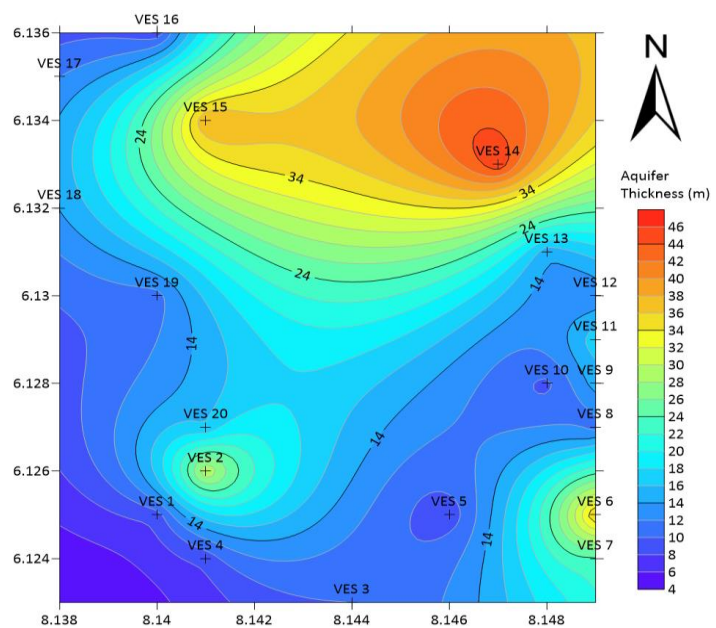


Figure 9. Aquifer thickness across the study area.

4.3. Depth to water table

Figure 10 shows the variation of depth to the fractured shale aquifers across the study area. Depth to water ranges from 11.4 m at Convocation arena (VES 5) to 55.3m at staff quarters. The variation in depths to the aquifer is geologically controlled. The area was affected by the Santonian tectonic activities which initiated fracturing in the shales at various depths. The shallow aquifers could be tapped by hand dug wells while the moderate and deeper aquifers would require borehole drilling in order to harness the water resources.

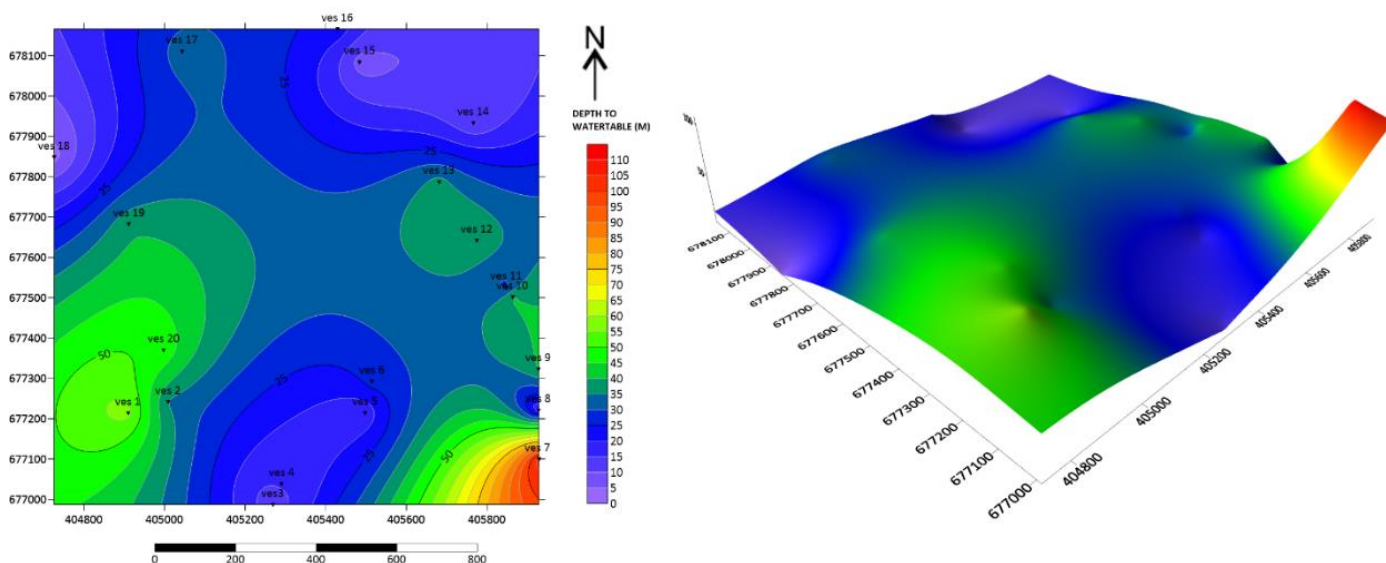


Figure 10. Depth to water across the study area.

4.4. Transmissivity

Table 3 shows the derived Transmissivity values across the study area. Transmissivity values range from 7.48 m²/day at VES 19 location to 127.78 m²/day at VES 14 respectively. **Figure 11** shows the variations of Transmissivity values across the study area with Zone A ranging from 90–130 m²/day (high Transmissivity). Transmissivity values across Zone B ranges from 45–90 m²/day (Moderate Transmissivity) while Zone C ranges from 10–45 m²/day (Low Transmissivity). The transmissivity values are largely determined by the development of fractures in the shales due to tectonism and other secondary geologic processes. These results are consistent with earlier results from groundwater studies in low permeability formations [6,4,28].

Table 3. Transmissivity values across the study area.

VES points	In-situ HC values (m/day)	Aquifer Resistivity (m)	Aquifer Thickness (m)	Hydraulic conductivity (HC) values at other VES locations (m/day)	Transmissivity (m ² /day)
1	-	171.00	8.98	2.24	20.08
2	2.236	17.70	30.10	2.24	67.31
3	-	365.00	10.00	9.80	98.00
4	9.800	4.54	8.75	9.80	85.75
5	-	59.70	8.70	2.20	19.10

Table 3. (Continued).

VES points	In-situ HC values (m/day)	Aquifer Resistivity (m)	Aquifer Thickness (m)	Hydraulic conductivity (HC) values at other VES locations (m/day)	Transmissivity (m ² /day)
6	-	42.30	36.30	2.20	79.69
7	2.195	43.80	23.60	2.20	51.81
8	-	530.00	11.30	2.20	24.81
9	-	16.50	15.00	2.32	34.73
10	2.316	10.60	9.57	2.32	22.16
11	-	374.00	17.40	2.32	40.29
12	-	7.55	12.60	2.80	35.31
13	2.802	22.00	14.60	2.80	40.91
14	-	41.50	45.60	2.80	127.78
15	1.547	85.10	38.10	1.55	58.92
16	-	9.60	8.66	2.91	25.20
17	2.910	7.30	12.00	2.91	34.92
18	-	57.10	14.10	1.55	21.81
19	-	8.80	11.30	1.55	17.48
20	-	12.80	16.20	2.24	36.23

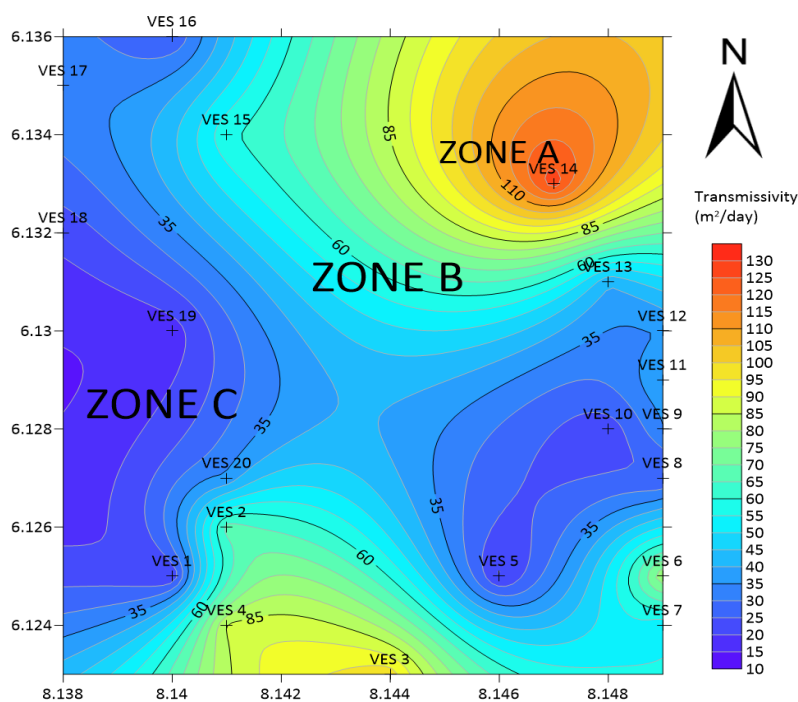


Figure 11. Transmissivity values across the study area.

5. Conclusion

The electrical resistivity method has proved to be a veritable technique in groundwater assessment within Alex Ekwueme Federal University Ndufu Alike; an area underlain by Shales of Albian age. The development of fractures in the shales as a result of secondary tectonic activities improved the water storage capacity and transmissivity in shales, which ordinarily would have been considered an aquitard.

The fluid filled fractures created the required contrast which the electrical resistivity method responds to by their characteristically low to moderate resistivity values when compared with the non-fractured sections in the Shales. The resistivity of the fractured sections of the shales, which serves as the aquifer ranges from 7.3–530 Ωm while depth to water ranges from 11.4 m to 55.3 m. Aquifer thicknesses range from 8.7 m at VES 5 to 36.3 m at VES 6 locations. Hydraulic conductivity ranges from 1.55 m/day at VES 15, 18, and 19 locations to 9.8 m/day at VES 3 and 4 locations respectively. Transmissivity varies from 17.48 m^2/day at VES 19 to 98 m^2/day at VES 3 locations respectively. It is therefore recommended that any water drilling scheme within the area should be preceded by detailed geophysical investigation to ensure prolific borehole within the campus. Areas with relatively high transmissivities coupled with good aquifer thicknesses should be the target of water resource planners and developers when proposing sites for drilling productive boreholes within Alex Ekwueme federal University Ndufu Alike.

Author contributions: Conceptualization, AE; methodology, AE, SE, VO and GA; software, SE and AE; validation, AU, NdidiamakaEluwa, VO and AE; formal analysis, SE, AE and AU; investigation, NE, VO and SE; resources, AE and GA; data curation, VO and AU; writing—original draft preparation, AE and SE; writing—review and editing, SE and GA; visualization, AE and NdidiamakaEluwa; supervision, AE; project administration, AE and GA; funding acquisition, AE, GA and AU. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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