Communication in Physical Sciences, 2025, 12(2) 367-385

Integrated Geoscientific Techniques for Water Resource Potential: A Case Study of Felele Campus, Federal University Lokoja

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Received: 19 November 2024/Accepted: 28 December 2025/Published 03 February 2025
https://dx.doi.org/10.4314/cps.v12i2.14

Abstract: *This paper presents the report of the investigation into a more suitable geoscientific tool for exploring and exploiting water resources on the Felele Campus of the Federal University Lokoja, Nigeria. The Felele Campus of the Federal University Lokoja surfers from inadequate water supply, thus requiring that water is harnessed from all available sources. Many water boreholes on the campus so far have either failed or yielded a low quantity of water due to the use of inappropriate tools for the geophysical survey. Given this, an integrated geoscientific approach was adopted involving geologic mapping, geoelectrical and electromagnetic (VLF-EM) tools. Geological field mapping reveals that most of the rocks are more of banded and ferruginized iron stones, with sediments overlain by medium- fine-grained sandstones in other places. The results of the geoelectrical imaging show four subsurface sections characterized by variable resistivities and thicknesses. The results of the VLF-EM show low resistivity of 0.00 to 0.12 Ωm, very high resistivity values between 0.23 to 2.32 Ωm and several varieties of fractures at depths ranging from 30 m to approximately 300 m. The VLF-EM tool provides a clearer structural image and better evaluates the characteristics of the aquifers compared with the 1-D Schlumberger tool, leading to more reliable recommendations for borehole drilling. Therefore, integrating the very low-frequency electromagnetic tool with the conventional vertical electrical sounding method is a more robust technique, which leads to a reduction of risks and uncertainties associated with groundwater exploration and exploitation on the Felele Campus of the University.*

Keywords: *Resistivity, Vertical electrical sounding, very-low frequency electromagnetic, aquifers, water supply*

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1.0 Introduction

The Federal University Lokoja, having recently moved to the Felele Campus (referred to as the main campus), has fully commenced operations. One of the essential amenities required for the smooth functioning of the university is a reliable and potable water supply. Water is indispensable for daily life, with significant needs for student hostels, offices, and other industrial purposes. Ensuring water security on the new campus is therefore critical, motivating this research. Water resources for the university are anticipated from two main sources: surface water and groundwater. While surface water can be harnessed from rivers and streams around the university, groundwater requires drilling boreholes to access aquiferous layers.

The Felele Campus of the Federal University Lokoja is uniquely located at the contact between the sedimentary basin (Lower Middle Niger Basin) and the hard rock (basement complex of Nigeria) terrain. It lies physiographically between Mount Patti and the Agbaja Plateau, creating a complex geological environment (Aku and Gani, 2015). This geological complexity poses challenges in determining viable aquiferous layers. Consequently, many boreholes drilled on the campus have either completely failed or yielded insufficient water, resulting in inadequate supply for domestic and industrial use.

To address this challenge, the research group at the Department of Geology, Federal University Lokoja, code-named ‘IREPad,’ embarked on a mission to resolve the water supply issues using an integrated geoscientific approach. Surface water availability was investigated using conventional geological field mapping techniques, while groundwater potential was evaluated using geophysical surveys. The integration of geoscientific methods—combining geological, geophysical, geochemical, and remote-sensing expertise—offers a multidisciplinary approach to understanding and developing water resources (Smith, 2022).

In the basement complex terrain, groundwater occurrence is primarily controlled by fractures and weathered zones (Amadi et al., 2011; Musa et al., 2023). Accessing groundwater requires detailed knowledge of geological structures, achievable through ground investigations using techniques such as Vertical Electrical Sounding (VES), electromagnetic (EM) surveys, seismic methods, magnetic surveys, aerial photography, and satellite imaging. Electrical resistivity surveys, particularly the VES method, have proven effective for locating viable aquifers due to their non-destructive nature, cost-effectiveness, rapid survey time, and reliable interpretability (Ghosh, 2011).

While the vertical electrical sounding method has been employed by contractors for pre-borehole geoelectrical surveys on the campus, these studies have often been limited to one-dimensional (1D) resistivity methods, resulting in outright failure or low water yields. The integration of geological and geophysical techniques, including two-dimensional (2D) electrical resistivity imaging and very low-frequency electromagnetic (VLF-EM) methods, provides a more robust approach.

This study demonstrates the use of field hydrogeological and hydrogeochemical mappings integrated with advanced geophysical techniques to produce highly resolved structural characteristics of the subsurface. The resulting resistivity models generate reliable information for groundwater exploration.

The knowledge gap in previous studies lies in the lack of an integrated approach combining geological and advanced geophysical techniques for locating prolific aquifers on the Felele Campus. Addressing this gap, the aim of this study is to develop a robust method for identifying aquifers that support the productive drilling of water boreholes to provide a sustainable year-round water supply for the university community. The study's objectives are to:

(i) Evaluate the hydrogeological and hydrogeochemical characteristics of the study area.
(ii) Conduct an integrated geophysical survey using VES and VLF-EM methods to determine subsurface resistivity structures.
(iii) Identify potential aquiferous zones and recommend drilling sites for productive water boreholes.

1.1 Geology of the Study Area

Lokoja and its environment is one of the most studied areas in North Central Nigeria due to its proximity and central nature in the country. Previous studies have indicated extensive information concerning the geology of some sections of Lokoja. Lokoja is located at the confluence of the Niger and Benue Rivers and the contacts between the Precambrian Basement Complex of Nigeria, and the Campanian-Maastrichian sedimentary Bida Basin (Fig. 1). The geology comprises in the Precambrian Basement Complex rocks are mostly gneiss, migmatite and sometimes migmatitic-gneiss with older granite intrusives. The mineral foliations defined by alternating biotite-rich and quartz-feldspar-rich are common in the gneiss. Major foliation and fracture trends are in the N-S and NNE, SSW directions markedly exhibited by the flow direction of the River Niger (Obaje et al, 2009). Rocks in the area had regionally been described in the past by previous workers; Jones and Hockey (1964) Grant (1978), Odigi and Amajor (2009) concluded that the dominant lithological units in the study area include migmatite and granite gneiss intruded by the NE-SW trending pegmatite dykes and covered by the Cretaceous – Recent coarse-medium grained sands to the East forming the bank of River Niger.

Oyawoye (1972) described the study area as a polymetamorphic Migmatitic-Gneiss complex, which is composed largely of migmatite and gneiss of various compositions and amphibolites, the relics of metasedimentary rocks represented by medium to high-grade calcareous politic and quartzitic rocks occurring within the migmatites and gneiss, which have been described as "Ancient Metasediment". Odigi (2000) indicated that the migmatite gneiss in the study area are meta-igneous rocks which show mildly alkaline characteristics and calc-alkaline in nature, suggesting they were derived from an ensialic calc-alkaline magma.

Turner (1983) divided rocks into three groups of which the Igarra-Kabba-Lokoja belt was prominent during his time of studying the rocks of western Nigeria.

Geologic mapping exercises during the data acquisition reveal the presence of the Agbaja Ironstone. Adeleye and Dessauvagie (1972) proposed the name Agbaja Ironstone. This formation forms a persistent cap for the Campanian – Maastrichtian sediments in the southern Bida Basin and is a lateral equivalent of the Batati Ironstone on the northern sub-basin. It consists of sandstones and claystone interbedded with oolitic, concretionary and massive ironstone beds. The sandstones and claystones were interpreted as abandoned channel sands and overbank deposits that were subjected to marine reworking forming massive concretionary and oolitic ironstones (Ladipo *et al*., 1994). Minor marine influences were also reported to have affected the dominantly continental environment of the upper parts of the Lokoja Sandstone and the Patti Formation (Braide, 1992b; Olaniyan and Olobaniyi, 1996).

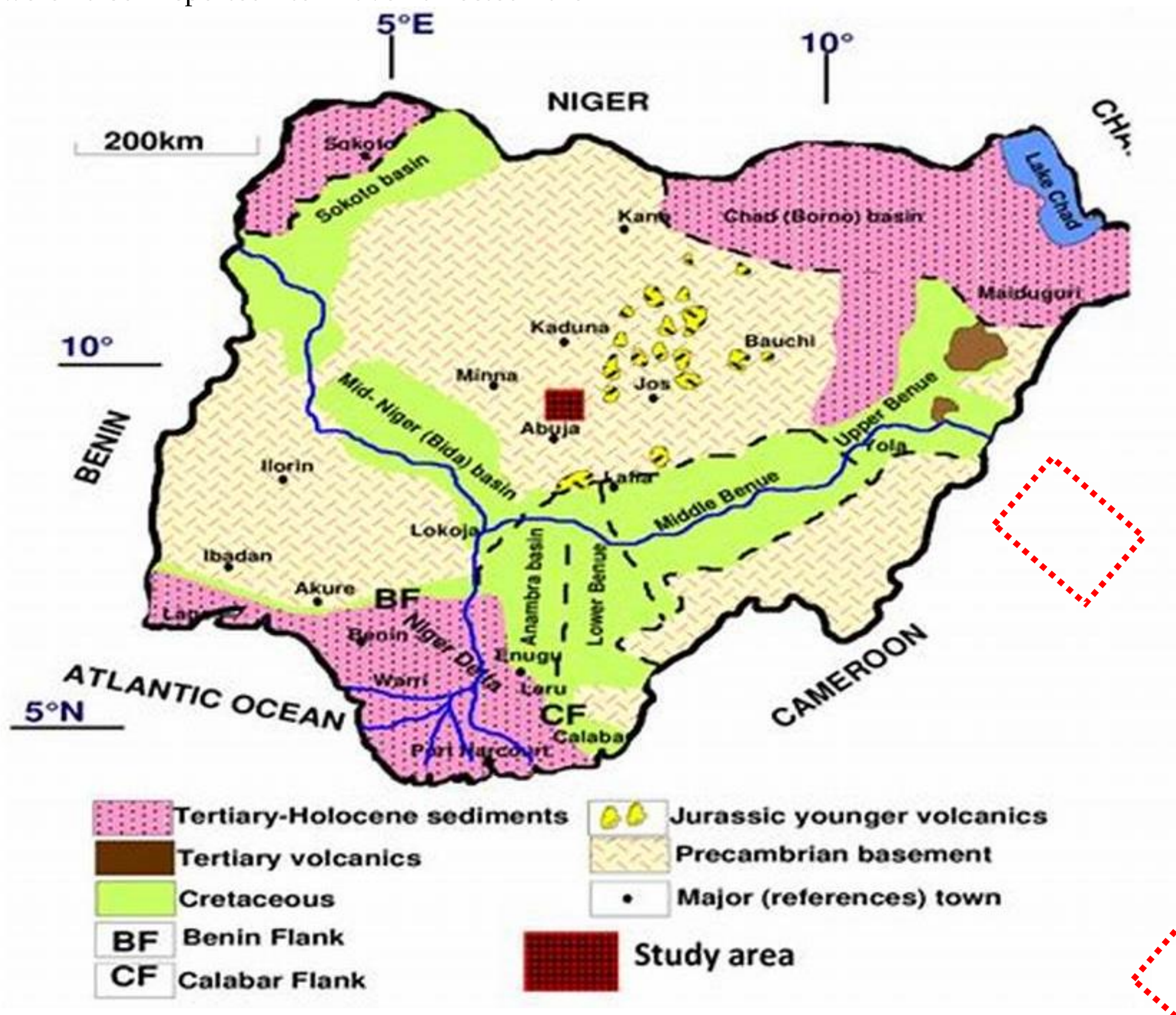


Fig. 1: Geological map of Nigeria showing Lokoja which is the studied Area (modified after Obaje et al, 2013).

The marine inundations appear to have continued throughout the deposition of the Agbaja ironstones in the southern Bida Basin (Ladipo *et al.*, 1994).

2.0 Research Methodology

This study adapted four methodical approaches including geological field mapping, geoelectrical imaging (ERI) techniques involving vertical electrical sounding, horizontal electrical profiling and very low-frequency electromagnetic methods.

2.1 Geological Field Mapping

The geological mapping comprised essentially of geological reconnaissance of the site followed by actual on-site traverses and outcrop study (observation of structures and their orientations including the strike and dips). The aim was to identify lithological types and their structural disposition, field geochemical impact of weathering, availability of sustainable rivers and stream, as well as for the understanding of the field orientation. The Felele Campus of the University, which has an approximate area cover of about perimeter within GPS location 4000 m^2 07° 49' 0" to 07° 51' 30"and longitude 006^0 38' 30" to 006^0 40'30" was mapped within the study area (Fig. 2). The rocks, their texture, grain size, mineral composition and the structures were carefully studied and detailed. The campus was observed to be sitting on the contact point between the basement complex of Nigeria to the western part and the Bida Sedimentary Basin to the eastern part.

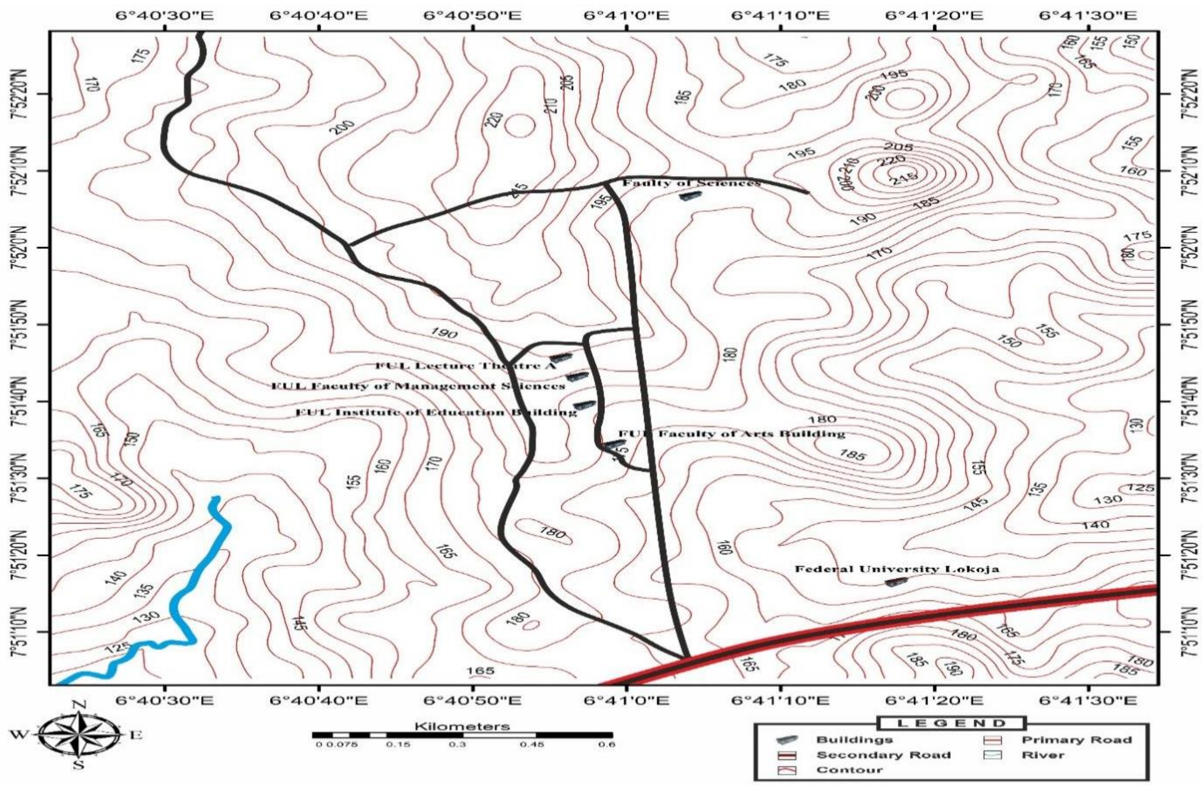


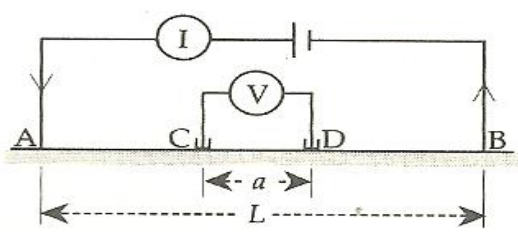
Fig. 2: Topographic map of the study area.

2.2 ERI Data Acquisition and Analysis

The ERI method provides a greater penetration depth to the subsurface, thereby making it possible to distinguish the various layers of rocks underlying the area, the morphology of the unit to be exploited, fracture zones to be identified, as well as the fluid, particularly groundwater. Using PASI 16 GL Earth resistivity meter we measure the electrical resistivity of the subsurface materials at the various locations (Fig. 3) in the study area, noting the variations in the geoelectric behaviour, from which 2D profiles of the subsurface through the earth materials was constructed, while studying and characterizing discontinuities in the subsurface. This measurement involves implanting numerous electrodes along profiles, bearing in mind, the relationship between the electrode spacing and the required resolution, depth, and objectives; the shorter the distance between the electrodes, the greater the resolution, whereas the greater the distance between the electrodes, the greater the depth at which readings were taken.

Fig. 3: VES data acquisition locations across the FUL Felele Campus.

The vertical thicknesses of the underlying rocks were unravelled by employing the vertical resistivity variation, based on Schlumberger's geoelectrical field acquisition design (Fig. 4). In the Schlumberger array, the potential electrodes were placed between the current electrodes, but the spacing between the potential electrodes was far less than that between the current electrodes i. e. distances between adjacent electrodes differ.



$$r_{AC} = (L-a)/2 \qquad r_{AD} = r_{CB}$$
$$r_{CB} = (L+a)/2 \qquad r_{DB} = r_{AC}$$
$$\boxed{\rho_a = \frac{\pi}{4}\frac{V}{I}\frac{(L^2 - a^2)}{a}}$$

Fig. 4: Geoelectrical configurations used in the proposed survey based on the Schlumberger array. From Auduson, 2018.

Using the geometrical configuration in Fig. 4, if A and B are the current electrodes (positive and negative respectively) placed on the ground surface and C and D are the potential probes, and taking V_{CD} as the voltage difference between C and D, leading to a generalized geoelectric equation:

$$\Rightarrow \rho = 2\pi \frac{V_{CD}}{I} * \frac{1}{K} \tag{1}$$

where $K = \frac{1}{AC} - \frac{1}{BC} - \frac{1}{AD} + \frac{1}{BD}$ is the coefficient geometric factor

Formulating the geoelectric configuration in Fig. 4 into equation (1), we have the geometric model for the Schlumberger as:

$$\rho_a = \frac{2\pi}{I}\left[\frac{1}{\left(\frac{2}{L-a} - \frac{2}{L+a}\right) - \left(\frac{2}{L+a} - \frac{2}{L-a}\right)}\right] \tag{2}$$

From 2, we hve

$$\rho_a = \frac{\pi}{4}\frac{V}{I}\left(\frac{L^2 - a^2}{a}\right) \qquad (3)$$

Several electrical resistivity imaging soundings were performed using Schlumberger arrays. These arrays remain stable and behave well in response to variations in the horizontal and vertical resistivities respectively, which make it useful when investigating horizontal layers for lateral facies changes and/or vertical structures. Next, the electrical tomography profiles were processed, using the RES2DINV software for the resistivity based on the least squares method with smoothing constraints modified by the Quasi-Newton optimization method. Data quality control (refining the apparent resistivity data before modelling, to remove the bad data points) was key at this stage. Then, data were inverted to construct a model of the subsurface using rectangular prisms and calculating the resistivity values for each while minimizing the differences between the observed and calculated apparent resistivities. Because of the anticipated wide variation in the measured resistivity values and the abrupt variations between neighbouring points, robust inversion and the combined Marquardt and Occam inversion methods were deployed; these also appear to provide better results in resolving compact structures. Finally, the electrical resistivity tomography profiles interpreted based on the generated apparent resistivity values for clear characterization of the subsurface rock materials.

2.3 EM (Very low frequency) Acquisition and Processing

In this study, we deploy the natural electric field method of the EM geophysical tool, which measures the electrical component of the electromagnetic field of the earth. The method is a frequency-dependent and inductive electromagnetic survey method, which is capable of mapping the variations in the electrical conductivity of the ground. Such variations generally are caused by changes in rock structure (porosity), clay content, conductivity of the rock water, and degree of water-saturation in the rock. The survey here was carried out along profiles juxtaposed at some VES points within the study area. At each point, the two electrodes, connected to the field device, were pegged into the ground ten 10 m apart along a straight profile line. The readings were taken by continually changing the electrode position at 1 m for the profile while still maintaining the 10 m interval. After a desired profile length of 28 m was covered and data taken along the profile line, the data was processed immediately to obtain the 2D imaging. The profile was then stored in the device with a reference number for further processing and evaluation.

We develop a simple method of data interpretation, deployable in rugged geologic terrain such as the contact point, which characterizes the Fedele Campus of the University, our case study. The interpretation scheme is based on identifying EM highs along parallel traverses of EM profiling data that are presented on one-dimensional (1-D) plots. The results show terrain conductivity distribution in the range of 10-70mS/m for the vertical dipole (VD) mode of the device and 22-79 mS/m for the horizontal dipole (HD) mode about the general conductivity distribution of the area, using a 10 m inter coil separation cable. The conductivities for the HD mode were observed relative to those for the VD mode and plotted. From the plots, the various patterns of EM signatures as indications of possible water-bearing features were then deduced. Based on the defined criteria, the best-ranking drill targets were indicatable and then selected for borehole drilling. With this method as a composite part, the interpretation of EM results helps to delineate water-bearing features for a high success drilling rate.

Using matrix laboratory (MATLAB) coding, a set of standard pre-processing techniques was applied to the radargrams:

- DC removal, to subtract the mean from the centre value of a window of 40ns and 75ns (smallest and largest profile, respectively);
- Application of corrected amplitude using trace equalization, where every trace is normalized according to the maximum absolute value of the amplitudes in a window of 160 ns and 300 ns (smallest and largest profile, respectively)
- Removal of unwanted frequencies using band-pass filtering, with 125 MHz and 325 MHz, as the lower and upper cut-off frequency points.
- Finally, removal of the average of several traces within a window of 22 ns, using the automatic trace subtraction method of muting background; thereby enhancing the signal-to-noise ratio (SNR) and reducing the effects of clutter (energy that is unrelated to the real target).

3.0 Results and Discussion

The results of the tripartite geoscientific tools integrated involving the analogue geologic field mapping, Vertical electrical sounding (1D Schlumberger) and very low-frequency electromagnetic (VLF-EM) methods are presented as follows. The basement rocks on the western part show evidence of weathering and exfoliation as dominant geologic processes on most outcrops. Most of the rocks are bounded with the alterations of iron bands, making the area to be more banded and ferruginized iron stones, in some locations, the sediments are overlain by medium- fine-grained sandstone and are well exposed in other places (Fig. 5).

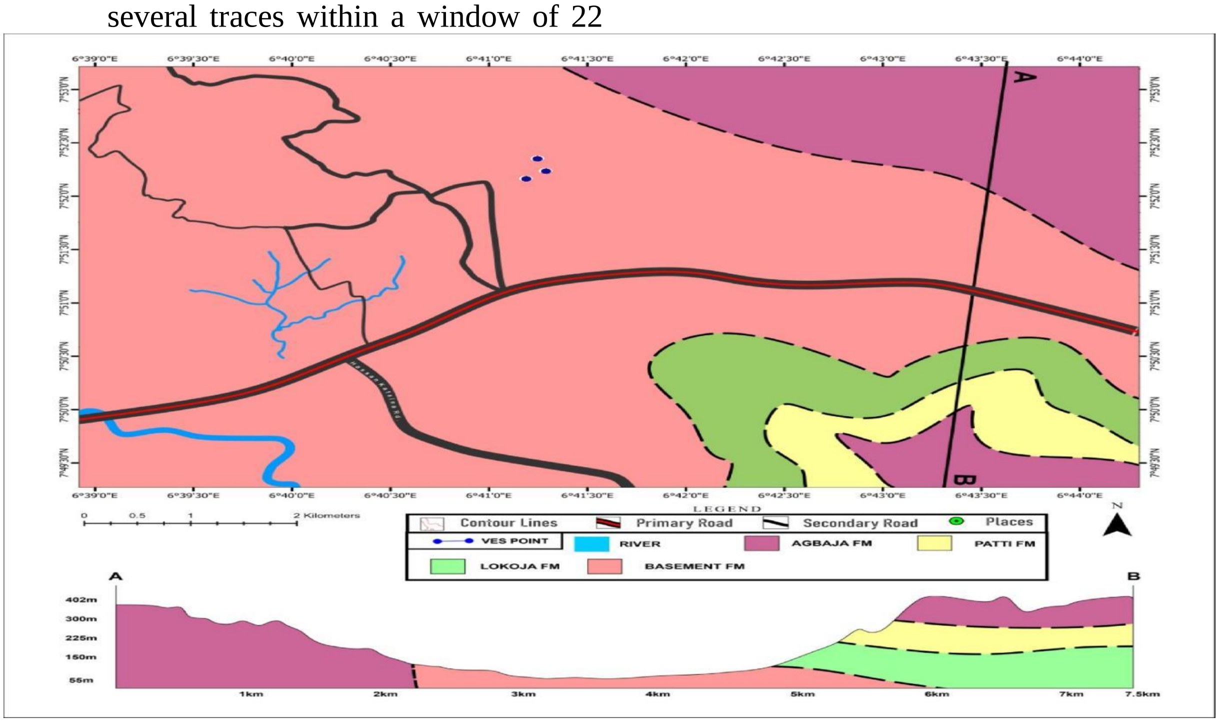


Fig. 5: Geological map of the study area, showing the various rock types.

The 1D Vertical Electrical Sounding (Schlumberger configuration) and VLF-EM were calibrated at different locations of the campus including FUL HOSTEL (VES 1), FULokoja-A (VES 2), FULokoja-B (VES 3) FULokoja-C (VES 4), FULokoja-D (VES 5) FULokoja-F (VES 6), etc. These surveys were exercised at several other locations, but the results from four locations are presented here as the representative samples. Tables 1, 2, 3, and 4 display the resistivity-sounding results as recorded at the FUL Hostel, FULokoja-A, FULokoja-B and FULokoja-F. Fig. 6, 8, 10 and 12 show the typical VES curves obtained based on results from FUL Hostel, FULokoja-A, FULokoja-B and FULokoja-F (based on the data in Tables 1 to 4 respectively), which predominantly H-types while Fig. 7, 9, 11 and 13 show the subsurface VLF-EM structural map indicating fractured zone calibrated at the FUL Hostel, FULokoja-A, FULokoja-B and FULokoja-F respectively.

Table 1: Resistivity sounding field record results (1D/Schlumberger) obtained at FUL Hostel (VES 1)

Elect. position	Half Current Electrode (m)	Half Potential Electrode (m)	Geometric Factor (G)	Current (I)	Resistance (Ohms)	Apparent Resistivity (Ohm-m)
	AB/2	MN/2	G	μ/mA/A	R(Ohm)	(Ohm-m)
0	1	0.25	6.28	12.3	76	477
1	2	0.25	25.13	13.3	14.8	372
2	3	0.25	56.55	11.7	8	452
3	4	0.25	100.53	14	4.9	492
4	6	0.25	226.19	11.3	5.1	1153
5	6	0.5	113.10	11.3	1.2	136
6	8	0.5	201.06	13.8	0.431	86
7	12	0.5	452.39	14.5	0.1996	90
8	15	0.5	706.86	9.2	0.1899	134
9	15	1	353.43	9.2	0.1447	51
10	25	1	981.75	12.1	0.0884	86
11	32	1	1608.50	5.8	0.1247	207
12	40	1	2513.27	5.4	0.0321	80
13	40	2.5	1005.31	5.4	0.2062	207
14	65	2.5	2654.65	10.2	0.2305	611
15	100	2.5	6283.19	11.1	0.1273	800
16	100	5	3141.59	11.3	0.2610	820

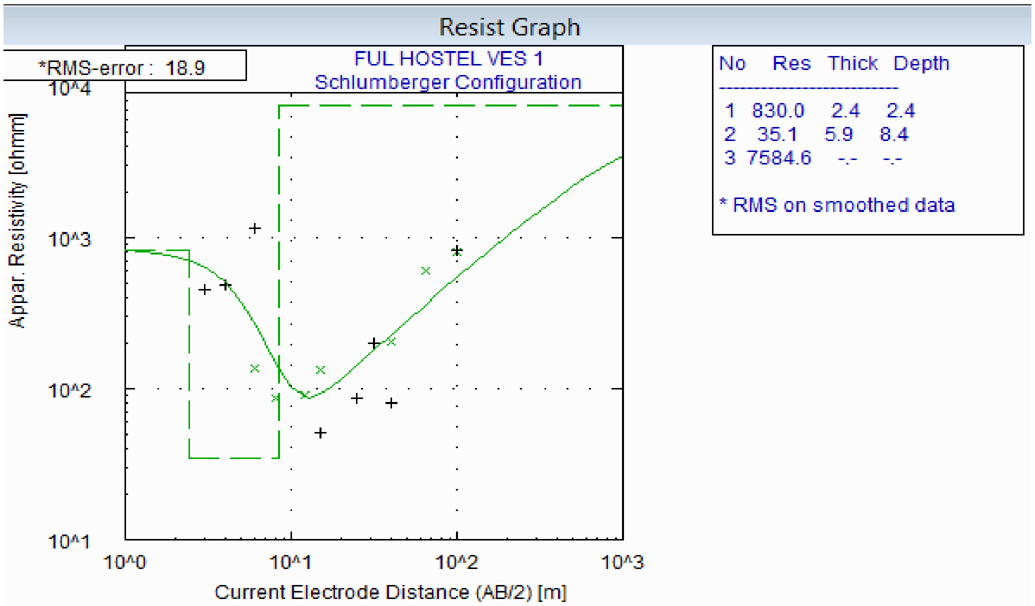


Fig. 6: A typical H-type VES curve obtained from FULokoja Hostel (VES 1) based on data in Table 1.

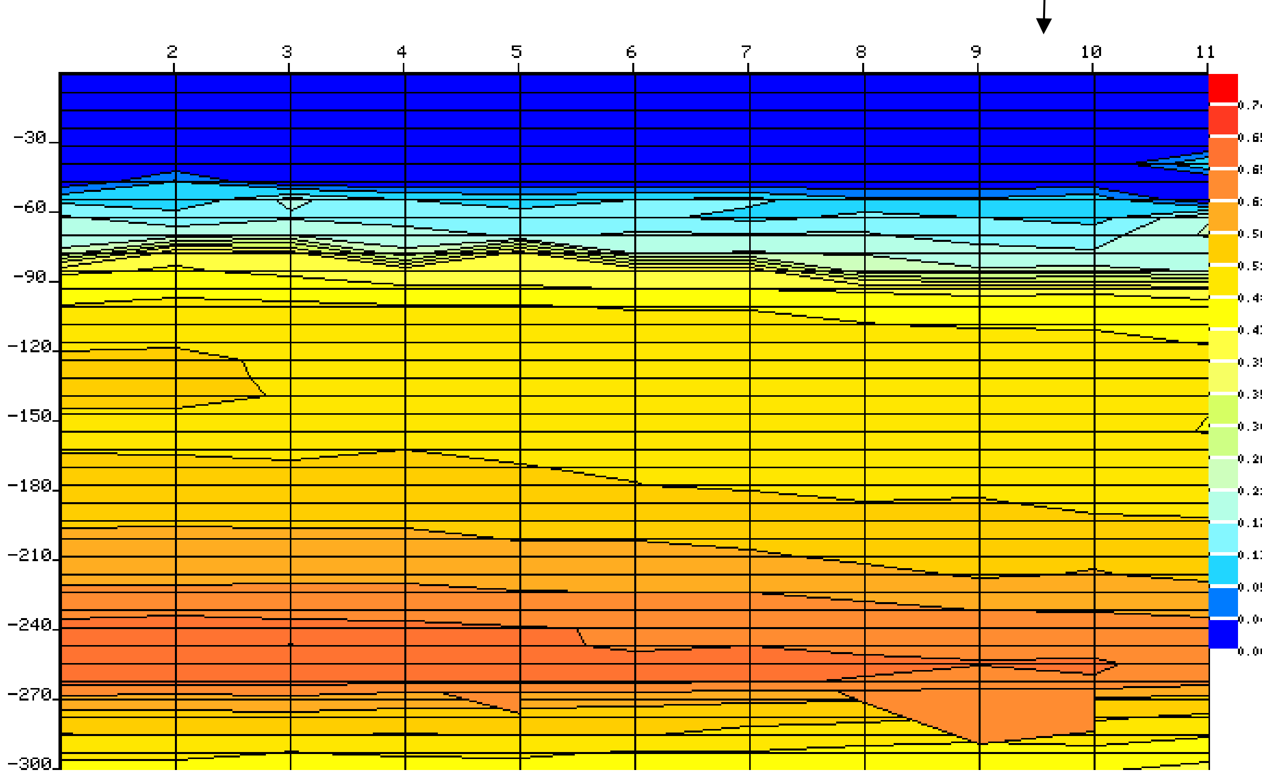


Fig. 7: Subsurface VLF-EM structural map showing fractured zone calibrated at FULokoja Hostel by VES 1. Recommended borehole depth to be drilled (indicated by the arrow towards the top right corner) at this location ranges between 85 and 90 meters. The Overburden thickness is about 5 m. Point of terminating the well is at the liberty or discretion of the supervising geologist or drilling Engineer based on the water yield.

Table 2: Resistivity sounding field record results (1D/Schlumberger) obtained at FULokoja-A (VES 2)

Elect. positio n	Half-Current Electrode (m)	Half-Potential Electrode (m)	Geometric Factor (G)	Resistance (Ohms)	Apparent Resistivity (Ohm-m)
	AB/2	MN/2	G	R(Ohm)	(Ohm-m)
0	1	0.25	6.28	225.7	141
1	2	0.25	25.13	24.4	613
2	3	0.25	56.55	4.5	215
3	4	0.25	100.53	1.3	131
4	6	0.25	226.19	0.2477	56
5	6	0.5	113.10	0.3196	36
6	8	0.5	201.06	0.2766	56
7	12	0.5	452.39	0.096	43
8	15	0.5	706.86	0.0945	67
9	15	1	353.43	0.1636	58
10	25	1	981.75	0.1166	114
11	32	1	1608.50	0.071	114
12	40	1	2513.27	0.0483	121
13	40	2.5	1005.31	0.1523	153
14	65	2.5	2654.65	0.068	181
15	100	2.5	6283.19	0.0316	199
16	100	5	3141.59	0.0344	108
17	125	5	4908.74	0.0356	101
18	150	5	7068.58	0.0388	274

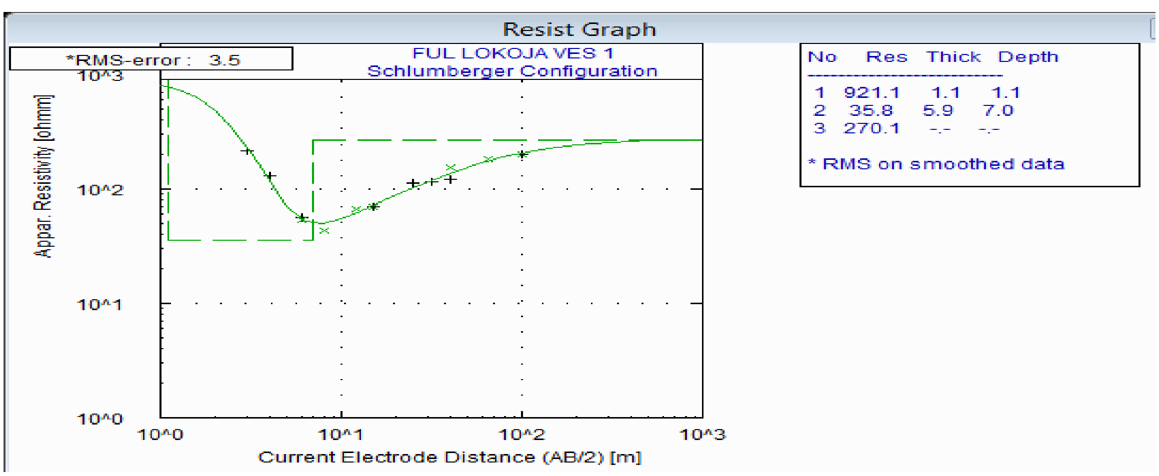


Fig. 8: A typical H-type VES curve obtained from FULokoja Hostel (VES 2) based on data in Table 2.

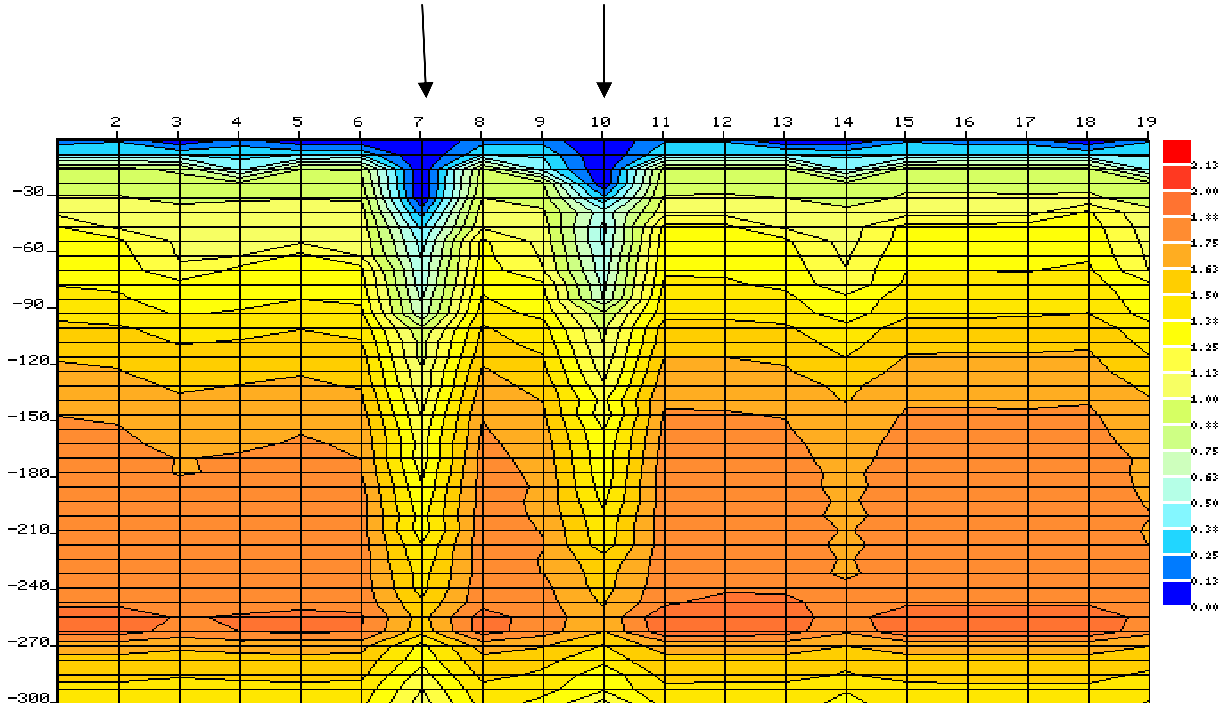


Fig. 9: Subsurface VLF-EM structural map showing fractured zone calibrated at FULokoja-A by VES 2. Recommended borehole depth to be drilled (indicated by either of the two arrows at 7 and 10 respectively) at this location ranges between 120 and 125 meters. The Overburden thickness is about 10 m. The point of terminating the well is at the liberty or discretion of the supervising geologist or drilling Engineer based on the water yield.

Table 3: Resistivity sounding field record results (1D/Schlumberger) obtained at FULokoja-B (VES 3)

Elect. position	**Half Current Electrode (m)**	**Half Potential Electrode (m)**	**Geometric Factor (G)**	**Resistance (Ohms)**	**Apparent Resistivity (Ohm-m)**
	AB/2	MN/2	G	R(Ohm)	(Ohm-m)
0	1	0.25	6.28	75.6	475
1	2	0.25	25.13	10.6	266
2	3	0.25	56.55	3.6	203
3	4	0.25	100.53	1.4	141
4	6	0.25	226.19	0.412	93
5	6	0.5	113.10	0.621	70
6	8	0.5	201.06	0.4874	98
7	12	0.5	452.39	0.236	107
8	15	0.5	706.86	0.4470	316
9	15	1	353.43	0.8996	318
10	25	1	981.75	0.427	420
11	32	1	1608.50	0.289	465

12	40	1	2513.27	0.204	514
13	40	2.5	1005.31	0.510	513
14	65	2.5	2654.65	0.219	584
15	100	2.5	6283.19	0.100	634
16	100	5	3141.59	0.209	657

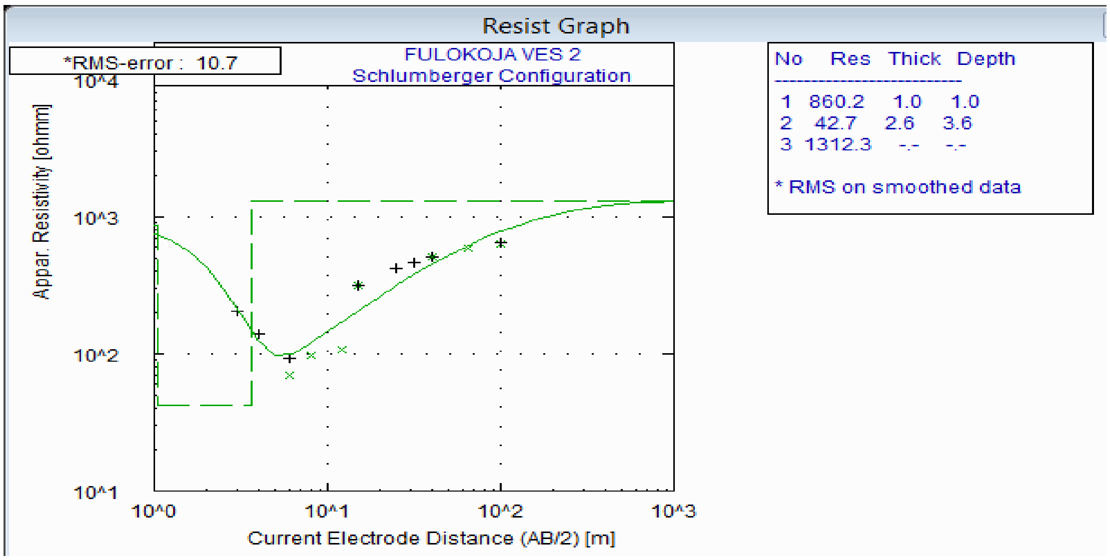


Fig. 10: A typical H-type VES curve obtained from FULokoja Hostel (VES 3) based on data in Table 3.

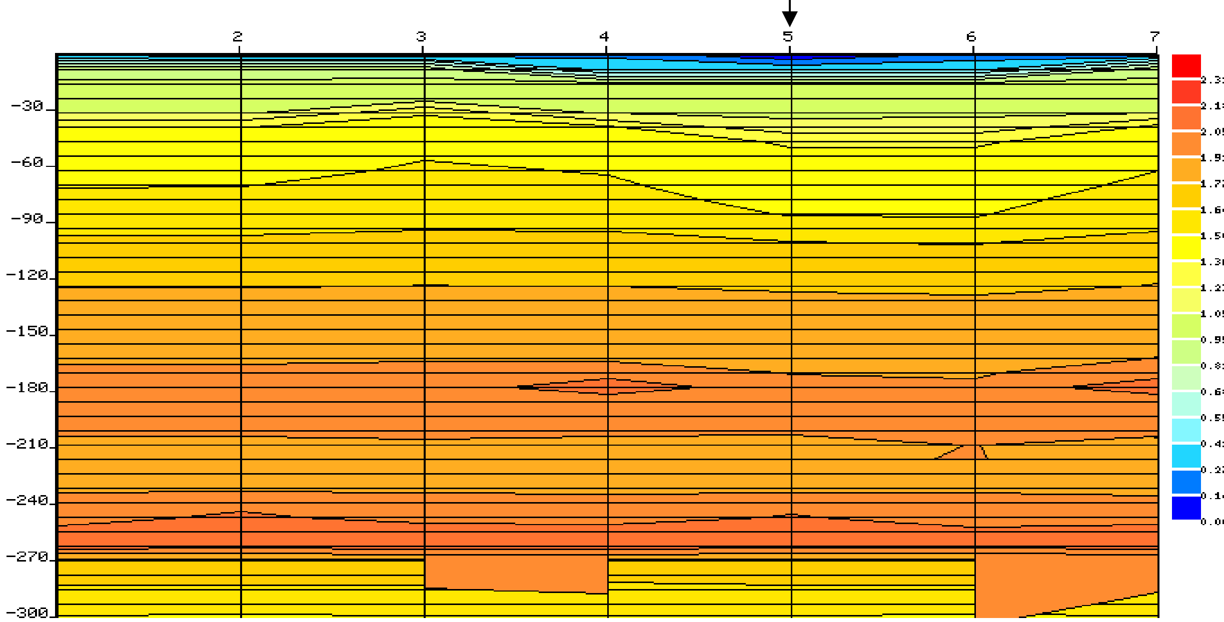


Fig. 11: Subsurface VLF-EM structural map showing fractured zone calibrated at FULokoja-B by VES 3. The pegged point (indicated by the arrow at point 5) by the most prospective point by the preliminary probe on the site should NOT be drilled due to thin overburden and the extremely resistive nature of the underlying rocks.

Table 4: Resistivity sounding field record results (1D/Schlumberger) obtained at FULokoja-F (VES 6)

Elect. position	Half Current Electrode (m)	Half Potential Electrode (m)	Geometric Factor (G)	Resistance (Ohms)	Apparent Resistivity (Ohm-m)
	AB/2	MN/2	G	R(Ohm)	(Ohm-m)
0	1	0.25	6.28	85.3	535
1	2	0.25	25.13	12.9	324
2	3	0.25	56.55	3.5	198
3	4	0.25	100.53	1.1	111
4	6	0.25	226.19	0.4465	101
5	6	0.5	113.10	0.9018	102
6	8	0.5	201.06	0.5819	117
7	12	0.5	452.39	0.2740	124
8	15	0.5	706.86	0.3763	266
9	15	1	353.43	0.7724	273
10	25	1	981.75	0.3888	381
11	32	1	1608.50	0.259	417
12	40	1	2513.27	0.2279	573
13	40	2.5	1005.31	0.5759	579
14	65	2.5	2654.65	0.235	626
15	100	2.5	6283.19	0.125	786
16	100	5	3141.59	0.2594	815

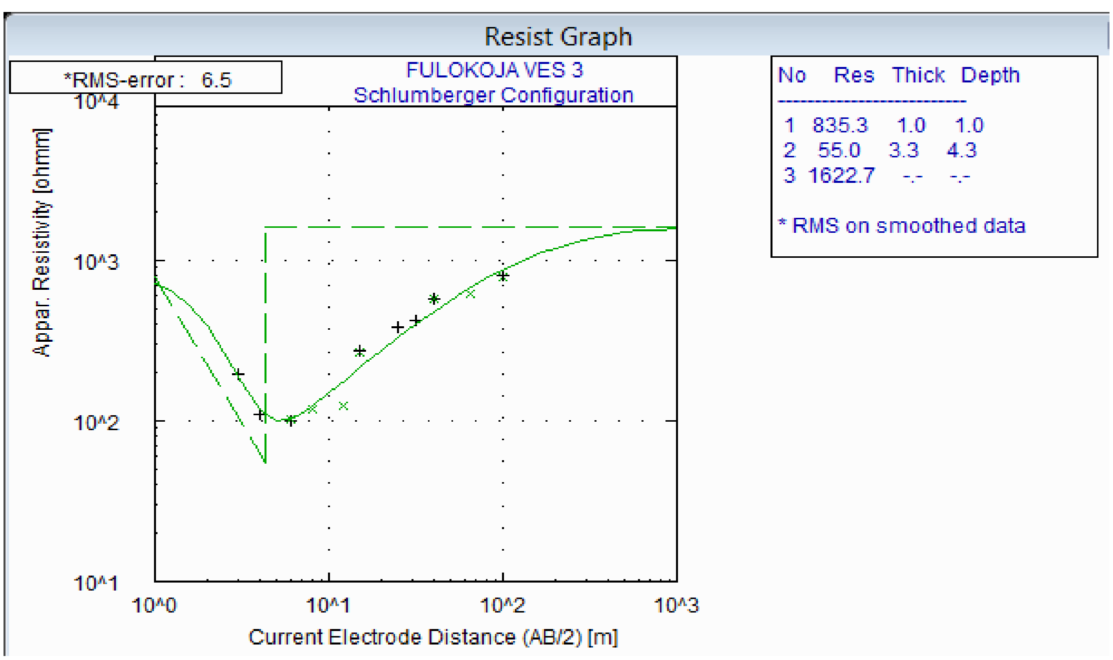


Fig. 12: A typical H-type VES curve obtained from FULokoja Hostel (VES 4) based on data in Table 1.

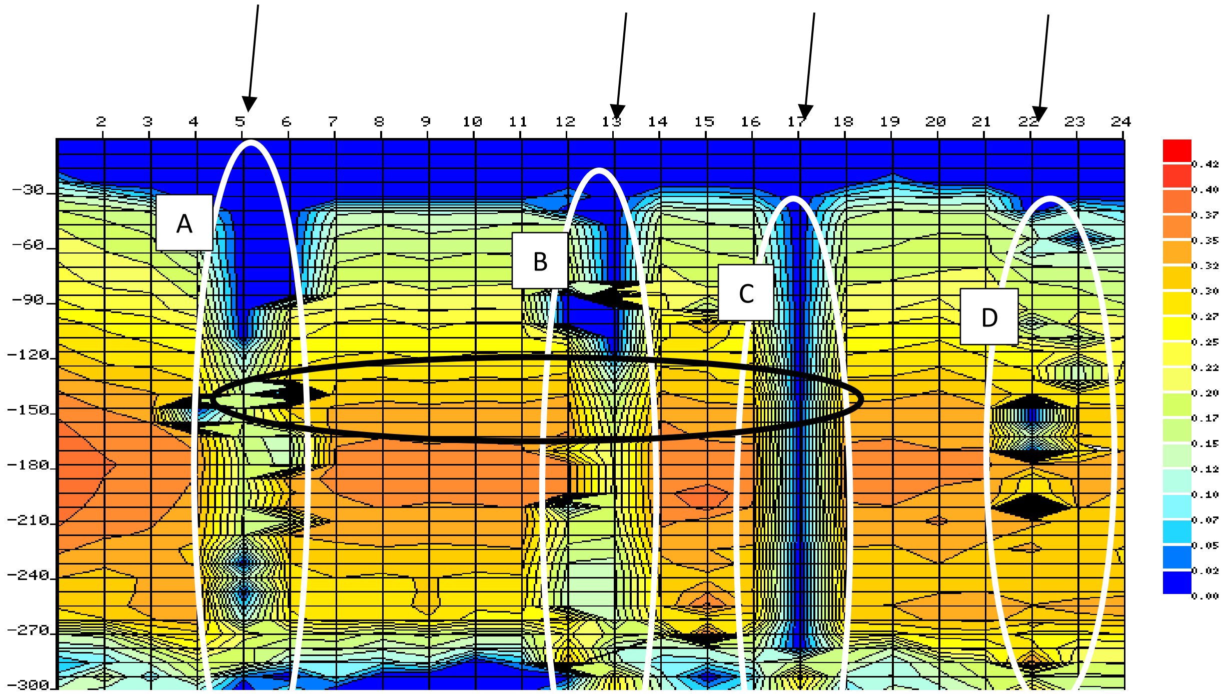


Fig. 13: Subsurface VLF-EM structural map showing fractured zone calibrated at FULokoja-F by VES 6. Recommended borehole depth to be drilled (indicated by either of the two arrows at 5) at this location ranges between 120 and 127 meters. The Overburden thickness is about 4 m. Point of terminating the well is at the liberty or discretion of the supervising geologist or drilling Engineer based on the water yield.

The results of the ERI surveys show that there are four geologic layers in the study area. The layers' sequence delineated are the topsoil, weathered basement, partially weathered/fractured basement and fresh basement in the basement part of the campus, where the surveys predominate. The topsoil has a resistivity value of 198-535 Ωm and a thickness of 1.0 m to 5.9 m; the weathered basement (second layer) is 2.0 m to 44.5 m thick, and resistivity value between 36-136 Ωm; the third layer (partially weathered/fractured basement) has resistivity value ranging from 80-300 Ωm with thickness of 6.0 m to 60 m across most of the area and the fourth layer is the fresh basement with resistivity of an average of 800 Ωm and above with infinite depth. This forms the bedrock of the study area and represents the weathered basement aquifer and partially weathered basement aquifer, but most of the groundwater aquifers are located within the partially weathered basement at a good depth of about 111 m.

The Electromagnetic survey (VLF-EM) section spans a profile length of 0-29 m and a depth of 300 m. The VLF-EM survey covers most of the western portion of the initial resistivity survey interpreted above. A low resistivity of 0.00 to 0.12 Ωm is seen on the legend with blue to light-blue colouration and a very high resistivity value ranging from 0.23 to 2.32 Ωm is seen with yellow/orange to red colouration. From a general view of the VLF section, several prominent fractures can be seen as evident at line 10 (Fig. 7), lines 7 and 10 (Fig. 9), while more complex fractures are observed (oval shapes A, B, C, D and D) in Fig. 12 with depths ranging from 30 m to approximately 300 m. From a depth of 0 to 30 meters, observation was ascertained of a very low resistivity (blue colour) along the profile showing the presence of water, it was deduced that the rocks at these depths must have been highly weathered to joints and fractures which facilitated the accumulation of the groundwater.

Comparative analysis reveals that the ERI method on the one hand, provides more general and basic information about the lithological units based on the electrical resistivity variation; hence, this technique was used at a preliminary stage for the estimation of the volume and distribution of the aquifers. On the other hand, the VLF-EM, imaged the structural units clearly and thus served in evaluating the characteristics of the aquifers (thereby facilitating the characterization of the stratigraphy, fabric and texture of the rock) as well as the structural anomalies (fractures, fracture types, holes, and so on). The VLF-EM results led to deterministic means of establishing and isolating the aquiferous zones, unlike the 1D vertical electrical sounding at the various locations. Recommendations of the borehole depths to be drilled are reliably and confidently made (as indicated by the arrows in Fig. 7, 9, and 13). This is also corroborated by the recommendation against drilling (NOT be drilled) in Fig. 10 due to the thin overburden and the extremely resistive nature of the underlying rocks. The observed complex/multiple fracture (Fig. 13) within the study is an isolated case, compared to the larger study area; therefore, the question about a possible threat to groundwater due to contamination does not arise. Therefore, exploration of groundwater and construction of all kinds of structures may be embarked upon on most parts of the campus, without the need for deeper excavation of the subsurface. However, before erecting any serious building on the campus, is recommended that a geotechnical investigation be carried out.

4.0 Conclusion

Integrated geoscientific methods involving the use of geologic mapping, and geoelectrical and electromagnetic geophysical tools were deployed in this study to harness and avail water resources for the Felele Campus of the Federal University Lokoja community. Geological field mapping adopted analogue real-time field traverses, observing and studying possible geological structures, and hydrogeological and hydrogeochemical occurrences. The geoelectrical tool utilized a vertical electrical sounding base on the 1-dimensional Schlumberger geometric configuration. The electromagnetic tool adopted the very low frequency electromagnetic (VLF-EM) profile to generate the 2-dimensional image of the subsurface.

The results of the geoelectrical imaging show four geologic layers including topsoil, weathered basement, partially weathered/fractured basement and fresh basement in the basement part of the campus, with variable resistivity values and thicknesses. The results of the VLF-EM show low resistivity of 0.00 to 0.12 Ωm indicated with blue to light-blue colouration and very high resistivity value ranging from 0.23 to 2.32 Ωm indicated with yellow/orange to red colouration (Fig. 6, 8, 10 and 12). The general overview of the VLF indicates several prominent fractures, which are very more complex at some locations (Fig. 12) with depths ranging from 30 m to approximately 300 m.

Comparative analysis reveals that the VLF-EM tool imaged the structural units clearly and thus served in evaluating the characteristics of the aquifers as well as the structural anomalies (fractures, fracture types, holes, and so on) better than the 1-D Schlumberger tool. Thus, recommendations of the borehole depths to be drilled are more reliably and confidently made. Therefore, integrating the very low-frequency electromagnetic tool with the conventional vertical electrical sounding method is a more robust technique which leads to the reduction of risks and uncertainties associated with groundwater exploration and exploitation on the Felele Campus of the University and elsewhere, depending on the geology of the terrain.

Acknowledgements

The authors, particularly, the team members of the Innovative Research for Exploration and Production (IREPad) domiciled at the Department of Geology, Federal University Lokoja Nigeria, would like to thank the Tertiary Education Trust Fund (TETFund) for granting the requisite fund via the 2022 Institution Based Research (IBR), which aided us in accessing all necessary facilities required to carry out this research. We also hereby thank the Management of Federal University Lokoja, for her proactivity and encouragement in putting in place and motivating the team to embark on this research work within the university.

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Compliance with Ethical Standards Declaration

Ethical Approval

Not Applicable

Competing interests

The authors declare that they have no known competing financial interests.

Funding

This project was sponsored by TETfund under Institutional Based Research (IBR).

Authors' Contributions :

AEA: design, acquisition of data, interpretation and manuscript development and supervision, AEB: physical planning of the site, manuscript development, KOM, KOM and MMS: analytical framework, study area information, MAI: crosschecking of results, data analysis, etc. IMA, BAM: literature review and technical support, FAA: hydrogeology investigation, analytical framework and reporting. PO and IO: data acquisition, logistics, manuscript development.