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Geophysical Investigation of Groundwater Potential at Alhudahuda College, Zaria Using Very Low Frequency Electromagnetic (VLF-EM) Method

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Abstract: *Geophysical investigation of groundwater potential at Alhudahuda College, Zaria, Kaduna State, Nigeria, was carried out using the Very Low Frequency Electromagnetic (VLF-EM) method in response to persistent water scarcity and recurrent borehole failure within the school. The study area is situated within the Nigerian Basement Complex, where groundwater occurrence is predominantly controlled by weathered and fractured crystalline formations. Five traverses were established across the area, and VLF-EM measurements were acquired in vertical mode to delineate subsurface conductive structures associated with groundwater accumulation. The acquired data were processed using Fraser and Karous–Hjelt filtering techniques to enhance anomaly resolution and generate pseudo-sections representing subsurface current density distribution. Interpretation of the filtered data revealed several conductive zones across the profiles with depths extending to approximately 15 m, indicative of potential aquiferous formations. Profiles 3 and 5 exhibited relatively homogeneous conductive responses, while Profiles 2 and 5 revealed distinct fractured zones suggestive of enhanced groundwater potential. High positive peaks in the in-phase component and corresponding high current density values were interpreted as conductive anomalies associated with groundwater-bearing zones, whereas low current density regions represented resistive formations with limited groundwater potential. Two principal prospective groundwater targets were identified along Profiles 2 and 5 and are recommended as suitable locations for borehole development. The results confirm the effectiveness of the VLF-EM method in delineating subsurface conductive structures and provide reliable guidance for groundwater exploration in basement complex terrains.*

Keywords: *VLF-EM; Groundwater potential; Basement complex; Fraser filter; Karous–Hjelt pseudo-section; Zaria*

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1.0 Introduction

Water is a very useful natural resource that is essential for the survival of mankind and the sustainability of the natural environment (Smith *et al*., 2018). The availability of clean and uncontaminated water has become increasingly important for domestic, agricultural, and industrial purposes, particularly in developing countries where population growth and urban expansion exert pressure on existing water resources (Brown *et al*., 2019). In many parts of northern Nigeria, surface water sources are seasonal and unreliable, thereby making groundwater the most dependable source of potable water.

Groundwater is considered a reliable water source because it is naturally protected from surface contamination and generally maintains a relatively stable supply throughout the year (USGS, 2022).The occurrence, distribution, and movement of groundwater are strongly influenced by the geological characteristics of the subsurface. In crystalline basement terrains, such as those found in Zaria and its environs, groundwater occurrence is mainly controlled by secondary porosity resulting from weathering, fracturing, faulting, and jointing of the bedrock. Fresh basement rocks are typically impermeable; hence productive aquifers are commonly associated with weathered regolith and fractured basement zones.

Previous hydrogeological studies in parts of Zaria and Kaduna State have highlighted the importance of fractures and weathered zones in groundwater occurrence (e.g., Aliyu et al., 2015; Musa et al., 2017), but few have applied VLF-EM surveys specifically to map these features at Alhudahuda College. To effectively explore groundwater in such complex geological environments, geophysical methods have been widely and successfully applied (Karami *et al*., 2009). These methods include electrical resistivity surveys, magnetic and magnetotelluric methods, seismic refraction, and electromagnetic techniques (Marjudar *et a*l., 2011). Among these, the Very Low Frequency Electromagnetic (VLF-EM) method has gained prominence due to its sensitivity to conductive subsurface features, rapid data acquisition, non-invasive nature, and cost-effectiveness (Telford *et al*., 1990).

The VLF-EM method utilizes electromagnetic waves in the frequency range of approximately 15–30 kHz transmitted by powerful communication antennas originally designed for military and navigation purposes (Telford *et al*., 1990). These electromagnetic signals penetrate the Earth's surface and interact with subsurface materials, inducing secondary electromagnetic fields that can be measured at the surface (Reynolds, 2011). Analysis of these responses enables the identification of conductive anomalies associated with water-bearing formations, fracture zones, faults, and shear zones.

The method is particularly effective in basement complex terrains where groundwater is localized within fractured and weathered zones, which usually exhibit higher electrical conductivity compared to fresh crystalline rocks (Sharma, 1997; Karous *et al*., 1983).The sensitivity of the VLF-EM method to such conductive features makes it a particularly valuable tool for hydrogeological investigations in basement complex terrains. In addition, its ability to map linear geological structures that act as conduits for groundwater flow further enhances its suitability for groundwater exploration (McNeill *et al*., 1991). Another major advantage of the VLF-EM method is its non-invasive nature. Unlike drilling and other intrusive techniques, the method does not require extensive ground disturbance, thereby reducing environmental impact and cost (Reynolds, 2011). The portability and ease of operation of VLF-EM equipment also make it suitable for surveys in remote or difficult-to-access areas (Bernard *et al*., 1991). However, despite its strengths, the VLF-EM method has limitations such as shallow depth penetration and ambiguity in data interpretation, especially in areas with complex geology. Consequently, careful survey design and data processing are required to obtain reliable results (Rao *et al*., 2017).

Despite the documented effectiveness of the VLF-EM method in basement complex terrains, specific investigations targeting groundwater potential at Alhudahuda College, Zaria, are scarce. Therefore, there is limited information on the spatial distribution of subsurface conductive zones suitable for borehole development in this area. The results of this study are expected to provide practical guidance for sustainable groundwater development, optimize borehole siting, and reduce drilling costs. Furthermore, it will contribute to water resource management strategies in similar basement complex terrains in northern Nigeria.

The study area, Alhudahuda College, is located in Zaria, Kaduna State, Nigeria, within latitude 11.0640°N to 11.0700°N and longitude 7.6980°E to 7.7020°E. The area lies within the Guinea Savanna climatic zone, characterized by distinct wet and dry seasons.

Geologically, the area is underlain by rocks of the Nigerian Basement Complex, predominantly composed of migmatites, gneisses, and older granites of Precambrian age. These rocks are typically characterized by low primary porosity; hence groundwater occurrence is mainly restricted to zones of weathering and structural discontinuities such as joints, fractures, and faults. These structural features are crucial because they serve as the main pathways for groundwater flow in otherwise impermeable basement rocks. Identifying their locations through geophysical methods like VLF-EM is therefore essential for locating productive aquifers and ensuring reliable water supply. The hydrogeological significance of these features makes geophysical investigation essential for effective groundwater exploration. The location of the study area and the layout of the survey profiles are presented in Fig. 1.

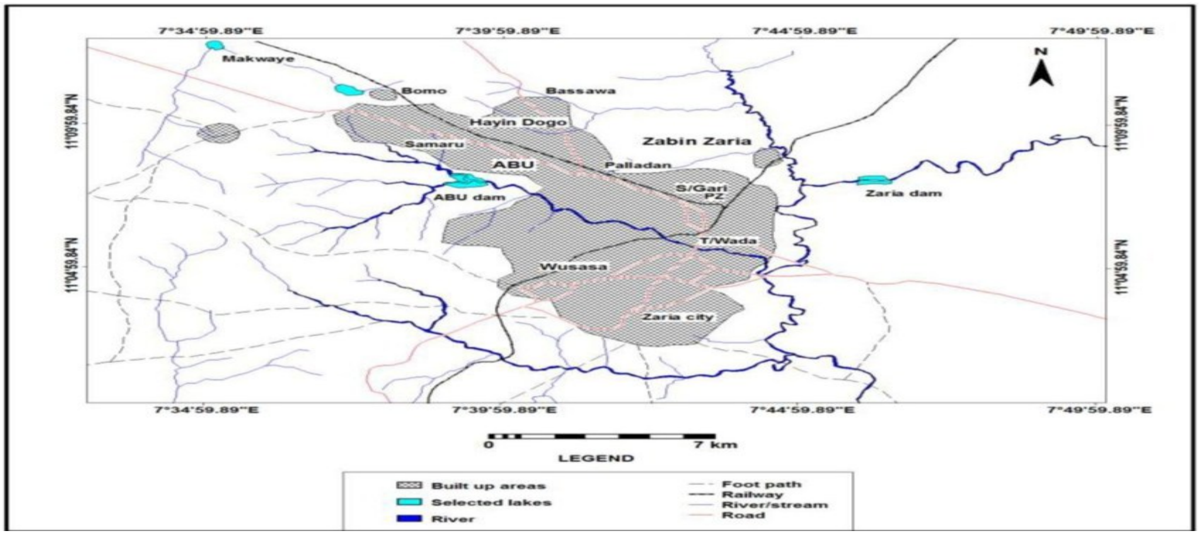


Fig 1: Location of the study area with points where the profiles were carried out

2.0 Materials and Methods.

2.1 *Materials*

The materials used for this study include a Very Low Frequency Electromagnetic (VLF-EM) receiver, capable of measuring both in-phase (real) and out-of-phase (quadrature) components of the electromagnetic field, which is essential for detecting conductive subsurface features. The T-VLF IRIS receiver used for field measurements is shown in Fig. 2.

A handheld Global Positioning System (GPS) device was used for precise spatial referencing of measurement stations, while a magnetic compass and measuring tapes ensured accurate traverse orientation and station spacing. Field notebooks were used for systematic data recording, and specialized data processing software was employed for Fraser and Karous–Hjelt filtering, enabling interpretation of the subsurface conductivity patterns

Fig 2: T-VLF IRIS Instrument

2.2 VLF-EM Data Acquisition & Processing

The VLF-EM survey was conducted along five profiles strategically oriented to intersect possible geological structures. The receiver was tuned to the [name of the transmitting station, e.g., NAA Cutler, Maine, USA] station operating at [frequency in kHz], which provides a strong and stable electromagnetic signal suitable for detecting near-surface conductive structures. Measurements were taken at regular station intervals using a VLF-EM receiver tuned to an appropriate transmitting station. Station spacing along each profile was [e.g., 5 m], and the traverses were oriented approximately perpendicular to the dominant structural trends to maximize the likelihood of intersecting fractures, faults, and shear zones. Both the in-phase (real) and out-phase (quadrature) components of the electromagnetic field were recorded along each traverse. The acquired VLF-EM data were first subjected to Fraser filtering, which suppresses noise and enhances the identification of near-surface conductive anomalies. Subsequently, Karous–Hjelt filtering was applied to produce current density pseudo-sections, providing a qualitative and semi-quantitative representation of the depth, orientation, and lateral extent of conductive features potentially associated with groundwater-bearing zones.

3.0 Results and Discussion

The interpretation of the VLF-EM data was carried out following the same qualitative approach adopted by (Umar *et al*., 2026) where emphasis is placed on identifying and counting conductive and non-conductive zones along each profile based on the behaviour of the in-phase and out-phase components, Fraser-filtered curves, and Karous–Hjelt (K–H) current density pseudo-sections. Conductive zones identified from the VLF-EM data are interpreted as potential groundwater-bearing structures due to their higher electrical conductivity, which is commonly associated with water-saturated fractures and weathered zones in crystalline basement rocks. Non-conductive zones correspond to resistive basement or low water-bearing formations, likely due to unfractured or less weathered rock. This interpretation framework ensures that geophysical anomalies are directly linked to hydrogeological relevance.

In general, high positive peaks in the in-phase component, accompanied by corresponding low negative peaks in the out-phase component, indicate conductive subsurface structures, which are potential pathways for groundwater. Conversely, maximum negative anomalies in both components suggest resistive zones with limited groundwater potential.

TThe Fraser-filtered response for Profile 1 is illustrated in Fig. 3.The corresponding Karous–Hjelt current density pseudo-section for Profile 1 is presented in Fig. 4. The Fraser-filtered response of Profile 1 reveals three distinct conductive zones, occurring at approximately 13–23 m, 47–58 m, and 100–113 m along the profile. These conductive zones correspond to areas of high current density on the Karous–Hjelt pseudo-section and are interpreted as fractured or weathered basement zones with good groundwater potential. In contrast, one non-conductive (resistive) zone is identified, characterized by low current density and corresponding negative anomalies in both in-phase and out-of-phase components. Overall, Profile 1 is dominated by conductive features, indicating favorable groundwater conditions.

The Fraser-filtered anomalies obtained along Profile 2 are shown in Fig. 5. However, the interpretation of Profile 2 indicates the presence of three conductive zones distributed along the traverse.

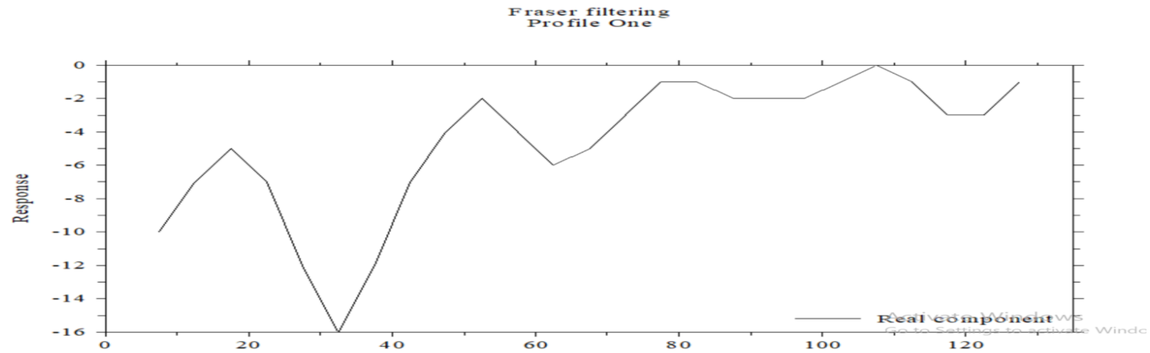


Fig. 3: Fraser Filtering of Profile 1

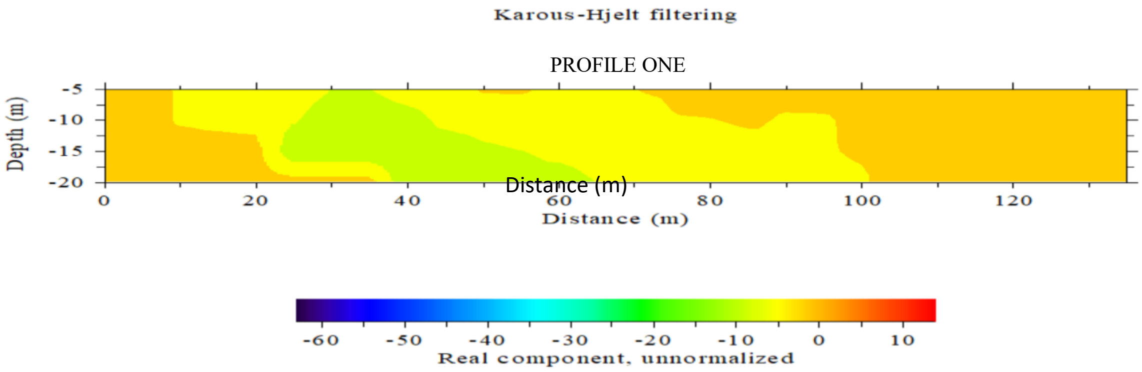


Fig. 4 : Fraser filter with K-H pseudo-section for profile 1

The Fraser-filtered curve highlights prominent anomalies, while the Karous–Hjelt pseudo-section shows moderate to high current density associated with fractured basement materials. The associated Karous–Hjelt pseudo-section highlighting subsurface current density distribution is presented in Fig. 6.

These conductive zones are interpreted as potential aquifer-bearing structures. No prominent non-conductive zone is observed along this profile, suggesting a generally favorable subsurface condition for groundwater occurrence.

The Fraser-filtered result for Profile 3 is displayed in Fig. 7. Profile 3 is characterized by three well-defined conductive zones identified from the Fraser-filtered anomalies at approximately 32–43, 53–63, and 82–92 m. The corresponding Karous–Hjelt pseudo-section illustrating the subsurface conductivity pattern is shown in Fig. 8.

The Karous–Hjelt pseudo-section shows high and relatively homogeneous current density across most of the profile, indicating extensive conductive materials within the subsurface. No distinct non-conductive zone is observed along this profile, implying a high groundwater potential controlled by widespread weathering and fracturing.

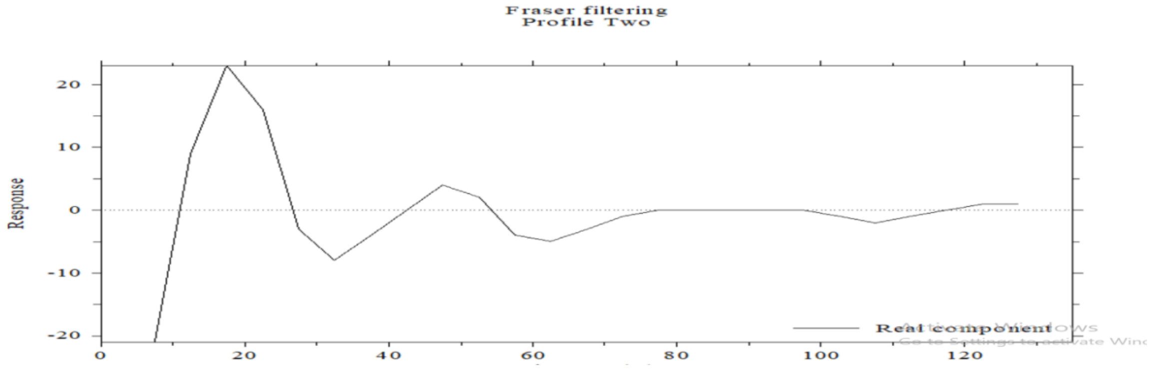


Fig. 5: Fraser Filtering of Profile 2

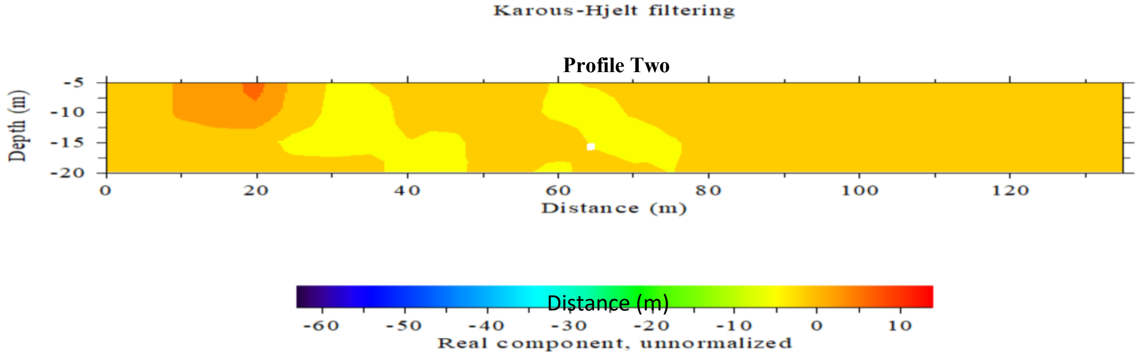


Fig.6 : Fraser filter with K-H pseudo-section for profile 2

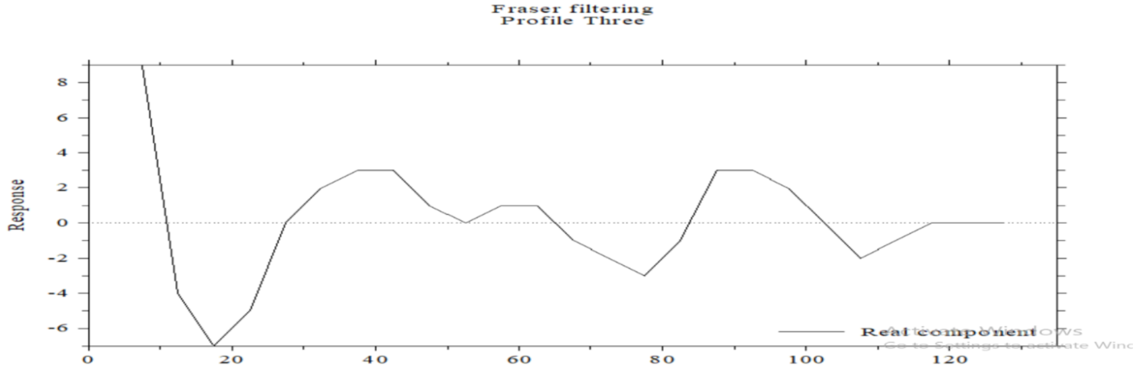


Fig.7 : Fraser Filtering of Profile 3

Distance (m)

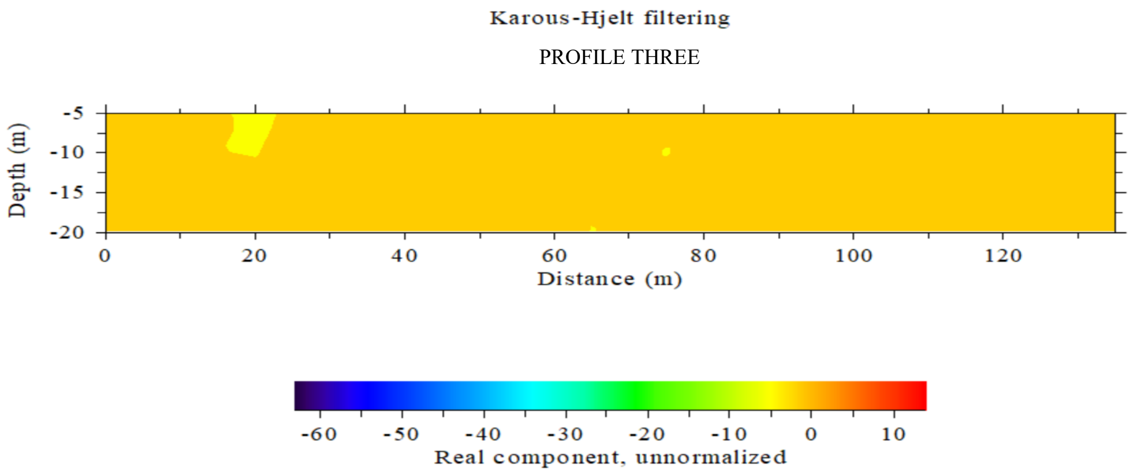
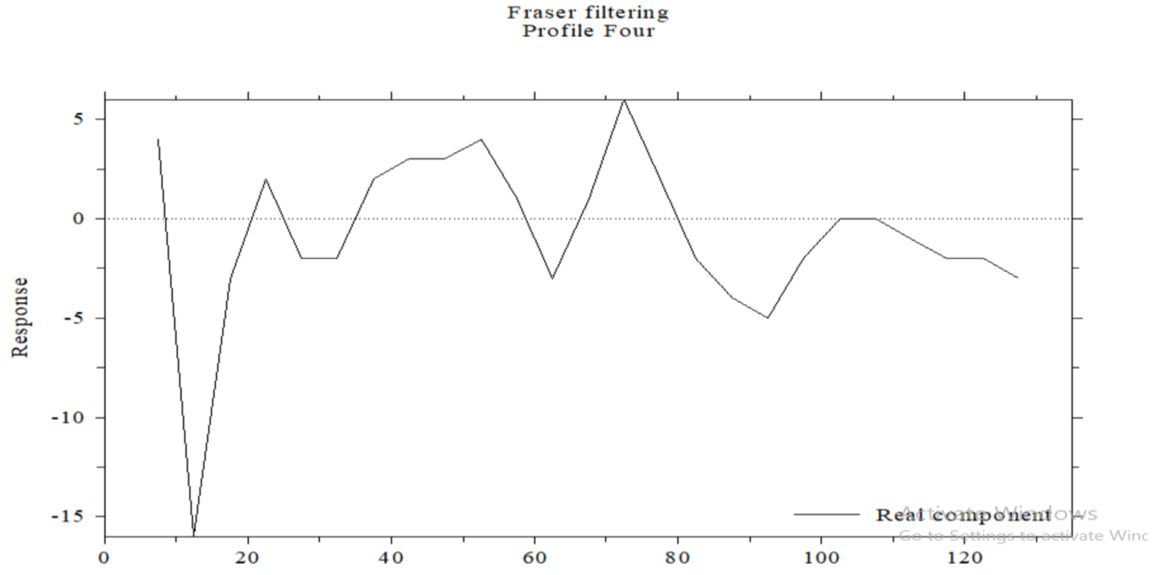


Fig. 8 : Fraser filter with K-H pseudo-section for profile 3

The Fraser-filtered response obtained along Profile 4 is presented in Fig. 9. Along Profile 4 indicates two (2) major conductive zones, occurring at approximately 28–40 m and 66–78 m along the profile. These zones are interpreted as fractured and weathered basement structures based on the combined in-phase, out-phase, and Karous–Hjelt pseudo-section responses. The conductive zones are associated with high current density anomalies and represent favorable groundwater pathways. In addition, one (1) non-conductive zone is identified around 90–102 m, characterized by low current density and dominant negative anomalies in both in-phase and out-phase components, suggesting shallow or competent basement rock with limited groundwater potential. The Karous–Hjelt pseudo-section corresponding to Profile 4 is illustrated in Fig. 10. Overall, Profile 4 exhibits a dominance of conductive features, indicating appreciable groundwater prospect.



Fig/ 9 : Fraser Filtering of Profile 4

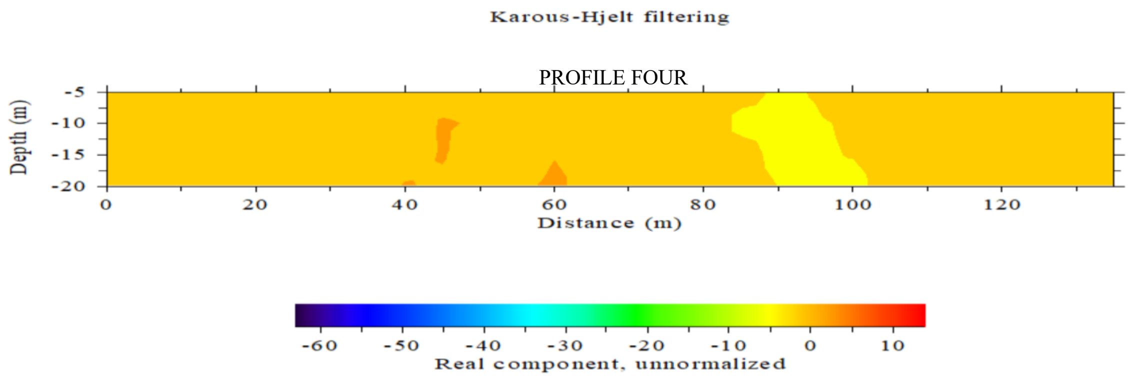
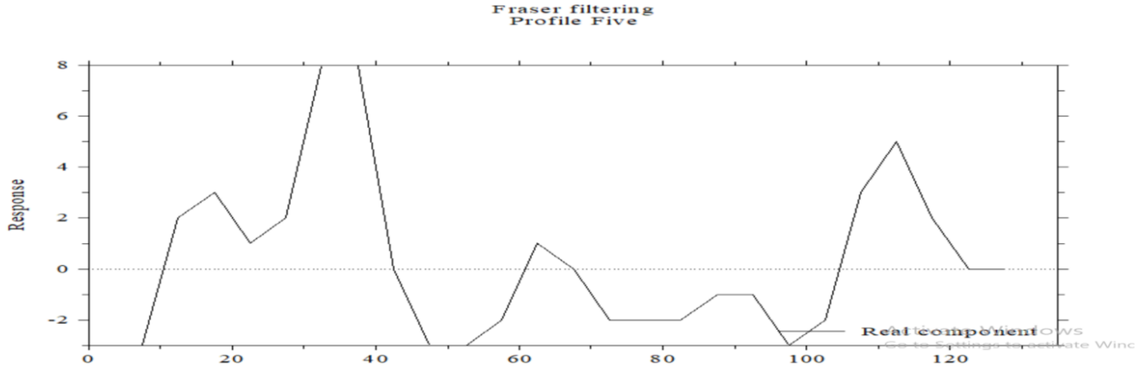


Fig. 10 : Fraser filter with K-H pseudo-section for profile 4

The Fraser-filtered anomaly for Profile 5 is shown in Fig. 11. Profile 5 reveals one (1) major conductive zone, occurring at approximately 44–56 m along the profile. This zone is identified by a positive in-phase peak and a corresponding low negative out-of-phase response, which is confirmed by a high current density anomaly on the Karous–Hjelt pseudo-section. The conductive zone is interpreted as a fractured basement structure capable of storing and transmitting groundwater. In contrast, two (2) non-conductive zones are identified . The corresponding Karous–Hjelt pseudo-section confirming the conductive structure is presented in Fig. 12.



Fig/11: Fraser Filtering of Profile 5

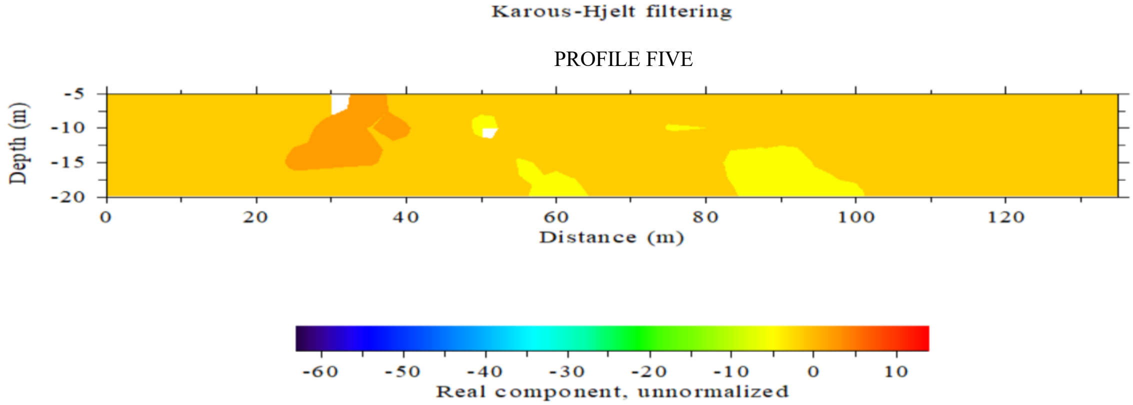


Fig. 12: Fraser filter with K-H pseudo-section for profile 5

around 10–22 m and 78–92 m, characterized by low current density and interpreted as resistive or low water-bearing formations. The presence of more non-conductive zones suggests that groundwater potential along Profile 5 is moderate when compared with other profiles.

Comparison across all profiles shows that Profiles 1–3 have the highest groundwater potential due to the dominance of multiple conductive zones, whereas Profile 5 exhibits comparatively lower potential, as indicated by the presence of more non-conductive zones. This variability highlights the importance of targeted borehole placement guided by VLF-EM survey results

Across the five profiles investigated, a total of twelve conductive zones and four non-conductive zones were identified. The conductive zones are spatially distributed across all profiles, suggesting that groundwater occurrence within Alhudahuda College, Zaria, is structurally controlled. Fractures and weathered zones serve as the main groundwater-bearing units, whereas non-conductive zones correspond to shallow or competent basement rock with limited water storage. The identified conductive zones constitute favorable targets for borehole siting, supporting effective groundwater development in the area.

4.0 Conclusion

The VLF-EM investigation of Alhudahuda College, Zaria, successfully delineated a total of twelve conductive zones associated with fractures and weathered basement rocks, highlighting areas with high groundwater potential. The application of Fraser and Karous–Hjelt filtering techniques enhanced the clarity and resolution of the VLF-EM data, allowing precise identification of conductive zones corresponding to water-bearing fractures and weathered basement materials. The study demonstrates that the VLF-EM method is an effective, rapid, and cost-efficient reconnaissance tool for groundwater exploration in basement complex terrains, particularly for guiding borehole siting and reducing exploratory drilling costs. The identified conductive zones are recommended as priority targets for borehole development to enhance water supply reliability at Alhudahuda College. Further hydrogeological investigations, such as pumping tests, are suggested to confirm aquifer yield and sustainability before large-scale development.

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Declaration

Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data public

Conflict of Interest

The authors declared no conflict of interest

Ethical Considerations

Not applicable

Competing interest

The authors report no conflict or competing interest

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Authors' Contribution

Umar Mahmood conceived the study, conducted field data acquisition, analysis, and manuscript drafting. Ahmed Zubairu and Abdullahi Abdullahi Bala contributed to methodology development and data processing. Usman Ahmed Kehinde supervised interpretation and provided technical guidance. Bala Balarabe assisted in data validation and literature review, while Abdulazeez Idris supported result interpretation, manuscript revision, and final proofreading.