

Application of Electrical Resistivity Method for Aquifer Characterization in the Crystalline Basement Complex of Kaduna North Lga, Kaduna State, Nigeria

Ingoroko T.S^{1*}, Adie D.B² and Sani B.S²

¹Department of Groundwater, National Water Resources Institute, Kaduna, Nigeria

²Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Nigeria

*Corresponding Author

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ABSTRACT

The exploitation of groundwater requires an understanding of the hydrogeological characteristics of subsurface aquifers within basement terrains. This study employed a geophysical investigation using the Vertical Electrical Sounding technique to determine subsurface geological formations and evaluate aquifer depth and thickness for groundwater potential. The survey involved injecting current into the ground through current electrodes using the Schlumberger array configuration. Sixteen VES stations were occupied, with electrode separation varying from 1 to 100 meters, to investigate geo-electrical characteristics. Field data were manually computed and processed using computer software. A Mc Ohm-EL resistivity meter was used for data acquisition, while IPI2Win software was applied for interpretation. Results revealed three to four geo-electric layers consisting of sandy or clayey topsoil, weathered basement, fractured basement, and fresh basement. Topsoil resistivity values ranged from 0.523 to 183 Ωm with thicknesses between 0.217 and 5.326 meters. Aquifer resistivity values ranged from 14.4 to 5182 Ωm , with an average thickness of 15.435 meters. Fractured layers showed resistivities between 18.04 and 7222 Ωm at depths of 1.48 to 32.3 meters, while fresh bedrock resistivities ranged from 58.52 to 9412 Ωm . Borehole locations identified at VES stations 6, 12, and 14, and compliance with recommended depths was advised.

Keywords: Aquifer characterization, Basement complex, Vertical Electrical Sounding (VES), Groundwater exploration, and Kaduna North LGA

INTRODUCTION

Groundwater development in crystalline basement terrains is inherently challenging due to low primary porosity and pronounced subsurface heterogeneity (Freeze and Cherry, 1979; Carruthers and Smith, 1992). Low primary porosity and significant subsurface variability make groundwater development in crystalline basement terrains intrinsically difficult (Freeze and Cherry, 1979; Carruthers and Smith, 1992). In these environments, secondary porosity formed in weathered regolith and fractured bedrock zones is the main factor controlling groundwater occurrence (Akanmu and Adewumi, 2016). Therefore, subsurface study methods that can resolve differences in lithology, weathering severity, and structural features are necessary for effective aquifer characterisation. Because electrical resistivity techniques are sensitive to subsurface characteristics including moisture content, porosity, and clay composition, they are commonly regarded as trustworthy instruments for groundwater investigation in basement terrains (Ishola and Bukar, 2024).

In Nigeria, rapid population growth, urbanization, and the inadequacy of surface water supply systems have increased dependence on groundwater resources, particularly within basement complex regions (MacDonald *et al.*, 2012). Recent electrical resistivity investigations across various Nigerian crystalline basement and related terrains continue to demonstrate the method's effectiveness for delineating aquifer zones and assessing

groundwater potential (Alhaji *et al.*, 2023; Olaseni and Nmoka (2025)). Northern Nigeria is largely underlain by Precambrian crystalline rocks, where groundwater potential is often localized, discontinuous, and difficult to predict (Offodile, 2002). Insufficient understanding of subsurface hydrogeological conditions in these terrains has frequently resulted in low borehole success rates and variable well yields, underscoring the need for detailed geophysical investigations prior to groundwater development (Olorunfemi and Fasuyi, 1993).

Kaduna North Local Government Area (LGA), situated within Kaduna State, lies entirely within the crystalline basement complex and is experiencing increasing water demand driven by urban expansion and socio-economic activities. Low porosity and almost nonexistent permeability are intrinsic characteristics of these rocks. In basement terrains, locations with heavy overburden covering cracked zones provide the maximum groundwater production. Relatively low resistivity values are a common characteristic of these zones. (Olorunfemi and Fasuyi, 1993). In hydrogeological research pertaining to aquifer delineation, lithologic boundaries, and geological structures to offer subsurface information, the electrical resistivity survey is most likely to be used (Bose *et al.*, 1973). However, groundwater can be found in the unweathered rocks' joints and fractured system or in the weathered mantle (Olorunfemi and Olorunniwo, 1985; Ako and Olorunfemi, 1989; Olayinka and Olorunfemi, 1992).

Comprehensive hydrogeophysical studies aimed at delineating aquifer geometry, depth, and groundwater potential within the area remain limited. Consequently, groundwater development has often relied on inadequate subsurface information, increasing the risk of borehole failure and inefficient resource exploitation. Electrical resistivity techniques, particularly vertical electrical sounding (VES), provide a cost-effective and non-invasive approach for identifying weathered and fractured zones that constitute productive aquifers in basement terrains (Sharma, 1997). Proper interpretation of resistivity data enables delineation of subsurface lithological units, estimation of aquifer thickness, and identification of groundwater potential zones. In order to evaluate the hydrogeologic characteristics and quality of the groundwater in the shallow weathered basement aquifers, a greater volume of electrical resistivity (vertical electrical sounding, or VES) and physicochemical data were collected throughout the entire Local Government Area. In parts of the world where basement rock is found, weathered basement aquifers are crucial sources of drinkable groundwater (Macdonald *et al.*, 2005; Bayowa *et al.*, 2023b).

METHODS

Materials

The field data was collected using a Mc Ohm-EL terrameter that was powered by a 12V battery. This device calculates and shows the subsurface resistance averaged over a certain number of cycles (four cycles for the purposes of this investigation). Metal electrodes, measuring tape, labeled tags (used to locate station positions), hammers (used to drive the electrodes into the ground), compass, connecting cables/wires, plugs, and clips are some more tools that are utilized. Each station's angular coordinates and height were calculated using a Global Positioning System (GPS).

Methods

Project Area

Kaduna North Local Government Area is one of the 23 Local Government Areas of Kaduna State, Nigeria. It has geographical coordinates of 10°35'0" north and 7°25'0" east. The Local Government consists of the following wards: Hayin Banki, Kawo, Unguwan Dosa, Badarawa, Unguwar Shanu, Unguwar Sarki, Unguwar Rimi, Maiburji, Shaba, Kabala, Sardauna and Dadi Riba. The area has a mean monthly minimum and maximum temperatures of 15.9°C and 35.35°C with the annual mean of about 19.45°C, the highest temperatures are being recorded in December and January. The annual rainfall in the area is about 1530mm. The location of the study area is shown in Figure 1.

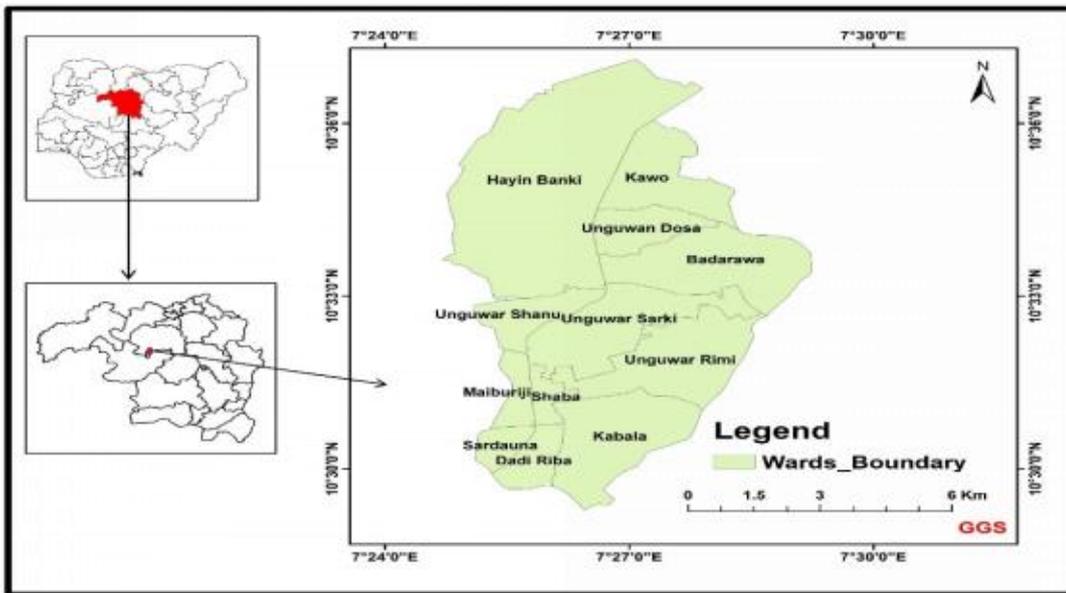


Figure 1: Location Map of the Study Area

The area of study lies within the tropical Savanna climate with distinct dry and wet seasons. The dry season occurs between October and April. There is a severe harmattan in December and January. This is the period when the north-east Trade winds begin to blow southwards into the country from the Sahara belt. At this period, it is generally cooler than normal and less humid, and visibility at certain times is restricted as a result of airborne dust. Vegetation in the area is of typical Sudan Savannah, characterized by sparse shrub and interrupted by large isolated trees. There is more continuous cover of grasses. Mean annual evaporation for the area ranges between 1110 – 1280mm.

Kaduna State is totally underlain by a basement complex of igneous and metamorphic rocks of mainly Jurassic to Precambrian ages. The basement complex rocks are basically granite, gneisses, migmatites, schists and quartzites. The geology of Kaduna North is mainly metamorphic rocks of the migmatite and biotite gneiss. The topographical relief is relatively flat with an elevation of 600 to 650 meters in large regions of the study area. It is over 650 meters above mean sea level in some places and below 500 meters in places that slope down wards towards the river. Groundwater occurrence in the basement complex as well as in the study area depends on the degree of development of fractures and weathered overburden. Figure 2 presents the hydrogeological map of Kaduna North LGA, illustrating the spatial distribution of water bodies, drainage patterns, and geology. Due to differential weathering, the basins of groundwater are habitually localized such that it becomes necessary for a geophysical investigation to locate the most appropriate point is carried out prior to drilling in order to avoid drilling abortive wells.

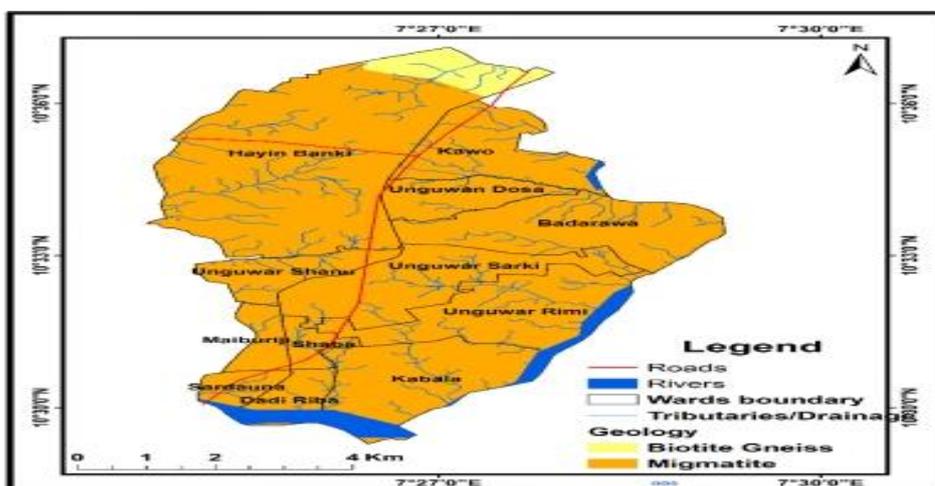


Figure 2: Hydrogeological Map of the study area

Geoelectrical Investigation

This study made use of the Electrical Resistivity Method's Vertical Electrical Sounding (VES) approach. With respect to an immovable center of the array, it measures the vertical variations in ground apparent resistivities. By applying current to the ground at the current electrodes and measuring the resulting potential difference at the potential electrodes, the resistivity of the ground can be determined. The apparent resistivity of the ground is then calculated by multiplying the recorded potential difference by a suitable geometric factor. The degree of saturation also affects the resistivity of rocks, and interconnected pores efficiently contribute to conductivity. Furthermore, because the fluid's viscosity reduces as temperature rises, the electrolyte's resistance tends to increase. Given that groundwater conditions fluctuate from one geo-electric section to another and that there are wide differences in the electrical resistivity values of various rocks and minerals, the electrical resistivity approach is extremely beneficial [10].

According to the depth and thickness of underlying strata as well as the thickness of the overburden, apparent resistivity values derived from measured potential differences can be understood [11]. To examine the nature and traits of the aquifer beneath the research region, the process was repeated. The change in resistivity with depth was investigated using the Schlumberger Electrode array. There were sixteen VES stations in use, with electrode separations (AB/2) ranging from one to one hundred meters.

Data Presentation

The apparent resistivity (ρ_a), on the y-axis, and the half current electrode spacing (AB/2), on the x-axis, were plotted on bi-log paper to create the VES curves that represented the apparent resistivity data from the VES survey. Based on combinations of layer resistivity, the resistivity VES curves were categorized.

Data Interpretation

Quantitative Interpretation: By using the partial curve matching technique developed by [8], the quantitative interpretation of the VES curves was carried out to ascertain the depth to new basement bedrock. The underlying layers, their matching resistivities, and thicknesses were shown by the geoelectric stations built using the interpretation results of the VES curves.

Qualitative Interpretation: Lithologic logs, when accessible, can help with lithological identification [12]. The VES curves were interpreted in terms of lithologies as a result of this classification or grouping of VES curves according to different geo-electric properties and calculation of the proportion of each category.

Hydrogeochemical Investigation

RESULTS AND DISCUSSION

Geoelectrical Investigation

Sixteen (16) Vertical Electrical Sounding (VES) points were selected and surveyed using schlumberger array. Schlumberger array was used to survey sixteen (16) Vertical Electrical Sounding (VES) points that were chosen. The results of the VES curves are presented in Figure 3 to 18 as digitized curves.

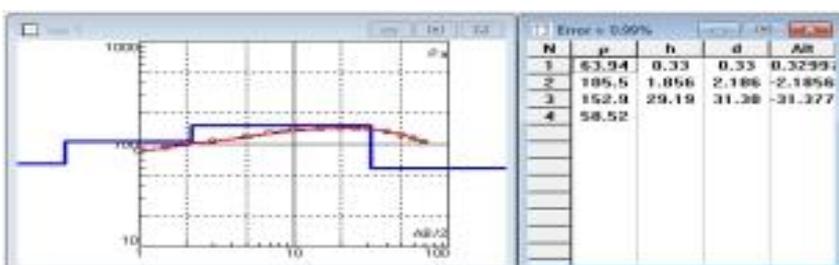


Figure 3: VES curve at NAF Area, Mando

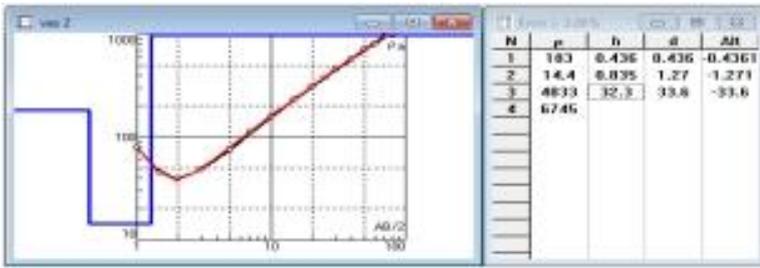


Figure 4: VES curve at Barkallahu, Rigachikun

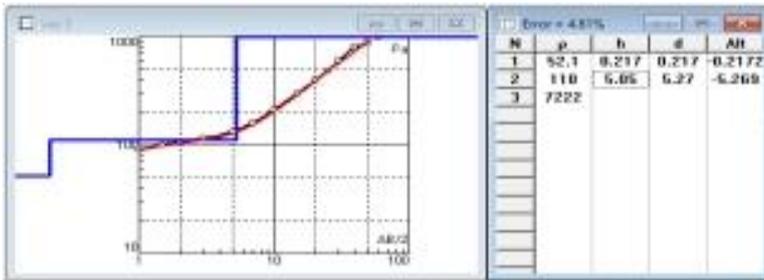


Figure 5: VES curve at NDC Area, Zaria Road

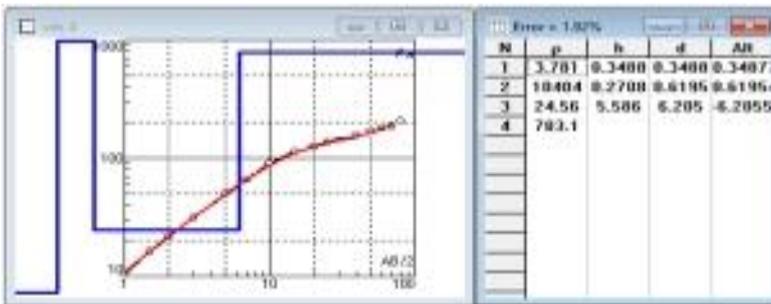


Figure 6: VES curve at Police quarters, Kawo

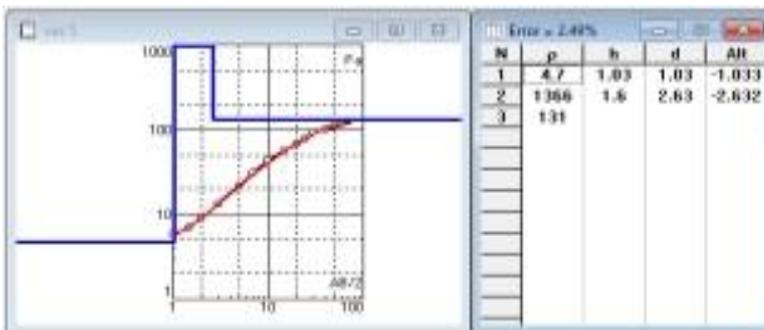


Figure 7: VES curve at NAF Area, Kawo Flyover

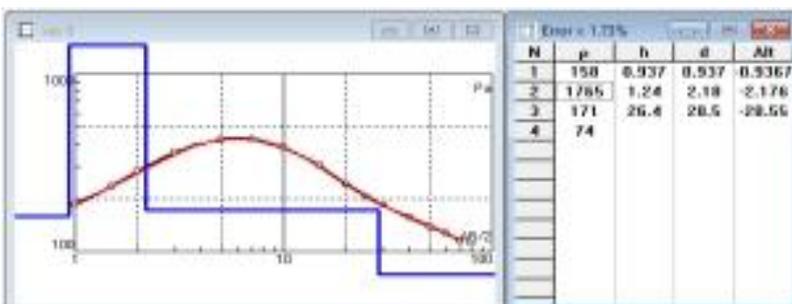


Figure 8: VES curve at NASFAT village, Hayin Banki

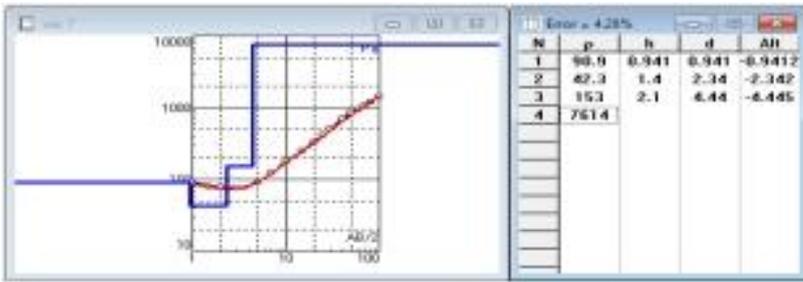


Figure 9: VES curve at NDA Area, Express way

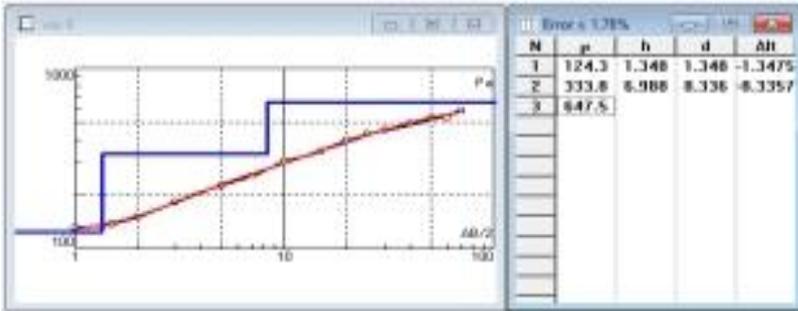


Figure 10: VES curve at NDA Area, Ali Akilu Road

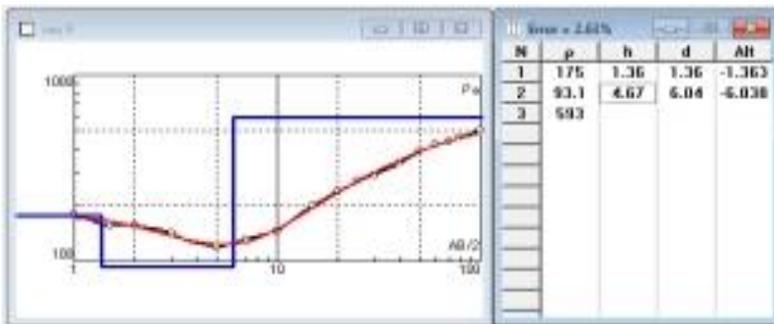


Figure 11: VES curve at SMC, Ungwar Dosa

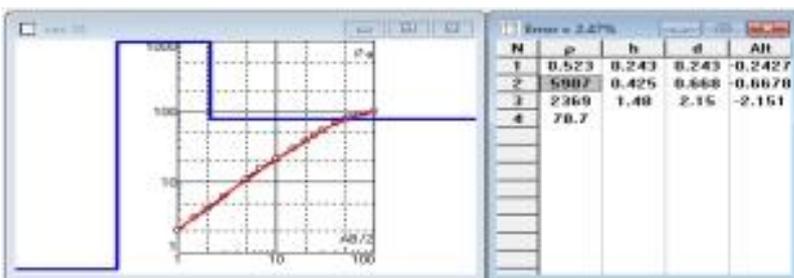


Figure 12: VES curve at Capital school, Ungwar Sarki

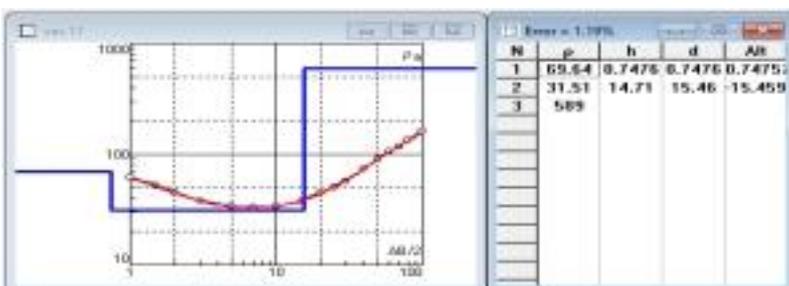


Figure 13: VES curve at Ungwar Yero, Badarawa Abakpa

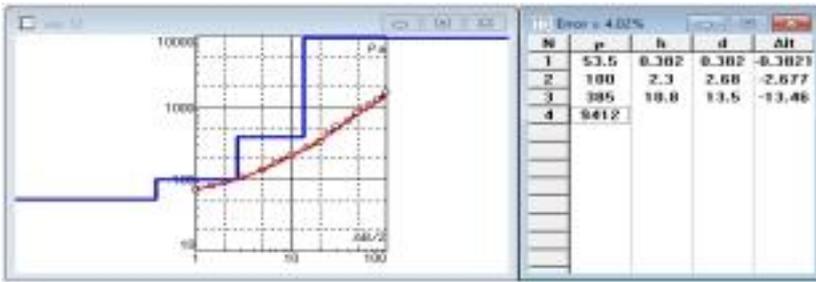


Figure 14: VES curve at KADRUWASSA Area, Ungwar Shanu

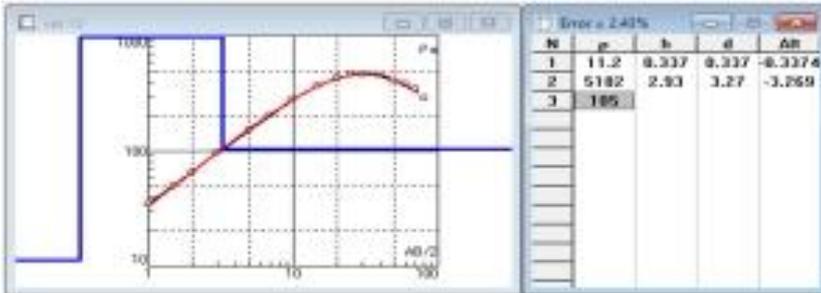


Figure 15: VES curve at Central mosque Area,

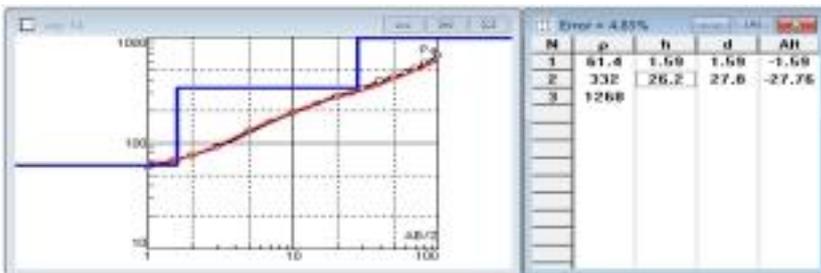


Figure 16: VES curve at Rimi College, Ungwar Ungwar Sarki Rimi

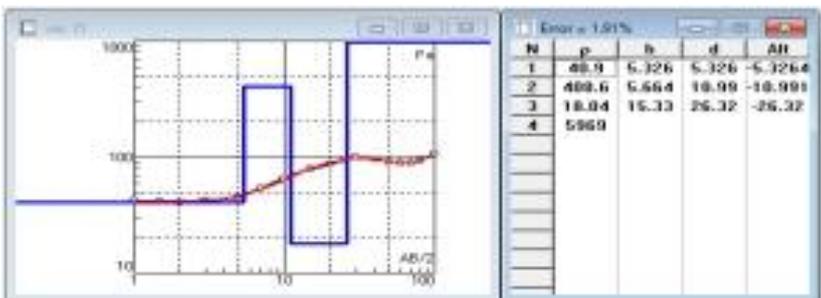


Figure 17: VES curve at Kigo road extension, Dadi Riba

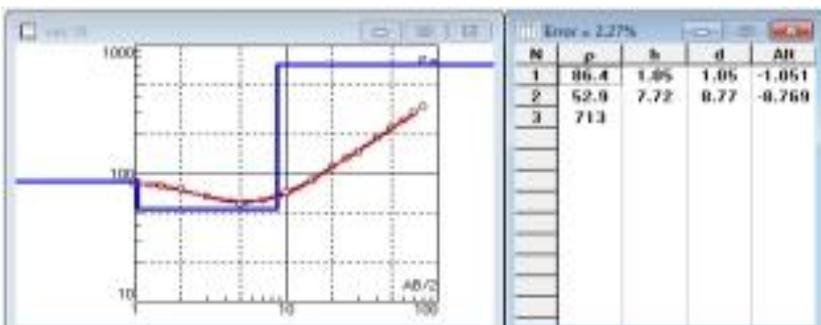


Figure 18: VES curve at Jaafaru estate, Costan Kabala

The result of the geo-electric interpretation and their inferred lithology is summarized in Table 1. The result of the interpretation revealed three to five geo-electric layers overlying a conductive geo-electric basement. The geo-electric layers are: Underlying the top soil (0.523 – 183 meters), the weathered layer (14.4 – 10404 meters), which is made up of sandy clay/sand/laterite, is the fractured basement (18.04 – 7222 meters), and the new basement (58.52 – 9412 meters). The large construction debris and waste that were strewn about this VES station may have had an impact on the high velocity that was recorded in VES 4. The fact that almost 70% of the resistivities are below 600 meters suggests a fractured formation with significant potential for groundwater storage. The remaining 30% measured high bedrock resistivity values indicative of potentially huge crystalline granitic rock with a little amount of fracture. It can be seen that the overburden material is made up of loose materials and ranges in thickness from 2.15 to 33.6 meters. Weathered layer and fractured zone thicknesses range from 0.425 to 26.2 meters and 1.48 to 32.3 meters, respectively while that of the fresh basement is in the range of 2.15 meters – ∞.

Hydrogeochemical Investigation

Table 1: Geo-electric interpretation and their inferred lithology

VES No.	Location	Coordinates	No of layers	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Inferred Lithology	Curve type	Curve characteristics	Longitudinal Conductance (S) (mhos)	Overburden thickness, Aquifer layer and thickness
1	NAF Area, Mando	10.60396 7.429226	1	63.94	0.33	0	Sandy Clay	AK	$\rho_1 < \rho_2 < \rho_3 > \rho_4$	0.20	31.38 meters, 3 rd & 4 th layer and ∞
			2	105.5	1.856	0.33	Weathered basement				
			3	152.9	29.19	2.186	Fractured basement				
			4	58.52	∞	31.38	Sandy Sand				
2	Barkallah u, Rigachikun	10.60505 7.452581	1	183	0.436	0	Fractured basement	HA	$\rho_1 > \rho_2 < \rho_3 < \rho_4$	0.06	33.6 meters, 2 nd & 3 rd layer and 33.13m
			2	14.4	0.835	0.436	Clay				
			3	4833	32.3	1.27	Fresh basement				
			4	6745	∞	33.6	Fresh basement				
3	NDC Area, Zaria Road	10.60903 7.455157	1	52.1	0.217	0	Sandy clay	A	$\rho_1 < \rho_2 < \rho_3$	0.10	5.27 meters, 2 nd layer and 5.05
			2	110	5.05	0.217	Weathered basement				
			3	7222	∞	5.27	Fresh basement				
4	Police quarters, Kawo	10.58431 7.454554	1	3.781	0.3488	0	Clay topsoil	KH	$\rho_1 < \rho_2 > \rho_3 < \rho_4$	1.50	6.21 meters, 4 th layer and ∞
			2	10404	0.2708	0.3488	Fresh basement				
			3	24.56	5.586	0.619	Sandy clay				
			4	783.1	∞	5	Fresh				

						6.205	basement				
5	NAF Area, Kawo Flyover	10.58838	1	4.7	1.03	0	Clay topsoil			0.24	2.63 meters, 3 rd layer and ∞
		7.445815	2	1366	1.6	1.03	Fresh basement	K	$\rho_1 < \rho_2 > \rho_3$		
			3	131	∞	2.63	Weathered basement				
6	NASFAT village, Hayin Banki	10.58416	1	158	0.937	0	Fractured basement	KQ	$\rho_1 < \rho_2 > \rho_3 > \rho_4$	0.19	28.57 meters, 3 rd & 4 th layer and ∞
		7.419275	2	1765	1.24	0.937	Fresh basement				
			3	171	26.4	2.177	Fractured basement				
			4	74	∞	28.577	Sandy clay				
7	NDA Area, Express way	10.56833	1	90.9	0.941	0	Sandy clay	HA	$\rho_1 > \rho_2 < \rho_3 < \rho_4$	0.08	4.44 meters, 3 rd layer and 2.1m
		7.417222	2	42.3	1.4	0.941	Sandy clay				
			3	153	2.1	2.341	fractured basement				
			4	7614	∞	4.441	Fresh basement				
8	NDA Area, Ali Akilu Road	10.57373	1	124.3	1.348	0	Weathered basement	A	$\rho_1 < \rho_2 < \rho_3$	0.03	8.33 meters, 3 rd layer and ∞
		7.440664	2	333.8	6.988	1.348	Fractured basement				
			3	647.5	∞	8.336	Fresh basement				
9	SMC, Ungwar Dosa	10.57333	1	175	1.36	0	Fractured basement	H	$\rho_1 > \rho_2 < \rho_3$	0.07	6.03 meters, 2 nd & 3 rd layer and ∞
		7.449444	2	93.1	4.67	1.36	Sandy clay				
			3	593	∞	6.03	Fresh basement				
10	Capital school, Ungwar Sarki	10.56094	1	0.523	0.243	0	Clay topsoil	KQ	$\rho_1 < \rho_2 > \rho_3 > \rho_4$	0.47	2.15 meters, 3 rd & 4 th layer and ∞
		7.458474	2	5907	0.425	0.243	Fresh basement				
			3	2369	1.48	0.668	Fresh basement				
			4	78.7	∞	2.15	Sandy clay				
11	Ungwar Yero, Badarawa	10.54948	1	69.64	0.7476	0	Sandy clay	H	$\rho_1 > \rho_2 < \rho_3$	0.47	15.46 meters, 3 rd layer and ∞
		7.48003	2	31.51	14.71	0.7476	Sandy clay				
							Fresh				

		3	3	589	∞	15.46	basement				
12	KADRU WASSA Area, Abakpa Ungwar Shanu	10.54526 7.424854	1 2 3 4	53.5 100 385 9412	0.382 2.3 10.8 ∞	0 0.382 2.682 13.482	Sandy clay Weathered basement Fractured basement Fresh basement	AA	$\rho_1 < \rho_2 < \rho_3 < \rho_4$	0.36	13.48 meters, 3 rd layer and 10.8m
13	Central mosque Area, Ungwar Sarki	10.53546 7.441438	1 2 3	11.2 5182 105	0.337 2.93 ∞	0 0.337 3.27	Clay topsoil Fresh basement Weathered basement	K	$\rho_1 < \rho_2 > \rho_3$	0.03	3.27 meters, 2 nd & 3 rd layer and ∞
14	Rimi college, Ungwar Rimi	10.52551 7.465107	1 2 3	614 332 1268	1.59 26.2 ∞	0 1.59 27.79	Fresh basement Fractured basement Fresh basement	H	$\rho_1 > \rho_2 < \rho_3$	0.08	27.79 meters, 2 nd layer and 26.2m
15	Kigo road extension, Dadi Riba	10.50259 7.429226	1 2 3 4	40.9 408.6 18.04 5969	5.326 5.664 15.33 ∞	0 5.326 10.99 26.32	Sandy clay Fractured basement Clay Fresh basement	KH	$\rho_1 < \rho_2 > \rho_3 < \rho_4$	0.89	26.32 meters, 3 rd layer and 15.33m
16	Jaafaru estate, Costan Kabala	10.50333 7.437574	1 2 3	86.4 52.9 713	1.05 7.72 ∞	0 1.05 8.77	Sandy clay Sandy clay Fractured basement	H	$\rho_1 > \rho_2 < \rho_3$	0.15	8.77 meters, 3 rd layer and ∞

The location map showing VES positions is shown in Figure 19. The curves types obtained in the study area after partial curve matching were H (VES nine, eleven, fourteen and sixteen), K (VES five and thirteen), A (VES three and eight), HA (VES two and seven), KH (four and fifteen), KQ (VES six and ten), AK (VES one) and AA (VES twelve). The curves types were analyzed as presented in Figure 20. The 3 layer curves constitute 50 % of all the curves while the 4 –layer curves constitute 50 % respectively. This is consistent with the research done by [13] who used the resistivity method to explore the groundwater resources of Rafin Guza area of Kaduna, Nigeria and discovered that the area had significant potential for groundwater.

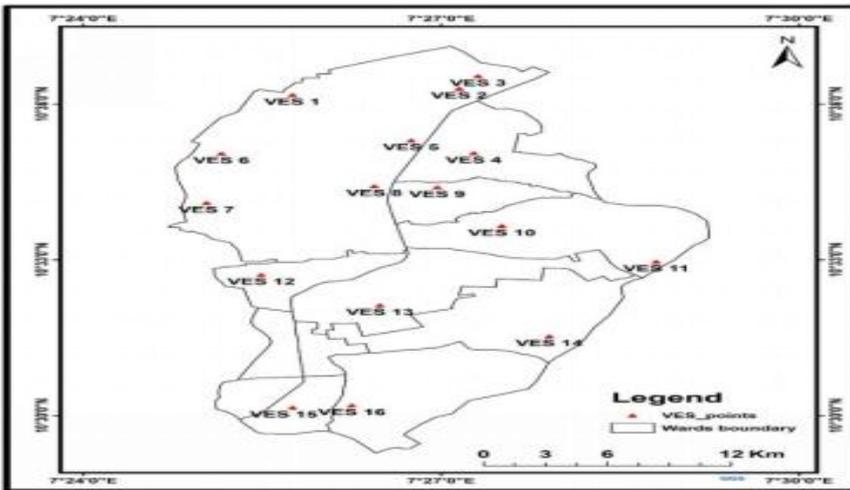


Figure 19: Location Map of the Study Area showing VES points

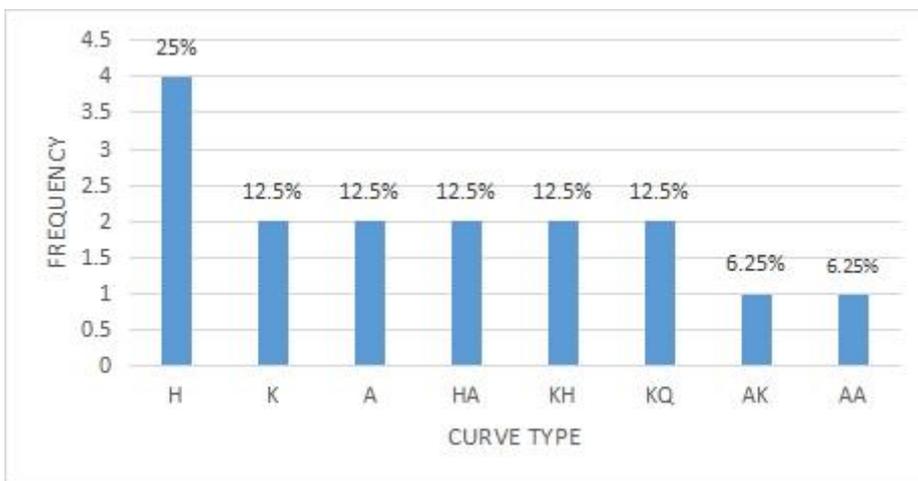


Figure 20: Bar chart of Curve types

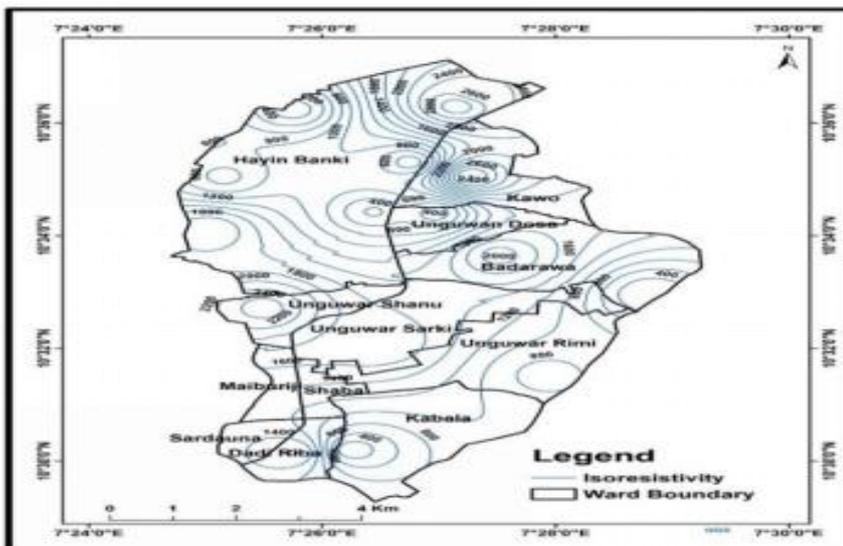


Figure 21: Isoresistivity map of the study area for $AB/2 = 200$

The Isoresistivity map in Figure 21 reveals the contours that link points of equal apparent resistivity. Isopach map which is another technique used to create a continuous picture of the subsurface from discrete sampling site was generated for the resistivity data as shown in Figure 22. Geologic material can be mapped using the isopach method based on how thick it appears to be. By determining the thickness of the unit in wells or at

exposures on the land surface and extrapolating the thickness between the known places, the thickness of a geologic unit (or a water-bearing unit) can be contoured throughout an area.

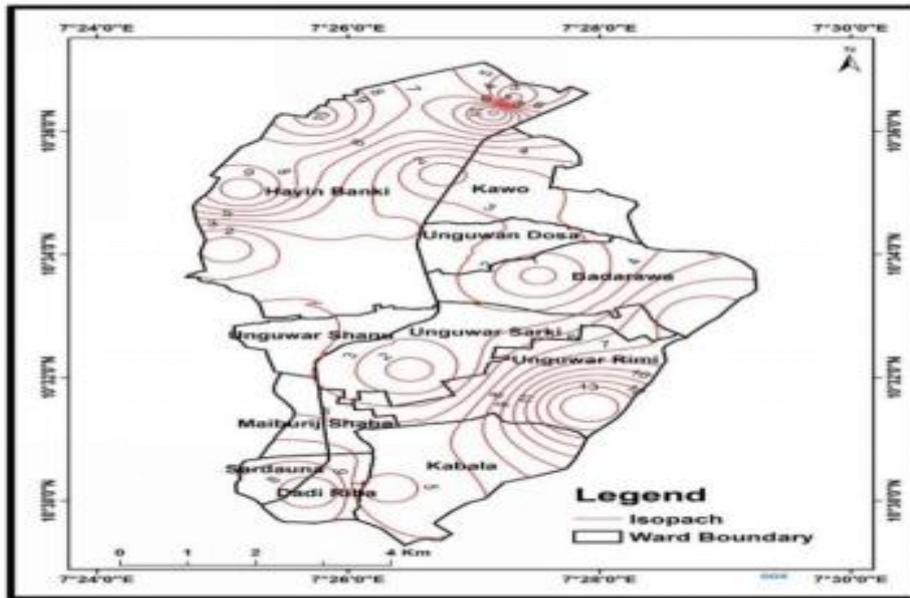


Figure 22: Isopach map of the study area

The limitation of the study include spatial coverage and seasonal variation (wet verses dry) which affects saturation, resistivity and water levels. The implication of the study for the area revealed that the preferred areas to site boreholes with maximum yield are areas with thick weathered or saturated overburden and major lineaments or fractures. Whereas drilling boreholes in clayey overburden or non-fractured basement stand the risk of failure as the study has recommended drilling depths to predict yield of wells in the area [14]. Finally, it was discovered that practically all of the VES points—mainly VES 6, VES 12, and VES 14—are probable locations for groundwater development utilizing the resistivities and the VES curves. Since percentages of error greater than five are typically the result of human and experimental error, the RMS error ranged from 0.99 to 4.83%.

CONCLUSION

The crystalline basement in Kaduna North hosts aquifers in the weathered overburden and fractured basement. Geophysical methods can demarcate layers which serve as a guide in siting productive borehole since some zones are promising while others are poor targets. In order to identify aquifer units and designate possible places for groundwater potential, a geo-electric analysis of an aquifer in Kaduna North LGA of Kaduna State, Nigeria, was carried out utilizing the VES curves and the resistivities. The principal prospective locations for groundwater development were determined to be VES 1, VES 2, VES 6, VES 11, VES 12, VES 14, and VES 15. The Research has also revealed significant variability in the distribution, extent, type, thickness and resistivity of the aquifers in the area. It was recommended that borehole should be properly designed with respect to depth, casing and screening in fractured zones and grouting to avoid influx of sand/clay leading to abortive wells; laws that will compel drillers in the study area to adhere to the suggested depths be enacted; and water level and yield of wells be monitored over time to detect decline in groundwater. Also, this research ought to be expanded to include other domains in order to provide the public and water managers with guidance on appropriate action plans.

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Author Contributions

T.S.: Conceptualization, investigation, funding acquisition, methodology, software, visualization, writing – original draft, writing – review and editing. D.B. and B.S.: conceptualization, project administration, resources, supervision, writing – review and editing.

Ethical Approval

This study involved human participants and was conducted in accordance with institutional and national ethical standards. Ethical approval was obtained from the appropriate Institutional Ethics Committee prior to the study. All participants provided written informed consent after being informed of the study's purpose and procedures. Participation was voluntary, and confidentiality and anonymity were strictly maintained.

Conflict of Interest

All the authors declared no conflict of interest.

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