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APPLICATION OF PRIMARY AND SECONDARY RESISTIVITY PARAMETERS IN EVALUATING AQUIFER POTENTIAL AND VULNERABILITY WITHIN KABBA, NORTH CENTRAL NIGERIA

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ABSTRACT

The study area depends on groundwater as a major source of potable and healthy water supply. However, its occurrence and quality vary with low yield or abortive borehole drilled in some part. Therefore, there is need to properly investigate the geology and groundwater condition of the area using Vertical Electrical Sounding (VES) and Dar Zarrouk parameters. The different rock types identified are migmatite-gneiss, granite-gneiss, schist, and charnockite. Forty (40) VES was carried out which revealed five to four geo-electric layers. These are top soil, lateritic clay, confining weathered basement, weathered/fractured basement aquifers and fresh basement. The types of curves identified are HA and KQ. The average depth to groundwater is 55.00m, this indicate that borehole should be drilled within or above the average depth to avoid later drying of wells. The value of aquifer resistivity and thickness was used to calculate longitudinal conductance, transverse resistance, hydraulic conductivity and transmissivity. The longitudinal conductance varies from poor to good in protective capacity class and revealed that the groundwater is easily exposed to contamination. The aquifer resistivity, thickness with transverse resistance, hydraulic conductivity, and transmissivity were used to classified the groundwater into different zones. The groundwater potential within the study area varies from low to very good with most of the area having moderate potential zones distributed mainly within the migmatite gneiss and the schist. The study area has fractures that can produce water for domestic, agricultural and industrial purpose and the result can be used for proper management of groundwater resources.

Keywords: Basement Aquifer, Potential, Vulnerability, Kabba, North Central Nigeria

INTRODUCTION

Kabba is one of the fast-growing towns in Kogi State owing to already existing University of Agriculture and the newly created State-owned University. This led to rural-urban migration which brings increment in the population thereby deteriorating the available surface water in the area. The major source of water supply in the study area are surface water, rain water and groundwater. The surface water is contaminated as mentioned above and the rain water is usually seasoner making groundwater the most reliable source of providing potable water to inhabitant of the area. However, low yield and abortive boreholes has been reported to be drilled in some part of the study area which is due to lack of detail geological and geophysical knowledge. This indicates the variation in distribution of groundwater in the area. This formed the basis on which this research is carried out.

Water availability has become a natural phenomenon that is of concern globally, because it is one of the indispensable and fundamental resources that sustains the livelihood of humans and animals within an environment. Water exists as groundwater (such as wells, and boreholes) and surface water (such as springs, lakes, and rivers). However, groundwater has been reported to be the major source of providing potable, uncontaminated and healthy water supply used for domestic, agricultural and industrial purposes (Obasi et al., 2022; Kizito et al., 2023b; Obaje et al., 2023). Exploration of groundwater within areas underlain by the basement rock is often difficult to carry out especially when the potential aquifer areas for groundwater are associated with fissures and fractures. As a result, the reservoir capacity of fractured crystalline basement rocks is limited, and the conductivity and transmissivity of groundwater take place along cracks and planar breaks (Adeniji et al., 2022; Simon et al., 2022; Kizito et al. 2023a). The occurrence of groundwater in basement complex is usually in closely spaced cracks and other fracture patterns characterized by large openings generated by the effect of tectonism and other related geological events. The sizes and connectivity of these fractures and fissures determines the volume of water within the basement complex.

Adeniji et al. (2020) stated that the study of groundwater is extremely important because it has a great impact on a healthy and favorably quality of life. Groundwater is naturally guarded against migrating contaminants by existing subsurface structures, but in an environment where there is thin overburden; groundwater could be easily endangered by leachate contamination (Qishlaqi et al. (2018). Ebokaiwe et al. (2018) and Obasi et al. (2022) indicate that there are contaminants in surface waters, which may as well infiltrate into the groundwater system if the overlying geological materials permit their smooth transmission. Daud et al. (2017) reported that leachate is generated from landfill sites and contains high levels of contaminants and is hazardous to our ecosystems and indirectly to groundwater.

Geophysical techniques have been used to resolve various exploration problems due to its ability to penetrate subsurface to a greater depth (Falae 2014, Oladunjoye et al., 2019; Mahmud et al., 2023). These methods include: Electrical resistivity Imaging, Ground penetration radar, Seismic, Electromagnetic, and magnetic. Electrical resistivity Imaging is the most used geophysical method for groundwater investigations due to its high capacity to determine hydrogeological properties like porosity, permeability, and conductivity (Helaly, 2017; Falae et al., 2019; Kizito et al., 2023a; Akpah et al., 2023). Hydraulic and electrical conductivities are physical parameters and lithological attributes that control the electric current and conduction as well as the fluid flow, hence, they are dependent on each other (George et al., 2015; Ogundana and Falae, 2023). Based on these principle, electrical resistivity technique is useful in accessing the hydrological condition of the subsurface and its aquifer protective capacity (Adeeko et al., 2019; Ogundana and Falae, 2023).

The application of Dar Zarrouk Parameters from secondary electrical resistivity data for evaluation of aquifer protective capacity or aquifer vulnerability has been carried out by Various researchers (Raji and Abdulkadir, 2020; Obasi et al., 2022; Adeniji et al., 2022; Simon et al., 2022; Kizito et al. 2023a; Ogundana and Falae, 2023). Within the study area, focus has been majorly on the study of the geology of the area (Kolawole et al., 2017; Bassey et al., 2021) which may be attributed to presence of Obajana Dangote cement company and the newly created Mangal cement and gold mineralization within the neighboring community. However, the study of groundwater potential and aquifer protective capacity is lacking. Therefore, the aim of this study is to use electrical resistivity method to investigate the groundwater potential and the protective capacity, thereby providing a comprehensive information that will serve as a guide for sustainable groundwater resources management within the study area.

Study Area Location and Geologic Setting

Kabba is one of the fast-growing towns in the western part of Kogi State, North-central Nigeria. It is situated in the basement complex of south-western Nigeria. The study area is bounded by latitude 7º 45` 00``N to 7º 52` 00``N and longitude 6º 00` 00``E to 6º 07` 36.67``E covering a total area of 75km2 (Figure 1). The study area is accessible through the major highway connecting Kabba-Okene and Kabba-Lokoja, minor roads and foot path. These make the study area accessible for the research purpose.

Geologically, the study area lies within the Nigerian basement complex which is one of the three major litho-petrological components that make up the geology of Nigeria. Gokii et al. (2010) noted that deformation of the basement appears to be in two phases, a ductile phase which is responsible for the formation of planar structures (foliations and lineations) and a brittle phase resulting in joints and fractures that have been filled with quartzo-feldspathic veins, pegmatite, aplite, and dolerite dykes. According to Kolawole et al. (2017), the area is underlain predominantly by migmatite-schist suite comprising migmatite gneiss, migmatite schist and a quartz-mica schist-quartzite complex in which quartzite occurs as elongated ridges. Bassey et al. (2021) added that, there are four major lithologic units in the study area which include; Migmatites, Granite-gneiss, Porphyritic Granite and Garnetiferous Schists. Minor rocks type include: pure quartzite, pegmatite, aplite and quartz veins. From this study as shown in Figure 1, the major rocks include; migmatite-gneiss, granite-gneiss, schist, and minor occurrence of charnockite. Structural features identified are foliations, lineations, folds, joints, fractures and faults. The structures observed on the rocks in are those formed due to compressional forces resulting in ductile structures and tensional forces resulting in brittle structures.

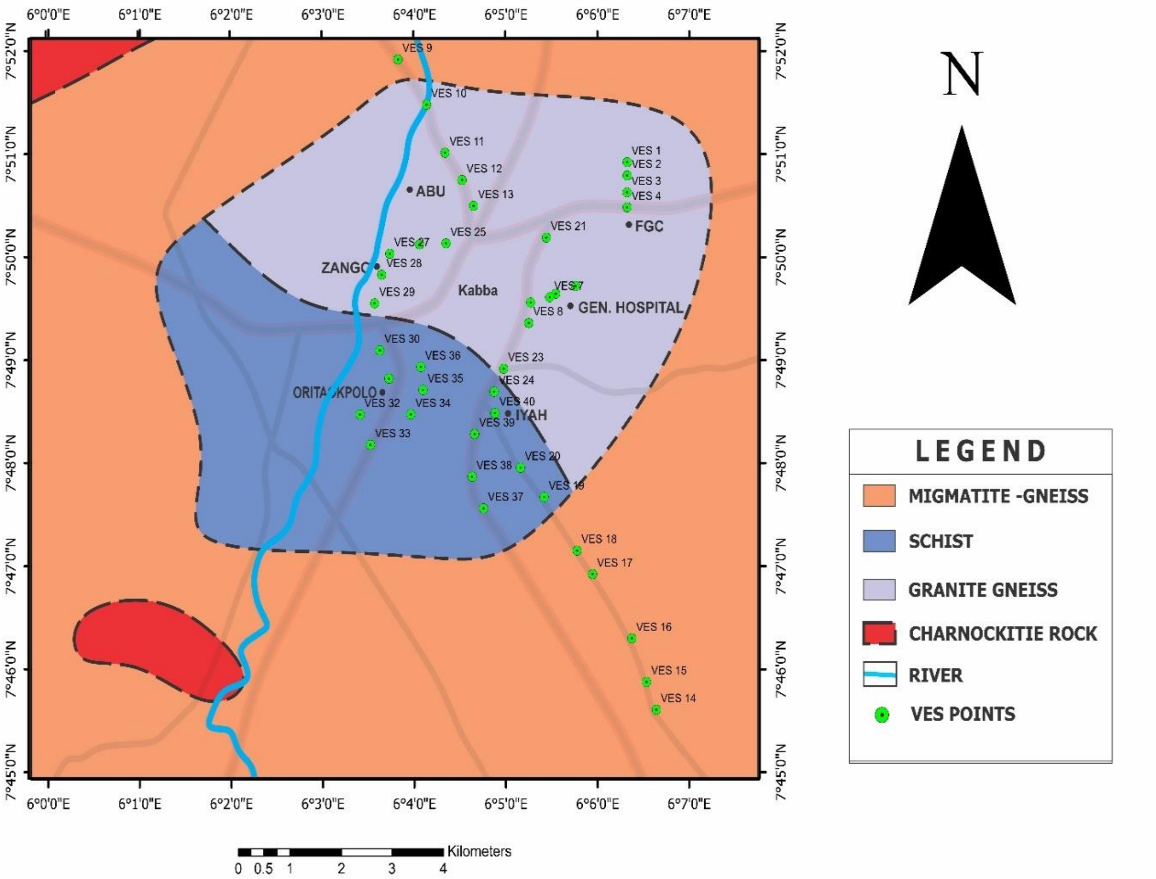

Figure 1: Geology Map of the study Area Showing VES Points

MATERIALS AND METHODS

The DDR-3 resistivity meter was applied in this study which is capable of measuring the subsurface resistivity variation at greater depth with high accuracy and precision. Other materials used are 2 pairs of current and potential electrodes, 2 pairs of reels cable, a Global Positioning System (GPS), a Direct Current Source (Dry Cell batteries), measuring tapes and survey data sheets. Vertical electrical sounding (VES) was carried out at forty (40) locations (see figure 1) so as to obtain detail information of subsurface resistivity variation across the different major rock types within the study area. Schlumberger electrode configuration was used. This array is a reliable method for delineating horizontal layers of rocks with adequate depth sensitivity. The depth that can be penetrated by resistivity survey is roughly 1/3 of the total current electrode distance (AB) (Maiti et al., 2011). The value of current electrode spacing (AB/2) ranges from 1m to 200m while the potential electrodes range from 0.5m to 15m. The field data were converted to apparent resistivity (ρa) in ohm-meter by multiplying the resistance value with Schlumberger geometric factor (k). The apparent resistivity (ρa) values versus AB/2 were plotted manually on a logarithmic sheet of paper to obtain the apparent field curves. The number of layers with their corresponding resistivity and depth obtained from the manual plotting through partial curve matching were incorporated into a computer program with the aid of a computer software WINRESIST version 1.0. The software helps in curve smoothening and enhancement and gives corresponding resistivity, thickness, and depth of various subsurface lithology called the geoelectric layers.

Aquifer resistivity and aquifer thickness are significant parameters that help in identifying the aquifer properties which are important factors in groundwater potential and vulnerability assessment. These parameters were used in deriving the secondary parameters described as Dar Zarrouk parameters. These include longitudinal conductance, transverse unit resistance, transmissivity and hydraulic conductivity. Longitudinal conductance (Lc) was calculated using Equation 1 as used by Akpan et al. (2015), Obasi et al. (2022), Kizito et al. (2023a, 2023b). Transverse unit resistance (Tr) was obtained from equation 2 as used by Simon et al. (2022), Adeniji et al. (2022), Kizito et al. (2023a, 2023b). Hydraulic conductivity (Hc) was calculated using Equation 3 as used by Obiora et al. (2016), Raji and Abdulkadir (2020), Obasi et al. (2022), Kizito et al. (2023a, 2023b). Transmissivity (Tm) was calculated using Equation 4 as used by Raji and Abdulkadir (2020), Kizito et al. (2023a, 2023b).

$$Longitudinal\ conductance\ (Lc) = \frac{h}{\rho_q}\ (Siemens) \quad (1)$$

$$Transverse\ resistance\ (Tr) = \rho_q h\ (ohm.m^2) \quad (2)$$

$$Hydraulic\ conductivity\ (Hc) = 386.40\ (\rho_q)^{-0.93283}\ (m/day) \quad (3)$$

$$Transmissivity\ (Tm) = Hc \times h\ (m^2/day) \quad (4)$$

Where ρ_q and h are the aquifer resistivity and thickness respectively.

All the value of parameters obtained were used to generated contour maps showing their spatial distribution using Surfer version 25.1.229.

RESULTS AND DISCUSSION

From the VES result as shown in Table 1, the study area is characterized by four (4) and five (5) geo-electric layers with majority having five layers. These layers consist of top soil having resistivity and thickness ranges from 79.1 Ωm to 989.6 Ωm and 0.5 m to 5.4 m, lateritic clay with resistivity and thickness ranges from 7.1 Ωm to 579.3 Ωm and 2.7 m to 13.0 m, partially weathered basement has resistivity and thickness ranges from 38.1 Ωm to 8065.3 Ωm and 508 m to 98.8 m, weathered/fractured basement aquifers has resistivity and thickness ranges from 8.0 Ωm to 1773.8 Ωm and 4.7 m to 37.2 m, while fresh basement has resistivity ranges from 174.5 Ωm to 21385.6 Ωm with infinite thickness. There are two types of curves as revealed from the result, these are HA and KQ types with majority having HA curves type. KQ curves types occur only in VES 21 and VES 28. Four sample of the curve as seen in Figure 2a, 2b 2c and 2d showed the basement complex signature with both decrease and increase in resistivity values. The resistivity of the aquifer layer ranges from 8.0 Ωm 1773.8 Ωm with an average value of 509.17 Ωm (Table 2). Resistivity ranges were used to generate the aquifer resistivity map (Figure 3a) to visualize the distribution of the aquifer types within the study area. It was observed that high (> 1000 Ωm) resistivity value are concentrated in some areas underlain by migmatite gneiss and granite gneiss while low (<600 Ωm) to moderate (600-1000 Ωm) resistivity are distributed within the various rock types. This resistivity range was use to classified the groundwater potential of the area. VES locations with aquifer resistivity less than 600.0 Ωm were classified as those with good groundwater potential (part of the central towards the north); those VES locations with resistivity less than 1000 Ωm were classified as having moderate groundwater potential (few parts of the south and northeast); while areas with resistivity greater than 1000 Ωm are classified as having poor groundwater potential (southwest and some portion in the northeast. However, majority of the VES locations within the study area were classified under moderate to good groundwater potential which corroborate with the findings of Okogbue and Omonona (2013), Raji and Abdulkadir (2020), Kizito et al. (2023a) in the southwestern basement complex.

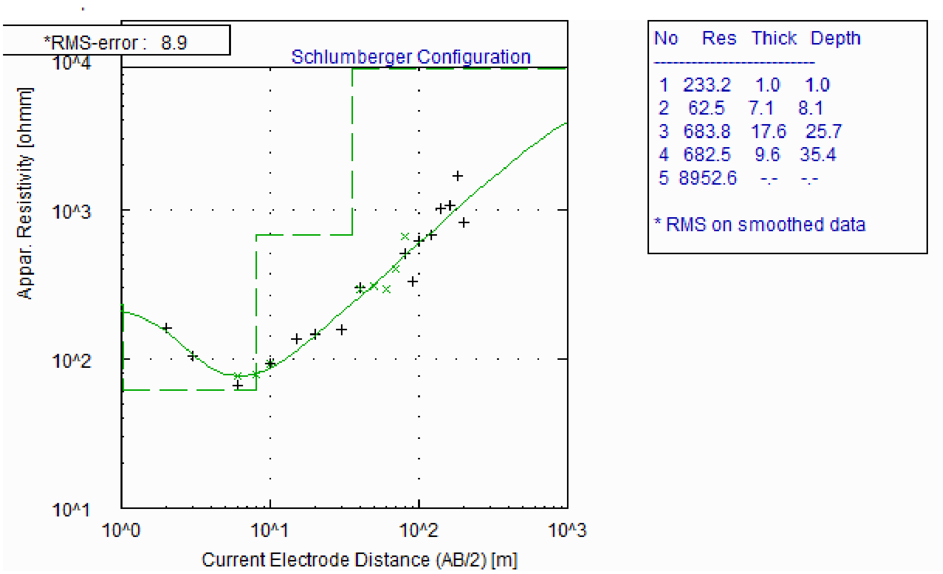

Figure 2a: VES Curve of Location 1

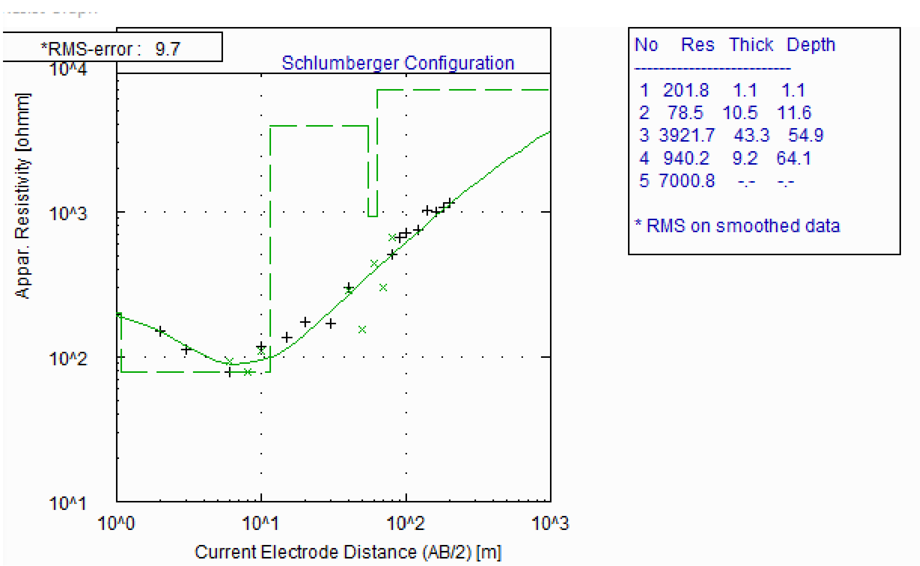

Figure 2b: VES Curve of Location 4

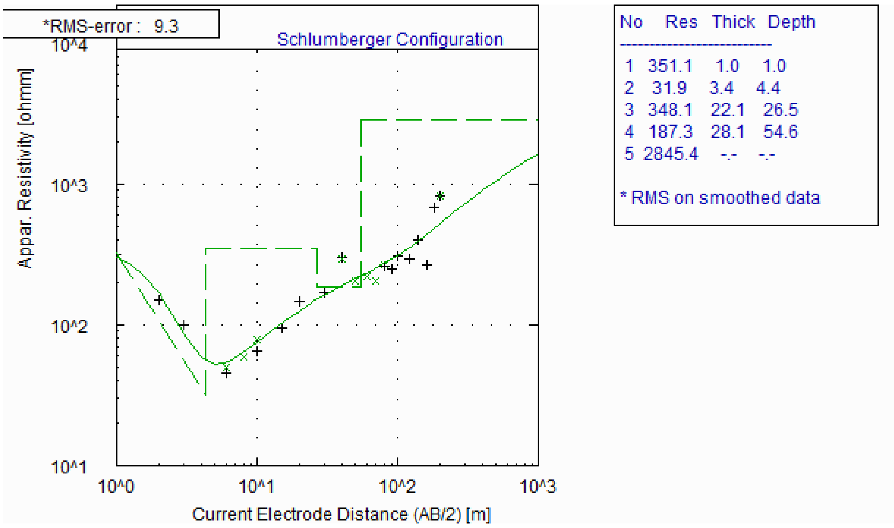

Figure 2c: VES Curve of Location 5

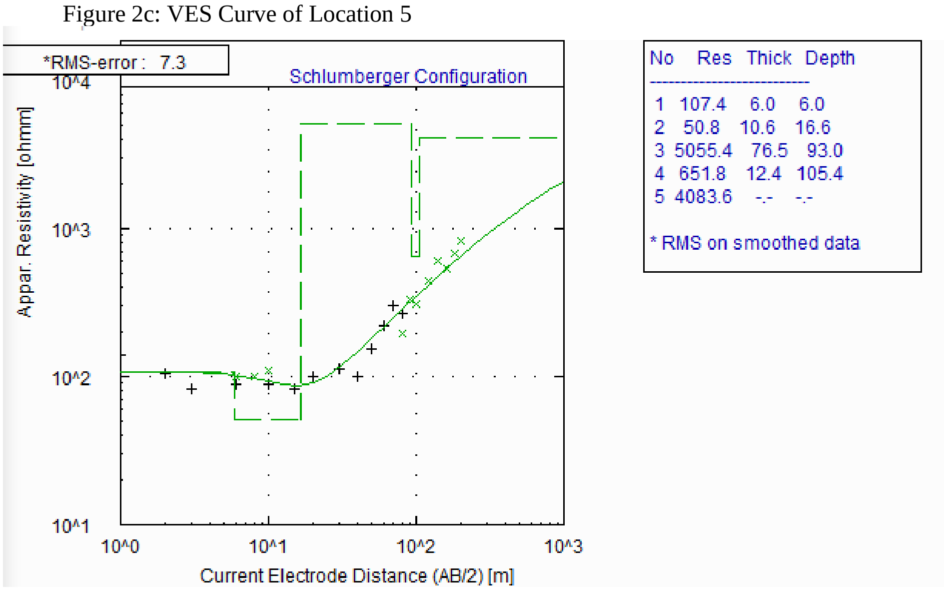

Figure 2d: VES Curve of Location 6

Table 1: Summary of VES Geoelectric Layer Parameters

VES No.	Resistivity	Thickness	Depth	Lithology	Curve Type
VES 1	233.2	1.0	1.0	Top soil	HA
	62.5	7.1	8.1	Lateritic clay	
	683.8	17.6	25.7	Confining weathered basement	
	682.5	9.6	35.4	Weathered basement aquifer	
	8952.6			Fresh Basement	
VES 2	324.2	0.8	0.8	Top soil/lateritic clay	HA
	24.7	5.4	6.3	Confining weathered basement	
	1006.8	5.0	11.3	Weathered basement aquifer	
	7973.4			Fresh Basement	
VES 3	447.9	1.0	1.0	Top soil/lateritic clay	HA
	67.6	2.6	3.6	Confining weathered basement	
	6773.8	19.1	22.8	Weathered basement aquifer	
	9730.9			Fresh Basement	
VES 4	201.8	1.1	1.1	Top soil	HA
	78.5	10.5	11.6	Lateritic clay	
	3921.7	43.3	54.9	Confining weathered basement	
	940.2	9.2	64.1	Weathered basement aquifer	
	7000.8			Fresh Basement	
VES 5	351.1	1.0	1.0	Top soil	HA
	31.9	3.4	4.4	Lateritic clay	
	348.1	22.1	26.5	Confining weathered basement	
	187.3	28.1	54.6	Weathered basement aquifer	
	2845.4			Fresh Basement	
VES 6	107.4	1.0	1.0	Top soil	HA
	50.8	10.6	11.6	Lateritic clay	
	5055.4	76.5	88.0	Confining weathered basement	
	651.8	12.4	100.4	Weathered basement aquifer	
	4083.6			Fresh Basement	
VES 7	105.1	1.9	1.9	Top soil	HA
	41.6	13.5	15.4	Lateritic clay	
	720.1	53.1	68.5	Confining weathered basement	
	199.2	32.3	100.8	Weathered basement aquifer	
	271.2			Fresh Basement	
VES 8	93.0	4.1	4.1	Top soil	HA
	70.2	6.2	10.4	Lateritic clay	
	1946.0	48.7	59.0	Confining weathered basement	
	724.1	26.8	85.9	Weathered basement aquifer	
	1567.1			Fresh Basement	
VES 9	489.0	4.2	4.2	Top soil/lateritic clay	HA
	96.8	1.3	5.5	Confining weathered basement	
	21.8	6.7	12.2	Weathered basement aquifer	
	9261.6			Fresh Basement	
VES 10	127.0	2.0	2.0	Top soil	HA
	11.2	6.7	8.7	Lateritic clay	
	103.7	28.1	36.8	Confining weathered basement	
	59.2	33.9	70.7	Weathered basement aquifer	
	291.9			Fresh Basement	
VES 11	496.4	1.0	1.0	Top soil	HA
	28.5	7.4	8.4	Lateritic clay	
	5770.1	98.8	107.2	Confining weathered basement	
	325.5	15.0	122.2	Weathered basement aquifer	
	1064.9			Fresh Basement	
VES 12	751.5	0.6	0.6	Top soil/lateritic clay	HA
	248.8	8.3	8.9	Confining weathered basement	
	105.9	10.5	19.3	Weathered basement aquifer	
	9332.3			Fresh Basement	
VES 13	91.1	4.8	4.8	Top soil	HA
	113.4	11.1	15.9	Lateritic clay	
	95.9	19.3	35.3	Confining weathered basement	
	246.9	17.4	52.7	Weathered basement aquifer	
	703.8			Fresh Basement	
VES 14	989.6	1.0	1.0	Top soil	HA
	196.1	15.0	16.0	Lateritic clay	
	1540.5	12.4	28.4	Confining weathered basement	
	1428.2	8.4	36.8	Weathered basement aquifer	
	8854.2			Fresh Basement	

VES No.	Resistivity	Thickness	Depth	Lithology	Curve Type
VES 15	425.5	0.9	0.9	Top soil	HA
	59.7	3.9	4.8	Lateritic clay	
	1069.9	23.8	28.5	Confining weathered basement	
	642.4	22.1	50.6	Weathered basement aquifer	
	3771.4			Fresh Basement	
VES 16	314.4	5.4	5.4	Top soil	HA
	28.4	10.4	15.8	Lateritic clay	
	318.8	13.6	29.4	Confining weathered basement	
	344.3	9.9	39.3	Weathered basement aquifer	
	5160.0			Fresh Basement	
VES 17	455.7	0.6	0.6	Top soil	HA
	38.2	13.7	14.3	Lateritic clay	
	1052.8	67.2	81.6	Confining weathered basement	
	203.1	20.9	102.5	Weathered basement aquifer	
	418.7			Fresh Basement	
VES 18	420.2	1.5	1.5	Top soil	HA
	22.0	5.6	7.1	Lateritic clay	
	535.0	5.9	12.9	Confining weathered basement	
	709.2	4.7	17.6	Weathered basement aquifer	
	21385.6			Fresh Basement	
VES 19	129.7	5.0	5.0	Top soil	HA
	13.7	7.3	12.3	Lateritic clay	
	344.5	52.2	64.5	Confining weathered basement	
	117.5	27.7	92.3	Weathered basement aquifer	
	174.5			Fresh Basement	
VES 20	496.1	1.0	1.0	Top soil	HA
	29.1	8.5	9.5	Lateritic clay	
	261.8	17.2	26.6	Confining weathered basement	
	379.5	11.6	38.2	Weathered basement aquifer	
	7268.2			Fresh Basement	
VES 21	143.9	2.3	2.3	Top soil/lateritic clay	KQ
	707.3	1.6	3.9	Confining weathered basement	
	13860.0	20.1	24.0	Weathered basement aquifer	
	184.0			Fresh Basement	
VES 22	166.5	1.6	1.6	Top soil	HA
	15.9	3.2	4.9	Lateritic clay	
	181.2	23.8	28.6	Confining weathered basement	
	77.5	27.6	56.2	Weathered basement aquifer	
	701.4			Fresh Basement	
VES 23	183.0	0.8	0.8	Top soil	HA
	16.1	6.6	7.4	Lateritic clay	
	38.1	11.4	18.8	Confining weathered basement	
	8.0	22.8	41.6	Weathered basement aquifer	
	455.5			Fresh Basement	
VES 24	91.7	2.5	2.5	Top soil	HA
	50.0	7.5	10.0	Lateritic clay	
	286.5	8.4	18.4	Confining weathered basement	
	531.0	8.2	26.6	Weathered basement aquifer	
	10187.1			Fresh Basement	
VES 25	121.3	1.2	1.2	Top soil/lateritic clay	HA
	9.7	2.7	3.9	Confining weathered basement	
	483.2	5.8	9.7	Weathered basement aquifer	
	18631.6			Fresh Basement	
VES 26	98.8	1.1	1.1	Top soil	HA
	7.1	3.0	4.1	Lateritic clay	
	3369.7	80.6	84.6	Confining weathered basement	
	258.0	32.5	117.2	Weathered basement aquifer	
	512.1			Fresh Basement	
VES 27	335.6	1.0	1.0	Top soil/lateritic clay	HA
	18.2	5.5	6.4	Confining weathered basement	
	373.5	5.3	11.7	Weathered basement aquifer	
	17030.1			Fresh Basement	
VES 28	54.7	1.9	1.9	Top soil/lateritic clay	KQ
	579.3	11.6	13.6	Confining weathered basement	
	4594.5	26.9	40.5	Weathered basement aquifer	
	251.7			Fresh Basement	

VES No.	Resistivity	Thickness	Depth	Lithology	Curve Type
VES 29	33.9	1.4	1.4	Top soil	HA
	10.4	2.7	4.0	Lateritic clay	
	4338.3	37.4	41.4	Confining weathered basement	
	655.6	6.9	48.4	Weathered basement aquifer	
	7278.5			Fresh Basement	
VES 30	139.1	2.4	2.4	Top soil	HA
	22.4	8.8	11.1	Lateritic clay	
	391.4	45.0	56.1	Confining weathered basement	
	131.1	21.9	78.0	Weathered basement aquifer	
	584.4			Fresh Basement	
VES 31	677.5	0.6	0.6	Top soil	HA
	42.1	10.8	11.4	Lateritic clay	
	1130.9	25.2	36.5	Confining weathered basement	
	617.4	10.6	47.1	Weathered basement aquifer	
	6454.6			Fresh Basement	
VES 32	419.9	1.6	1.6	Top soil	HA
	36.0	13.0	14.6	Lateritic clay	
	791.8	62.7	77.3	Confining weathered basement	
	118.1	37.2	114.5	Weathered basement aquifer	
	293.0			Fresh Basement	
VES 33	286.6	4.7	4.7	Top soil/lateritic clay	HA
	281.5	7.7	12.3	Confining weathered basement	
	1069.5	13.3	25.6	Weathered basement aquifer	
	23731.4			Fresh Basement	
VES 34	490.9	1.3	1.3	Top soil/lateritic clay	HA
	21.3	3.2	4.5	Confining weathered basement	
	847.7	10.3	14.8	Weathered basement aquifer	
	19888.3			Fresh Basement	
VES 35	158.7	0.5	0.5	Top soil	HA
	29.1	9.2	9.6	Lateritic clay	
	5926.7	95.5	105.1	Confining weathered basement	
	523.4	12.3	117.4	Weathered basement aquifer	
	3011.3			Fresh Basement	
VES 36	79.1	1.4	1.4	Top soil	HA
	50.9	10.2	11.6	Lateritic clay	
	60.9	11.0	22.6	Confining weathered basement	
	306.3	10.9	33.5	Weathered basement aquifer	
	11235.7			Fresh Basement	
VES 37	506.9	1.3	1.3	Top soil/lateritic clay	HA
	49.6	2.5	3.8	Confining weathered basement	
	9795.0	22.6	26.5	Weathered basement aquifer	
	1510.7			Fresh Basement	
VES 38	425.3	1.5	1.5	Top soil	HA
	47.7	4.2	5.7	Lateritic clay	
	127.1	18.9	24.7	Confining weathered basement	
	227.0	11.8	36.5	Weathered basement aquifer	
	6235.9			Fresh Basement	
VES 39	407.6	2.3	2.3	Top soil	HA
	25.3	6.6	8.8	Lateritic clay	
	8065.3	76.0	84.8	Confining weathered basement	
	1045.2	14.8	99.6	Weathered basement aquifer	
	55811			Fresh Basement	
VES 40	454.2	0.6	0.6	Top soil/lateritic clay	HA
	15.9	3.3	3.9	Confining weathered basement	
	398.7	2.7	6.5	Weathered basement aquifer	
	98082.7			Fresh Basement	

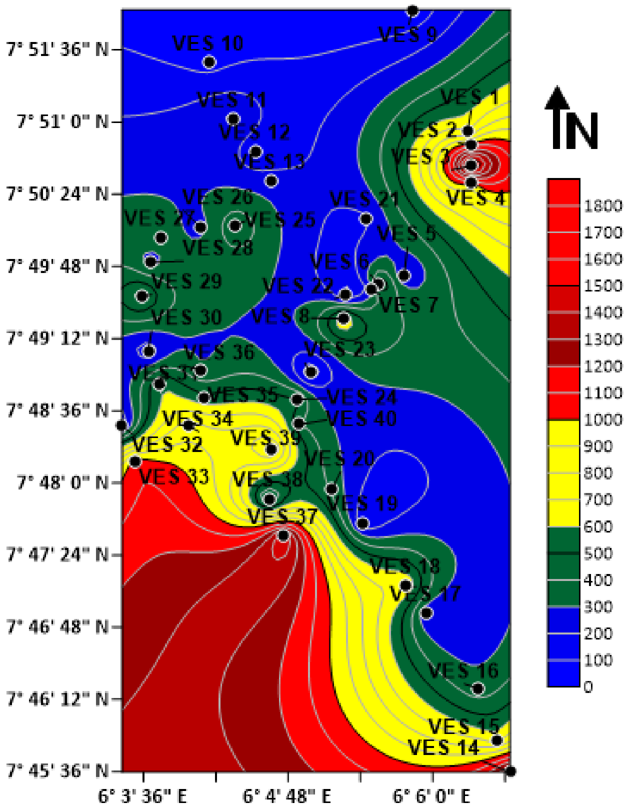

Figure 3a: Aquifer Resistivity Variation Map of the Study Area

The aquifer thickness ranges from 2.7 m to 37.2 m with an average value of 16.4 m (Table 2). These thickness values reveal that the study area has good groundwater potential for drilling motorized boreholes or hand-dug wells, which will serve both domestic and industrial purposes. The map showing the distribution of the aquifer thickness (Figure 3b) further reveal that areas with low resistivity has higher thickness which showed relationship between the aquifer thickness and resistivity (Adeniji et al., 2022; Ogundana and Falae, 2023).

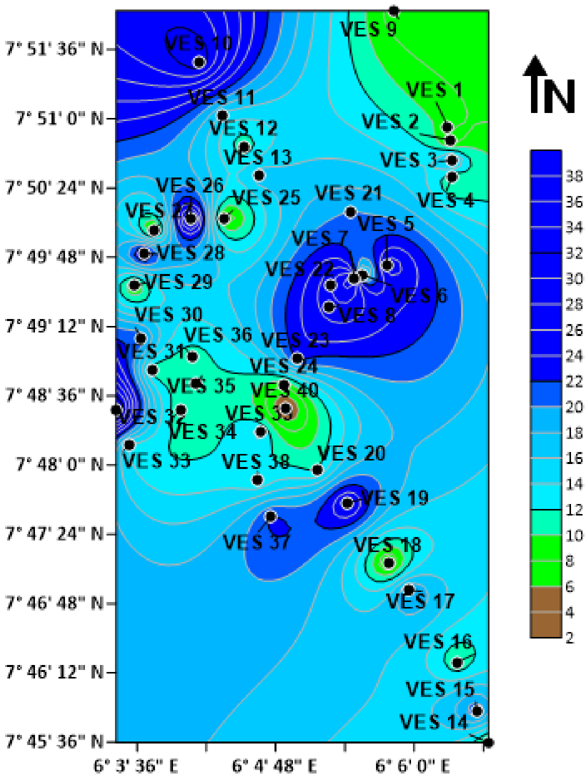

Figure 3b: Aquifer Thickness Variation Map of the Study Area

The depth to aquifer layer varies from one location to other and ranges from 6.5 m to 122.2 m with an average value of 52.94 m (Table 2). The average depth value reveals that the study area has a shallow aquifer depth which is less than 55.00 m as indicated in Figure 3c. The average depth to groundwater in this study correlate with the work of Aizebeokhai et al. (2018), Raji and Abdulkadir (2020), Kizito et al. (2023a, 2023b) within the basement Complex of Nigeria.

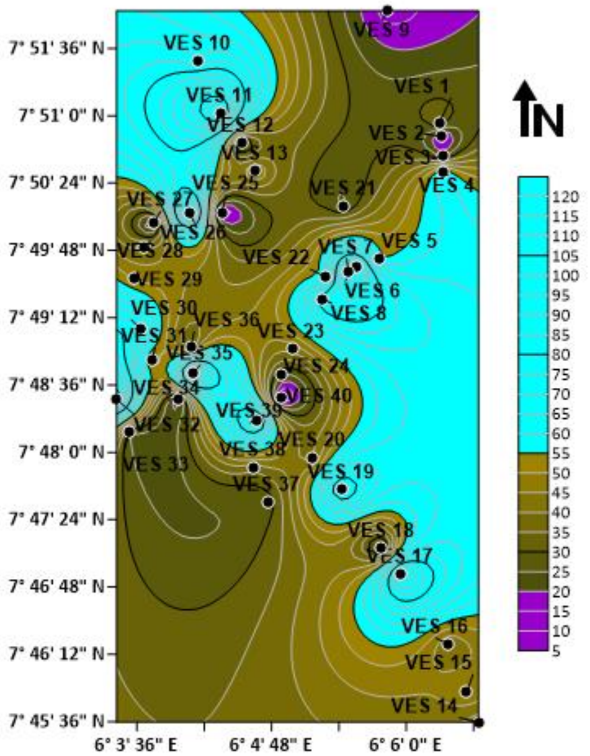

Figure 3c: Aquifer Depth Variation Map of the Study Area

Longitudinal conductance value ranges from 0.01 siemens to 2.85 siemens with an average value of 0.16 siemens (Table 2 and Figure 3d). Longitudinal conductance is used to describe the aquifer protective capacity of an area. Areas that have poor and weak longitudinal conductance are more prone to contamination, areas that are moderate are less vulnerable and areas with good protective capacity are not vulnerable to contamination from leachate and infiltration. According to Henriet (1976) and Oladapo *et al*. (2004) classification (Table 3) as used by other authors, the aquifer protective capacity of the study area is classified into poor, weak, moderate and good. However, majority of the area has poor to weak protective capacity as seen in Figure 3d and the mean value of longitudinal conductance indicates that the study area has moderate protective capacity and this showed that the study area is more vulnerable to contamination from leachate and infiltration.

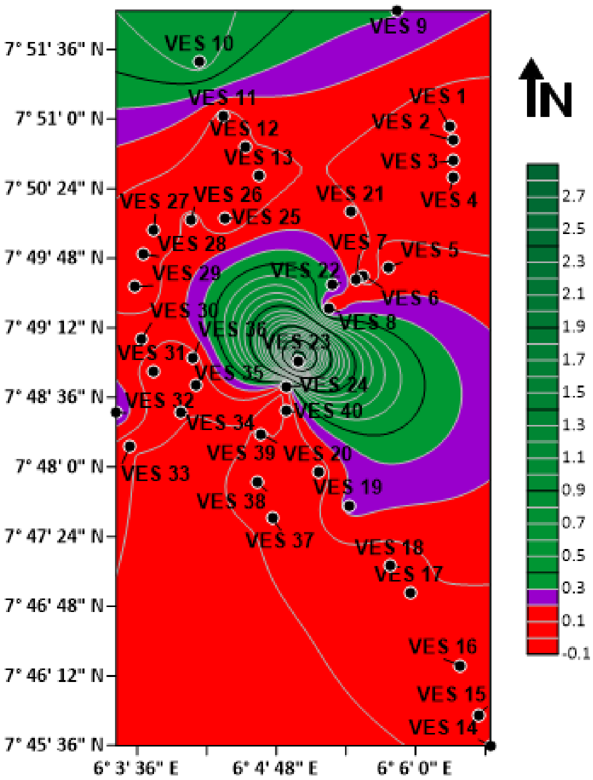

Figure 3d: Longitudinal Conductance Variation Map of the Study Area

The transverse unit resistance (Table 2 and Figure 3e) value ranges from 146.06 Ωm^2 to 34141.82 Ωm^2 with an average value of 7133.11 Ωm^2. The highest borehole yields usually come from the zone with the highest transverse value (Opara et al., 2012; Simon et al., 2022). Highest values are found in the southwest and part of northeast of the study area, this indicate that these areas have higher aquifer thickness. However, the mean value revealed that the study area has moderate to good to groundwater yield as indicated earlier by other parameters.

Table 2: Summary of Aquifer Parameters of the Study Area

	ρ_q (Ωm)	h (m)	d (m)	Lc (Siemens)	Tr (Ωm^2)	Hc (m/day)	Tm (m^2/day)
Minimum	8.00	2.70	6.50	0.01	146.06	0.36	3.05
Maximum	1773.80	37.20	122.20	2.85	34141.82	55.54	1266.32
Average	509.17	16.40	52.94	0.16	7133.11	3.88	76.72

Table 3: Protective Capacity Class (Henriet, 1976; Oladapo *et al*., 2004)

S/N	Longitudinal Conductance (mhom)	Soil Protective Capacity Classification
1.	>10	Excellent
2.	5 - 10	Very good
3.	0.7 - 4.9	Good
4.	0.2 - 0.69	Moderate
5.	0.1 – 0.19	weak
6.	<0.1	poor

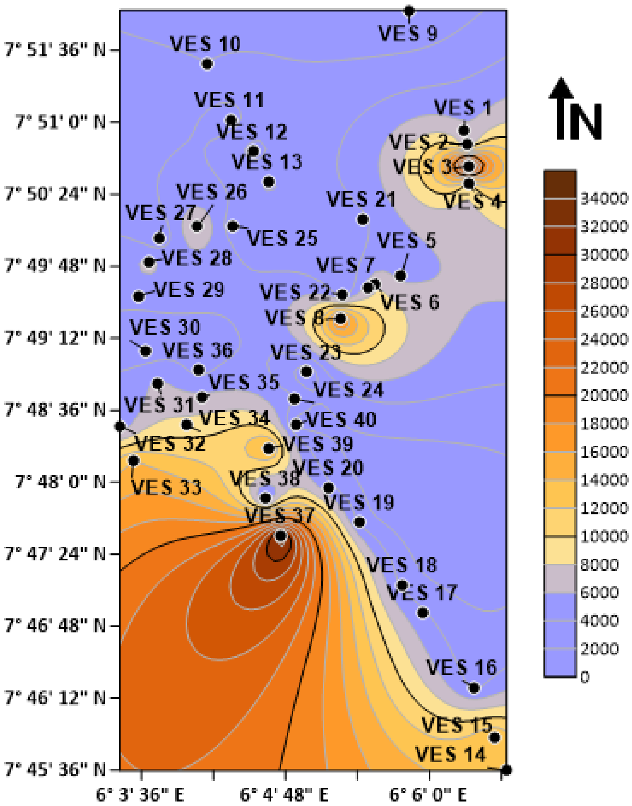

Figure 3e: Transverse Resistance Variation Map of the Study Area

The value of hydraulic conductivity ranges from 0.36 m/day to 55.54 m/day with an average value of 3.88 m/day (Table 2 and Figure 3f). Hydraulic conductivities describe the vertical movement of water in the aquifer and can be used to express aquifers potential recharge (Adeniji et al., 2022; Obasi et al., 2022). Higher hydraulic conductivity greater than 10.00 m/day is found in the central and the extreme end of the northern part while lower to moderate hydraulic conductivity values were observed in the remaining part using the classification scheme of Singhal and Gupta (1999) as in Table 4.

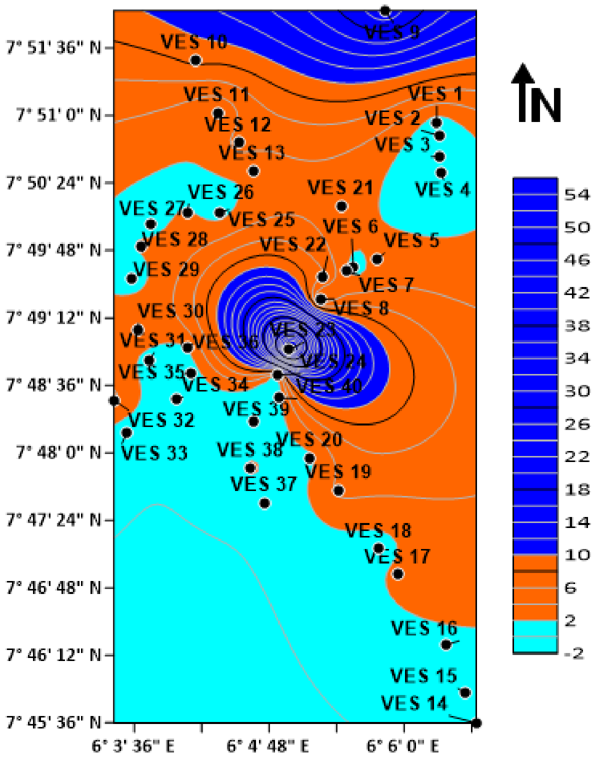

Figure 3f: Hydraulic Conductivity Variation Map of the Study Area

The value of transmissivity ranges from 3.05 m^2/day to 1266.32 m^2/day with an average value 76.72 m^2/day (Table 2 and Figure 3g). Aquifer transmissivity has been used as an indirect indicator of borehole yield and it describes the lateral movement of groundwater in the aquifer (Graham et al., 2009 and MacDonald et al., 2012). Based on Krasny (1993) classification of transmissivity (Table 5) have an intermediate transmissivity and the remaining part of the area have lower transmissivity. Therefore, the study area has good groundwater potential. Both transmissivity and hydraulic conductivity plots showed the same spatial distribution indicating that the eastern part of the study area have highest groundwater potential. The average value of hydraulic conductivity and transmissivity from this study using resistivity data correlate with the result obtained by Okogbue and Omonona (2013) Sule and Ayenigba (2017) and Kizito et al. (2023b) using pumping test data.

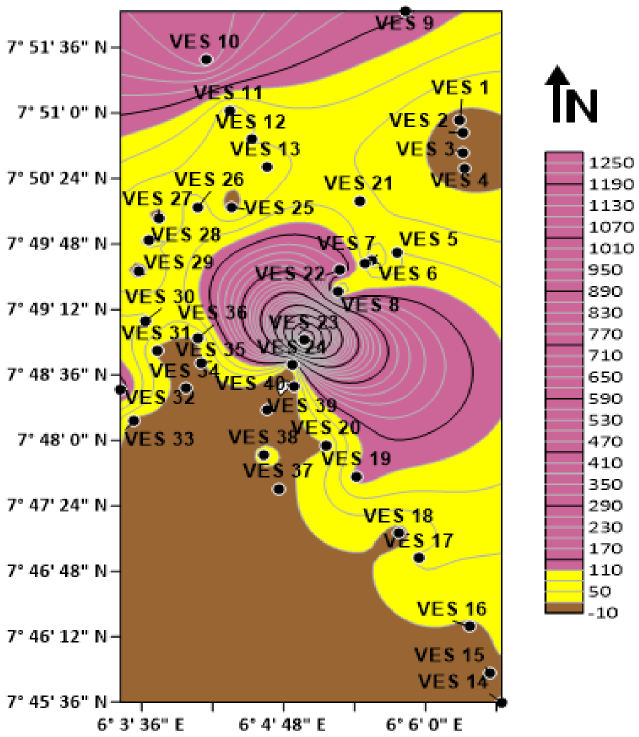

Figure 3g: Transmissivity Variation Map of the Study Area

Table 4: Classification of Hydraulic Conductivity (Singhal and Gupta, 1999)

S/N	Hydraulic Conductivity (m/day)	Class	Designation
1.	>1000	I	Very high
2.	10 – 1000	II	High
3.	0.1 – 10	III	Intermediate
4.	0.001 – 0.1	IV	Low
5.	0.00001 – 0.001	V	Very low

Table 5: Classification of Transmissivity Magnitude (Krasny, 1993)

S/N	Magnitude of Transmissivity (m^2/day)	Class	Designation
1.	>1000	I	Very high
2.	100 - 1000	II	High
3.	10 - 100	III	Intermediate
4.	1 - 10	IV	Low
5.	0.1 - 1	V	Very low
6.	<0.1	VI	Imperceptible

CONCLUSION

Evaluation of aquifer parameters using the geology, primary and secondary resistivity parameters was carried out within the study area with the view to assess its potential and vulnerability. Four major rocks were identified and they include: migmatite-gneiss, granite-gneiss, schist, and minor occurrence of charnockite. The geoelectric layers are made up of topsoil, lateritic clay, confining basement, weathered/fracture basement aquifers, and fresh basement. The primary parameters (aquifer resistivity, thickness and depth) from VES result revealed that the groundwater can be classified into good, moderate and low. This was further confirmed by secondary parameters like transverse resistance, hydraulic conductivity and transmissivity and correlate with the finding of Okogbue and Omonona (2013), Raji and Abdulkadir (2020), Kizito et al. (2023a). Aquifer potential zones compared with the geology of the area revealed that migmatite gneiss, and schist have very good potential for groundwater except where fractures are not well pronounced. Granite gneiss and charnockite lack pronounced fractures, but where these fractures are identified in granite gneiss, it can produce water for domestic use at low or moderate yield. Average depth to groundwater is 52.94 m indicating shallow to deeper aquifer depth within the study area. Shallow aquifer depth is distributed within the different rock types while deeper aquifer depth is found mostly in the migmatite gneiss and granite gneiss. The longitudinal conductance showed that the aquifer protective capacity of the study area varies from poor to good with majority of the study area having weak and poor protective capacity. This indicate that the groundwater is susceptible to contamination. In conclusion, the study revealed that the area requires geological and geophysical investigation for groundwater exploration especially in the granite gneiss and charnockitic rocks which are dominant towards the Northeastern and few of western parts.

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