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Geoelectrical Assessment of Groundwater Potential within Zamfara and its Environs, Northwestern Nigeria

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Groundwater potential assessment was carried out within Zamfara environs, Northwestern Nigeria using geoelectrical technique with a view of solving the problem of incessant failure of boreholes in the study area. A total of one hundred and eighty-three (183) vertical electrical soundings (VES) were used to identify potential groundwater bearing zones capable of sustaining economic development of the study area. Two hydrogeological units were investigated (basement rock units and sedimentary rock unit), using Omega resistivity meter Model No. 122, to measure and record the resistance of the subsurface by Schlumberger configuration. The data obtained were interpreted quantitatively and qualitatively using the partial curve matching and computer iteration techniques to generate the first order geoelectric parameters. Generally, the VES result from the basement rock units revealed, four geoelectric layers which correspond to lateritic top soil, weathered basement (clay), partially fractured layer/fractured layer and fresh basement. The weathered/fractured layer was identified as the water bearing layer, within the basement rock units of the study area. From geospatial analysis of both weathered thickness/fracture thickness layers, South and Northeastern part tends to be the most prospective area with the best hydrogeologic conditions for borehole siting within the basement rock units. Consequently, three geo-electric layers were delineated from VES result obtained from Gundumi formation, which correspond to sandy clayey top/gravelly sandy top soil, second layer are mostly silty-clay/compacted sandstone/sandy gravel layers, the third layer were majorly saturated sandstone in some instances silty clay. However, the aquiferous layer is saturated sandstone/sandy gravel layer. The Dar Zarrouk result revealed excellent groundwater potential within the Gundumi formation. The values of coefficient anisotropy obtained from Gundumi rock units range from 0.44 to 3.79, which implies moderate saturation of groundwater. This is an indication that the aquifers of the Gundumi formation is more promising and it can be tap for both domestic and agricultural uses.

Keywords: Vertical electrical sounding, Fractured layer, Saturated Sandstone, Basement rock units, Gundumi formation.

1. Introduction

Groundwater exploration is gaining more and more importance in Nigeria owning to the ever increasing demand for water supplies, especially in areas with inadequate surface water supplies. Already, ten percent of the world's population is affected by chronic water scarcity and this is likely to rise to one third by about 2025 (Coker, 2012). High increases in industrial development, urbanization and agricultural production have resulted in freshwater shortages in many parts of the world. As a result of this increasing demand for portable water for these various purposes, there is need to have a planned and optimal utilization of water resources. Aquifer parameter is necessary for the management of groundwater resource. The parameters necessary for the description of the dynamics of aquifer, include, geometry of the pore space, geometry of the rock particles, secondary geologic processes such as faulting and folding. These parameters jointly affect the rate and pattern of groundwater flow (Udoinyang and Igboekwu, 2012).

The ease of developing groundwater in Nigeria is restricted by the fact that most parts of the country are underlain by Basement Complex rocks. (Kazeem, 2007). Development of secondary porosity and permeability by weathering in such terrains bring about the occurrence of groundwater. The aquifers are inherently discontinuous; hence, the need to conduct geophysical investigation to locate areas with abundance of such fractures capable of holding economic quantity of water in place for productive borehole placement.

Groundwater could be found in either basement or sedimentary terrains of the study area. Basement rock lacks a defined primary porosity but possesses secondary porosity with the presence of joints, fracture and fault. Most sedimentary rocks serve as good aquifers because they possess primary porosity and their pores spaces are interconnected. These two factors (the primary porosity and the rock unit permeability) determine whether a unit of rock can serve as a good aquifer.

Olawuyi and Abolarin, (2013) Alabi *et al*., (2013) and Badmus and Olatinsu (2010) note that the characteristics of basement aquifer vary with the mode of geological formation, mineralogical composition and structure of the substrate as well as the topography in which they occur. Generally, fractured crystalline rocks yield smaller quantities of groundwater in many environments in comparison with sedimentary aquifer. This makes it an important resource which can act as a natural storage that can buffer against shortages of surface water, as in during times of drought. Groundwater is naturally replenished by surface water from rivers when this recharge reaches the water table.

The Vertical Electrical Sounding (VES) is a geophysical method for measuring vertical variations of electrical resistivity due to inhomogeneity in the subsurface. The method has been recognized to be more appropriate for hydrogeological study of sedimentary basin and that crystalline environment.

Its wide applicability is associated with the simplicity of instrumentation. Also, the field logistics are easy and straight forward while the analyses of the sets of acquired data are less tedious and economical (Olowofela *et al.,* 2005; Batayneh, 2009; Ezeh and Ugwu, 2010; Ologe *et al.,* 2014).

Several researchers have carried out systematic hydrogeological and geophysical studies in the different region of the world (Bose and Ramakrishna 1978; Singhal 1997; Rai *et al.,* 2011; Adeoti and Uchegbulam, 2010; Ratnakumari *et al.,* 2012; Rai *et al.,* 2013) to delineate aquifers and the occurrence and movement of groundwater in intertrappeans/vesicular and fractured zones within the trap sequence and sedimentary formations below the traps, which are considered to be a potential source of groundwater.

The area under investigation is fast growing in terms of population and business activities. It is characterized by the shortage of potable water suitable for domestic and economic purposes. Virtually all the hand dug wells dry up during the dry season, mostly within the dominant basement terrain, which might be due to the nature of the patch aquifers. Thus, there is a great problem of locating prolific aquifers in different parts of the study area. Hence, there is need to find good quality water source(s) must be found for the residents of this area with a view to saving communities from shortage of water supply and unknown health hazards. To address these challenges, Electrical resistivity methods of geophysical prospecting might be very useful.

In this study, the vertical electric sounding using Schlumberger array was employed to investigate the groundwater potential of Zamfara State to assist in planning, improvement and management of the groundwater resource of the area.

1.1 Study Area

This research covers the entire Zamfara State with estimated area coverage of 39,762 Km^2, within the NW Nigeria (Figure 1), with latitude 7˚18'13.709˝E to 10˚49'4.152˝N and Longitude: 5^{0}1'27.638˝E to 13^{0}10'45.537˝N. The study area belongs to the Sudan savannah region of Africa; an area mostly affected by droughts (Figure 1).

Temperatures are generally extreme, with average daily minimum of 18°C, during cool months of December and January and in the hottest months of April to June, an average maximum of 38°C and minimum of 24°C temperatures are recorded.

Rainfall is generally low; the average annual rainfall ranges from 600 to 1000 mm across the entire State (Nigeria Meteorological Agency, 2020). Much of the rain, falls between the months of May to September, while the months of October to April experienced little or no rainfall. Evaporation is high, ranging from 80 mm in July to 210 mm in April to May (Nigeria Meteorological Agency, 2020).

A monthly average evapo-transpiration range of about 140 mm represent 30 of monthly average precipitation into the catchment.

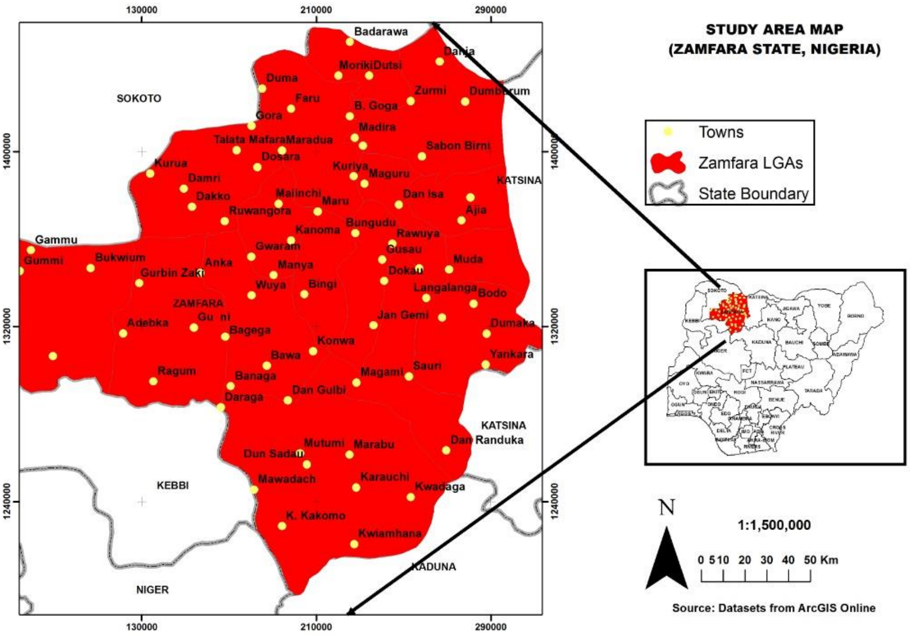

Figure 1. Map of the Study Area

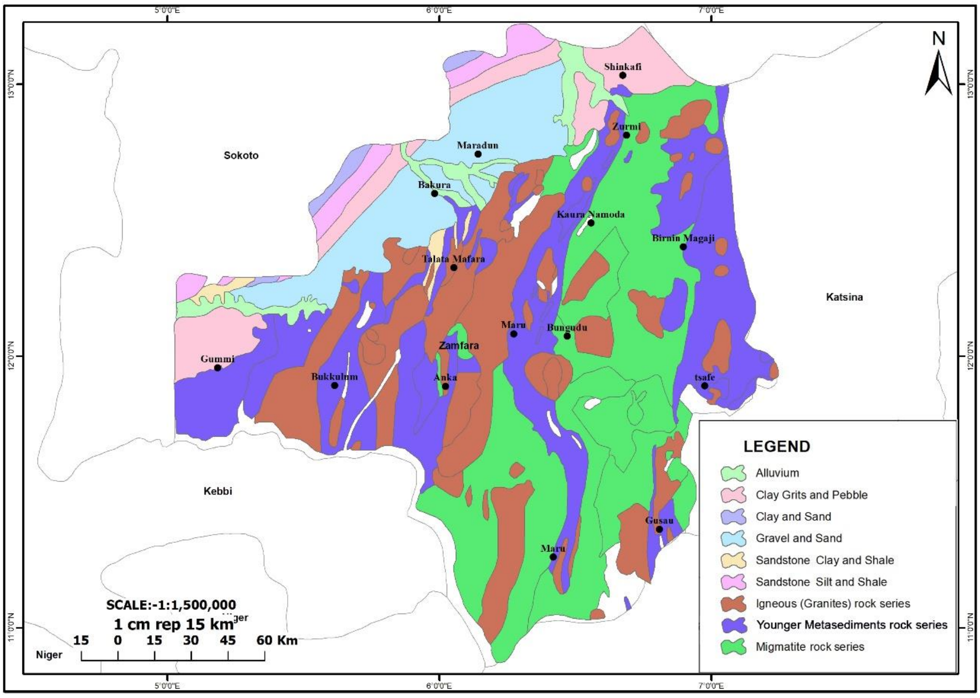

Figure 2. General Geological Map of Zamfara State, (Nigeria Geological Survey Agency, 2006).

1.2 Geological Setting of the Study Area

About 90% of the State is underlain by a variety of crystalline rocks of the basement complex of north western Nigeria described by McCurry (1976) to be composed largely of gneiss, schist, migmatite, granite and granodiorite (Figure 2). The structural features commonly exhibited by the basement rocks include foliation, lineation, folds, rock-rock contacts, faults and joints. The rest of the state is occupied by the oldest sediments of the Sokoto (Illullemeden) basin described by Oteze (1976) and Kogbe (1976). Groundwater in the basement rocks of the state are mainly sourced from fractures and joints and in the intergrannular pores of fine to coarse (white or light grey) sand or gravel in the sedimentary areas (Oteze, 1976).

About 10% of the State is underlain by Gundumi formation which consists of clays, sandstones and pebble beds, thought to be lacustrine and fluviatile in origin (Figure 2). Its maximum thickness is reported to be up to 300 m, near the Niger border (Anderson and Ogilbee, 1973). The base is marked by conglomeratic beds which are well preserved and exposed by the road side at Tureta and Ruwan Kalgo (Kogbe, 1976). These basal beds contain rounded quartz cobbles and pebbles and attain a thickness of about 3m. The formation is the oldest sedimentary rocks in the Northern parts of the basin it, lies uncomfortably on the Basement Complex. Other exposures of the Formation are found by Rivers Zamfara and Dutsin Dambo, near Bakura. The indication, from borehole sections, is that the basal conglomerates are overlain by beds which are more argillaceous from the bottom to the top.

2. Methodology

A total of one hundred and eighty-three (183) Vertical Electrical Sounding (VES) points were carried out within the study area using Schlumberger array with Omega resistivity meter Model No. 122, to measure and record the resistance of the subsurface. The VES stations were systematically selected at different locations based on the major rock units within the study area.

The potential electrodes remain fixed and the current electrodes were expanded simultaneously about the center of the spread. The maximum electrode separation used was AB/2 = 100 m and a maximum potential electrode spacing MN/2 = 0.5 m which are normally arranged in a straight line, with the potential electrode placed in between the current electrodes. This configuration is mostly used as it would provide sub-surface information considering the depth of penetration. The field data were converted to apparent resistivity (ρ) in ohm-meter by multiplying with Schlumberger geometric factor (k). The sounding curve for each point was obtained by plotting the apparent resistivity on the ordinate against half electrode spacing on a bilogarithmic paper and edited in the Interpex 1-D software until a smooth layered model with a minimum percentage error of <1 is gotten in which a model graph is plotted for each VES point (Figure 3.7a-c). The curves obtained were then compared to the H, K, Q, and A curve types. Dar-Zarrouk parameters (Longitudinal conductance) were used to define target areas of groundwater potential and also used in aquifer protection studies within the sedimentary section of the study area. The total longitudinal conductance values were utilized in evaluating the overburden protective capacity of the area underlain by sedimentary formation. This is because the earth medium acts as a natural filter to percolating fluids.

Dar Zarrouk Parameters: some parameters are generally very important in the understanding and interpretations of geological model (Egbai and Iserhein-Emekeme, 2015). These parameters are related to different combination of the thickness and resistivity of each geo-elcetric layers in the model (Braga *et al,* 2006). For a sequence of horizontal, homogeneous and isotropic layers resistivity ρi and thickness hi, the Dar Zarrouk parameters (longitudinal conductance S and transverse resistance T are respectively defined as:

$$S = \sum_{i=1} \frac{hi}{\rho i} \quad (1)$$

$$T = \sum_{i=1} hi\rho i \quad (2)$$

If the total thickness of the layers in the geoelectric section considered is h, then the average longitudinal resistivity ρ_L is given by

$$\rho L = \sum_{i=1} \frac{hi}{si} \quad (3)$$

And the average transverse resistance ρl is given by

$$\rho l = \sum_{i=1} \frac{Ti}{hi} \quad (4)$$

ρ_l is always greater than ρ_L. Therefore, the entire section will thus be anisotropic with regards to electrical resistivity. The coefficient of electrical anisotropy is defined as:

$$\lambda = \sqrt{\frac{\rho l}{\rho L}}$$

Where λ is real and greater than 1.

The reflection coefficient (Rc) and resistivity contrast (Fc) of the fresh basement rock of the study area was calculated using the method of Oladunjoye and Jekayinfa (2015).

$$Rc = \frac{\rho n - \rho n - 1}{\rho n + \rho n - 1}$$

And

$$Fc = \frac{\rho n}{\rho n - 1}$$

Where ρn is the layer resistivity of the nth layer and ρn-1 is the layer resistivity overlying the nth layer. The Dar Zarrouk parameters of the study area were evaluated based on the weathered layer thickness, resistivity of overburden thickness, transverse resistance (T), coefficient of electrical anisotropy (λ), reflection coefficient (Rc) and resistivity contrast (Fc). Values of various formation parameters are in table 6.

ArchGIS 10.0 was used to generate Iso-patch contour map, fracture depth map, and groundwater potential map of the study area.

3. Results and Discussion

The Vertical Electrical Soundings (VES) data were interpreted qualitatively and quantitatively. The results show details of the measured parameters such as thickness of layers, resistivity of layers, fitting error and curve-type for all the sounded points and including transverse resistance, longitudinal conductance for the sedimentary terrain. From the curve type distribution of the 183 VES in the study area (table 1, 2 3 & 4). There are about three to four (4) different geo-elcetric layers.

A total of thirty-seven (37) Vertical Electrical Sounding (VES) points were conducted within the older metasedimentary rocks in the studied area and the results interpretation revealed three subsurface layers, the top layer which mainly composed of laterite, sandy soil and in some instance clayey, the thickness of this layer range from 0.5 to 8.5m with resistivity (ohm-m) value of 265.7 Ωm and 287 Ωm respectively. The weathered layer range in thickness between 1.8 to 22.9 m with resistivity value of 34.3 Ωm and 130 Ωm respectively. While the fractured thickness range between 31.2 to 90 m with resistivity value of 193.4 Ωm and 2844.5 Ωm respectively. Table 5 show the statistics of curve types of the studied VES data, the older metasediments revealed H, KH, Q, AK, K and HK-curve type with H-curve type being the dominant (table 1).

The aquiferous layers are majorly partly fractured with some well fractured layers, however weathered layer equally serve as aquifer within this rock units (table 1). This is typical of crystalline environment.

Table 1. Summary of Vertical Electrical Sounding within Older Metasediments (showing aquiferous layers)

VES Locations	Layer/Curve Type	Resistivity ohm-m	Thickness (m)	Depth (m)	Layer Characteristics
1	Q	24.1	31.2	45	Fractured Basement (Schist)
2	H	193.4	38.2	45	Fractured basement
3	Q	707.4	5.8	6.6	Weather (Lateritic layer)
4	Q	55	36.9	80	Fractured basement
5	H	57.1	20.9	24.1	weathered Basement (Clay)
6	H	29.3	29.2	32.2	weathered Basement (Clay)
7	H	2844.5	82.6	90	Fractured basement
8	A	118.1	18.8	90	Partly fractured
9	A	250.7	54.2	60	Fractured basement
10	H	206.8	41.2	50	Fractured basement
11	H	161.5	31.4	60	Fractured basement
12	H	229.7	42.9	60	Fractured basement
13	A	222.3	73.3	80	partly fractured basement
14	H	691.8	74.9	50	partly fractured basement
15	KH	249.2	77.6	80	partly fractured basement
16	H	79.5	78.1	80	partly fractured basement
17	HK	32.7	71.5	80	partly fractured basement

18	H	264.7	74.6	90	partly fractured basement
19	H	690.6	72.4	80	partly fractured basement
20	A	556.3	75.6	80	partly fractured basement
21	AK	219.2	65.8	80	partly fractured basement
22	H	353.7	37.8	50	partly fractured basement
23	AK	261	79	80	partly fractured basement
24	H	300.6	77	80	partly fractured basement
25	HA	748.2	74.1	80	partly fractured basement
26	HA	675.6	66.6	70	partly fractured basement
27	AK	727.7	60.8	70	partly fractured basement
28	H	410.7	72	80	partly fractured basement
29	HK	121.8	71.6	80	partly fractured basement
30	KH	207.6	9.4	47.4	fractured basement
31	H	16.6	34	52	fractured basement
32	HK	85.2	35	52.3	fractured basement
33	A	1213	12.6	22.1	slightly fractured basement
34	KH	121			fractured zone
35	H	195	15	41.5	fractured zone
36	H	180.2	12.3	23.5	fractured basement
37	A	36.6	21.1	26.5	fractured basement

A total of forty-five (45) Vertical Electrical Sounding (VES) points were conducted within younger metasediments rock units and the result interpretation revealed three subsurface layers, the top layer which mainly composed of laterite, sandy soil and in some instance clayey, the thickness of this layer range from 1 to 2.8 m with resistivity value of 172.9 Ωm and 133Ωm respectively. The weathered layer range in thickness between 4.1 to 31.8m with resistivity value of 38.9 Ωm and 85.9Ω m respectively. While the fractured thickness range between 8 to 90m with resistivity value of 257 Ωm and 558.1 Ωm respectively (Table 2). The interpreted VES data for this rock unit revealed H, A, KH, Q, AK, K, HK and AH-curve.

The aquiferous layers are majorly well fractured layers, however weathered layer equally serve as aquifer (well saturated with anticipated moderate yielding capacity) within this rock units (table 2).

Table 2. Summary of Vertical Electrical Sounding within Younger Metasediments (showing aquiferous layers)

VES Locations	Layer/Curve Type	Resistivity ohm-m	Thickness (m)	Depth (m)	Layer Characteristics
1	Type H	30.9	5.7	7.2	weathered basement (clay)
2	Type AK	22.4	34.7	45	Fractured basement (schist)
3	Type Q	24.1	31.2	45	Fractured Basement (Schist)

4	Type QH	41.3	11.5	13.3	Weather (Clayey layer)
5	Type K	72.7	38.2	80	fractured Basement (Schist)
6	Type H	79.6	14.8	18.5	weathered basement
7	Type H	142.7	52.1	60	Fractured basement
8	Type H	183	40.9	50	Fractured basement
9	Type A	98.1	38.7	60	Fractured basement (schist)
10	Type A	91.8	42.4	60	Fractured basement (schist)
11	Type HA	462.2	34.2	50	Fractured basement
12	A	462.3	2.6	6.6	Fractured Basement
13	A	947	2.6	11.3	Fractured Basement
14	HA	186	6.7	10.5	Weathered Layer
15	AK	100000	17.6	18.4	Fractured Basement
16	A	14965.6	6	7.2	Fractured Basement
17	AH	498.8	78.8	80	partly fractured basement
18	QH	176.5	72.2	80	partly fractured basement
19	QH	1280.8	71.6	80	partly fractured basement
20	HK	162.8	52	60	partly fractured basement
21	A	91.1	73.2	80	partly fractured basement
22	A	6835.4	87.8	90	partly fractured basement
23	H	2250.3	67	80	partly fractured basement
24	H	524.9	75.4	80	partly fractured basement
25	H	319.9	38	50	partly fractured basement
26	AH	307.7	76.4	80	partly fractured basement
27	QH	216.9	41.6	50	partly fractured basement
28	H	173.8	62.3	70	partly fractured basement
29	A	322.7	56.2	80	partly fractured basement
30	H	852.8	76.8	80	partly fractured basement
31	KH	169.6	72	80	partly fractured basement
32	KH	487.9	74.1	80	partly fractured basement
33	H	545.7	74.1	80	partly fractured basement
34	KH	235.4	48.2	80	partly fractured basement
35	HK	558.1	55.9	80	partly fractured basement
36	H	240.3	13.7	25.8	fractured basement

37	AK	163.8			fractured basement
38	HK	87.8	28.1	35.8	partly fractured basement
39	H	257	8	13.4	fractured basement
40	KH	180.8			fractured basement
41	H	40	3	10	fractured basement
42	H	45.9	3.9	15.5	fractured basement
43	H	63.4	5.4	16.8	fractured basement
45	K	129.2			fractured basement

A total of sixty-two (62) Vertical Electrical Sounding (VES) were conducted within the Pan-African granites and the result revealed three subsurface layers, the top layer which mainly composed of topsoil, laterite, and sandy and in some instance clayey, the thickness of this layer range from 0.9 to 3.7m with resistivity value of 43.5 Ωm and 69.3 Ωm respectively. The weathered layer range in thickness between 2.9 to 24.3m with resistivity value of 38.9 Ωm and 186.3 Ωm respectively. While the fractured thickness range between 35.8 to 90m with resistivity value of 605.7 Ωm and 264.7 Ωm respectively (Table 3). Biotite Gneiss forms the country rock, above which laterite is noted. Resistivity values of less than 500 Ωm are reported from 55% of stations but 45% of stations are having values between 500 Ωm and 1000 Ωm. Those stations where resistivity values are less than 1000 Ωm are representing the deeper and fractured coarse biotite granites formations.

Fresh Basement: This represents the deepest layer which is semi-infinite with resistivity ranges between 51.5 to 3621 Ωm within the study area. It is not a source of groundwater unless fractured. Its ability to conduct electrical current arises mainly from their porosity, permeability and the fluid contained within the matrix. The development of secondary porosity by jointing and fracturing, results in a further reduction of the resistivity; consequently, the resistivity of water bearing formation decreases when highly saturated in most cases. However, there is a steady increase in resistivity, it probably indicates fresh basement rock without fractures. It is advisable to stop further probing.

Table 3. Summary of Vertical Electrical Sounding within Pan-African Granites (showing aquiferous layers)

VES Locations	Layer/Curve Type	Resistivity ohm-m	Thickness (m)	Depth (m)	Layer Characteristics
1	H	245.1	40.3	45	Fractured basement
2	KH	849	1.2	1.8	Weather (Lateritic layer)
3	Q	97.1	4.6	6.3	Weather (Clayey layer)
4	K	254.8	35.8	45	Fractured Basement (Schist)
5	H	16.2	11.7	17.6	weathered basement (Clay)
6	AK	53.1	32.7	80	Fractured Basement
7	Q	54.9	33.9	80	Fractured Basement (schist)
8	Q	54.6	35.5	80	Fractured Basement (schist)
9	H	36.3	18	21.7	weathered Basement (Clay)
10	H	272.1	83.4	90	partly fractured basement
11	H	418.2	87.5	90	partly fractured basement
12	H	605.7	35.8	60	partly fractured basement
13	HK	162.8	52	60	partly fractured basement
14	H	4027.5	75	90	partly fractured

					basement
15	H	264.7	74.6	90	partly fractured basement
16	H	55.8	78.1	80	partly fractured basement
17	HK	947.8	78.1	80	partly fractured basement
18	H	605.7	35.8	60	partly fractured basement
19	H	452.3	78	80	partly fractured basement
20	AK	13.9	77.8	80	partly fractured basement
21	HK	13.5	77.4	80	partly fractured basement
22	A	2349.1	72.6	80	partly fractured basement
23	KH	292	71.5	80	partly fractured basement
24	H	2060	72.9	80	partly fractured basement
25	H	1301.3	76.2	80	partly fractured basement
26	H	35	80.3	90	partly fractured basement
27	H	279.3	54.8	60	partly fractured basement
28	H	745.4	69.7	70	partly fractured basement
29	Type H	17.3	3.2	4.2	weathered basement
30	KH	1199.4	78.2	80	partly fractured basement
31	AK	374.2	75.6	80	partly fractured basement
32	KH	576.6	78.2	80	partly fractured basement
32	AH	272.5	87.2	80	partly fractured basement
33	A	449.4	73.6	80	partly fractured basement
34	H	632.3	47.1	50	partly fractured basement
35	KH	15779	77	80	partly fractured basement
37	KH	487.9	74.1	80	partly fractured basement
38	KH	270.9	34.9	50	partly fractured basement
39	H	662.9	78.8	80	partly fractured basement
40	H	2242.7	67	80	partly fractured basement
41	H	925.2	67.2	80	partly fractured basement
42	H	2883.4	76.8	80	partly fractured basement
43	H	391.1	66.1	70	partly fractured basement
44	H	11982.2	62.9	70	partly fractured basement
45	A	256	50	80	partly fractured

					basement
46	H	1587.3	69.8	70	partly fractured basement
47	A	140.5	29	52.1	fractured basement
48	H	321.4	10.1	16.9	slightly fractured basement
49	H	228.5	13.4	28.4	fractured basement
50	HA	547.5			fractured basement
51	H	596.9			fractured basement
52	A	1151	23	43	slightly fractured zone
53	HA	16.8	23.5	56.8	fractured zones
54	H	21.2	23.7	53.7	fractured zone
55	H	54.7	14.5	44.7	fractured zone
56	H	21.4	26.5	38.8	fractured zone
57	H	523.1			fractured basement
58	H	320.9			fractured basement
59	H	172.5			fractured basement
60	A	145.6			fractured basement
61	H	52	20	52.5	fractured zones
62	A	3297.2			slightly fractured basement

Thirty-eight VES was conducted within Gundumi Formation in other to delineate its groundwater potential. The results revealed three major layers that varies from sandy clayey top soil and in some instances gravels sand top soil while the second layers are mostly silty clay, compacted laterite, compacted sandstone and sandy gravels, the third layer were majorly sandstone, in some instance silty clay (Table 4). However, where there exist a fourth layer silty clay or sandstone are mostly the delineated lithology.

The aquiferous units within this formation are mostly the saturated sandstone and sandy gravel layer as shown in table 4. Though, compacted sandstone when it possessed a secondary porosity via fracturing can equally yield enough water to the well.

Table 4. Summary of Vertical Electrical Sounding within Sedimentary Formation (showing aquiferous layers)

VES Locations	Layer/Curve Type	Resistivity ohm-m	Thickness (m)	Depth (m)	Layer Characteristics	Longitudinal Conductance (S)
1	Q	131	35.8	60	saturated sandstone	0.32 (moderate)
2	Q	189.4	34.7	60	saturated sandstone	0.24 (weak)
3	Q	40	35	60	saturated sandstone	1.01 (good)
4	H	200.9	32.9	60	saturated sandstone	0.86 (good)
5	Q	44.8	37.9	60	saturated sandstone	0.91 (good)
6	AK	87.1	29.8	60	saturated sandstone	0.46 (moderate)
7	Q	124.9	30.6	60	saturated sandstone	0.32 (moderate)
8	KH	238.8	27.9	60	sandstone	0.76 (good)
9	A	270.9	19.3	27.1	sandstone	0.82 (good)
10	H	158.5			saturated sandtone	1.05 (good)
11	KA	3357			sandstone	0.58 (moderate)
12	H	1649	0.629	0.629	gravels	0.35 (moderate)

13	H	83.2	34.42	40.6	silty clay	0.47 (moderate)
14	HA	98.5	28.71	34.8	saturated sandstone	0.58 (moderate)
15	H	1312	1.08	1.08	garavels and sand	0.47 (moderate)
16	HK	64			silty clay	0.47 (moderate)
17	HK	3067	7.8	13.4	sandstone	0.47 (moderate)
18	K	1507	13.27	20.52	compacted sandstone	0.35 (moderate)
19	K	366			saturated sandstone	0.47 (moderate)
20	K	282	18.3	18.7	sandstone	0.58 (moderate)
21	K	489	21.17	25.01	sandstone	0.47 (moderate)
22	K	30.3			saturated sandstone	0.82 (good)
23	K	165			sandstone	0.35 (moderate)
24	K	38.2			silty clay	0.35 (moderate)
25	K	1674	2.9	5.77	sand and gravels	0.35 (moderate)
26	K	266	10.1	13.17	sandstone	0.47 (moderate)
27	K	113.43			sandstone	0.35 (moderate)
28	K	644	22.46	24.31	sandstone	0.35 (moderate)
29	HQ	75.7	30.9	54.5	saturated sandstone	0.47 (moderate)
30	H	436	49.1	52.3	saturated sandstone	0.47 (moderate)
31	K	354	42.5	52.3	saturated sandstone	0.47 (moderate)
32	K	354	41.8	52.3	saturated sandstone	0.47 (moderate)
33	HK	242			saturated sandstone	0.70 (moderate)
34	K	354	41.8	52.3	saturated sandstone	0.47 (moderate)
35	K	407			saturated sandstone	0.47 (moderate)
36	H	488			saturated sandstone	0.47 (moderate)
37	K	354	41.8	41.8	saturated sandstone	0.35 (moderate)
38	HK	242			saturated sandstone	0.35 (moderate)
39	H	189	15.4	27.2	saturated sandstone	0.47 (moderate)

4. Geospatial Analysis of VES Data of the Study Area

The resistivity of the second layer (ρ_2) is the effect of fractured or weathered rocks (Figure 3 & 4). These layers determine whether the aquifer has groundwater potential or not. Figure 6 show the variation in weathered thickness across the area study area and it varies from 1.8 to 31.8m with average thickness of about 12m. For good groundwater yield in a well, Olayinka *et al,* 1997 suggested 20 – 30 m weathered thickness while Olorunfemi and Okhue, (1992) and Oladapo *et al.,* (2007) gave 25 m as the thickness of overburden that is viable for groundwater abstraction. The average thickness of weathered basement in the investigated area is 12m which is far less than the suggested average thickness in literatures. It is evident from the result that more than 50 % of the area is less than the value suggested and the only area that meets the value is south-eastern and the central part of the study area. However, most of the weathered layer is either overlying a partly fractured layer or well fractured layer except in some few cases where it serves as the main aquifer layer.

From the apparent resistivity values, it is vivid that North-eastern and southern parts of the study area have much likelihood for good groundwater storage (figure 6). The resistivity ranges from 17.8 ohm-m and 600 ohm-m and 65% of stations out of 183 stations have shown the resistivity between 17.8 ohm-m and 500 ohm-m. The range of resistivity values between 500 ohm-m and 1000 ohm-m and that between 1500 ohm-m and 2500 ohm-m are 30% and 5% respectively. Whereas, the number of locations, having resistivity values greater than 2500 ohm-m are only 5 out of total 183 stations.

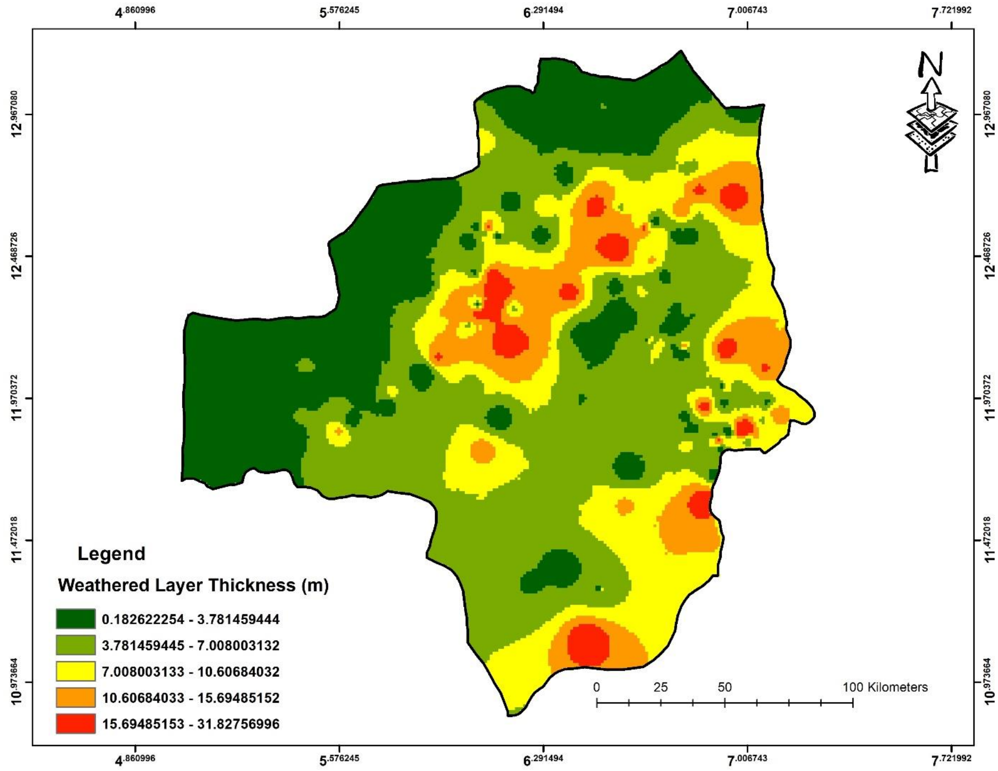

Figure 3. Weathered Thickness Map of the Study Area

Fracture is one of the factors that influence the occurrence of groundwater mostly in crystalline geologic environment. Consequently, the geospatial fractured map of the studied VES was produced from fractured thickness value as shown in figure 4. The map depicts intense fracturing at the N-E and S-W part of the study area. This equally revealed that the dominant structural trend of the studied area is in NE-SW direction. Thus form the basis for groundwater flow and storage capability (see figure 6).

Based on Olayinka *et al.,* 1997 and Oyedele and Olayinka (2012), classification of aquifer potential as a function of the basement rock, the basement rock can be classified as high fractured permeability as a result of fractured layer with resistivity less than 750 Ωm which can be seen in the northeastern and the southeastern and northeastern parts of the area investigated which is an indication of good aquifer potential. Also, basement resistivity value from 750 to 1500 Ωm is classified as medium aquifer potential which has reduced influence of weathering on it and can be seen in the southwestern and northwestern portion of the area investigated.

Areas that are underlain by older and younger metasediments rock units shows moderate degree of fracturing and weathered layer thickness compare to that of the Pan-Africa granites (Figure 2 and 6), thus more promising for groundwater development (see figure 5).

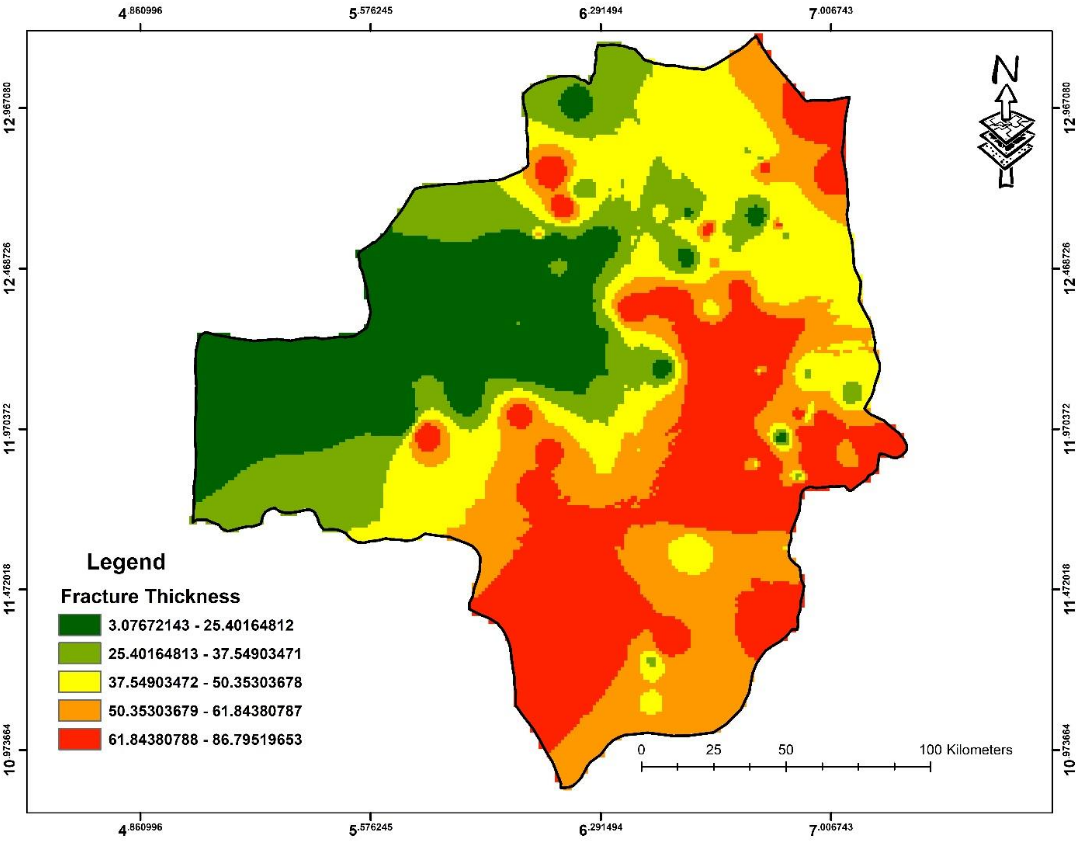

Figure 4. Fractured Thickness Map of the Study Area

The results of weathered layer thickness and fractured thickness were used to produce a groundwater potential map for the studied area (figure 5), based on the notable fact that where there is high thickness of weathered layer overlying fractured layer represent plausible zone for good or excellent groundwater potential. From the figure 3 and 6, it is clear that H type curves and KH type curves denote areas for an excellent groundwater prospect. Comparing this result with the lineament map of the studied area in figure 7 it become obvious that the area that exhibits high degree of fracturing tends to have more plausible tendencies of forming excellent water saturated aquifer. Wells or boreholes that penetrated this horizon can usually provide sufficient water to sustain even hand-pump.

This lend credence that proper rating of curve-type obtained from VES data interpretation could be used to decipher area for groundwater potential.

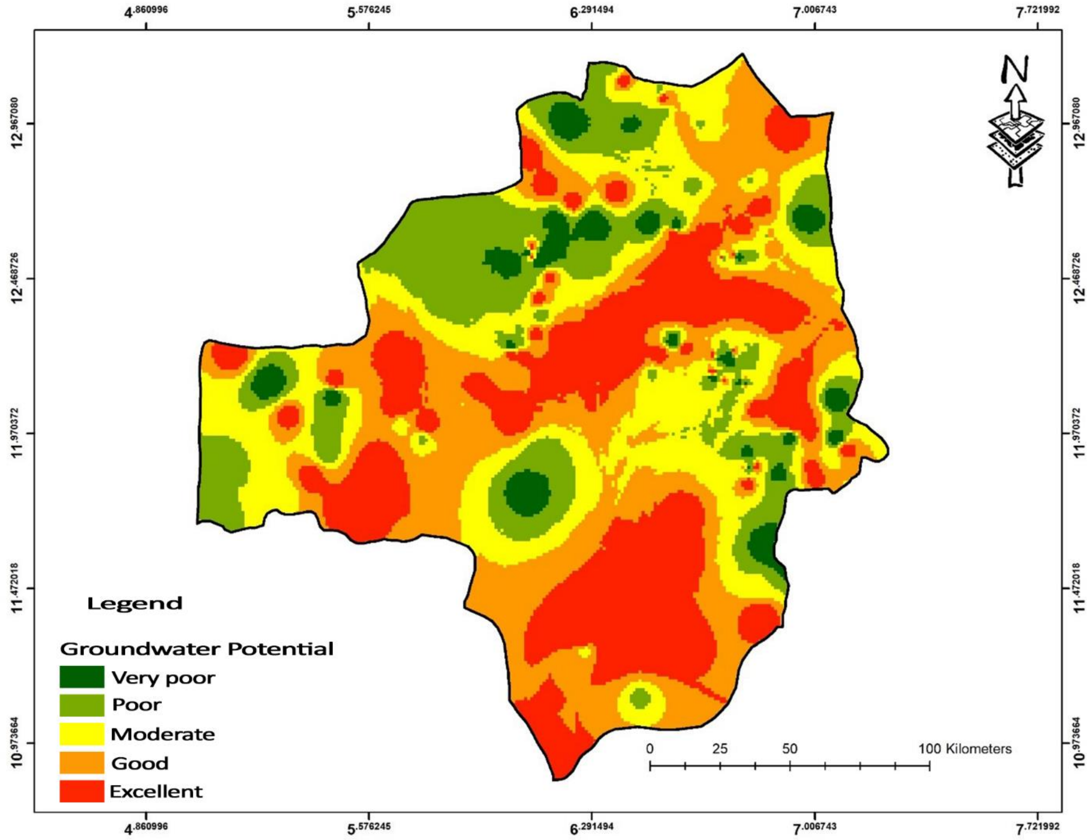

Figure 5. Groundwater Potential Map

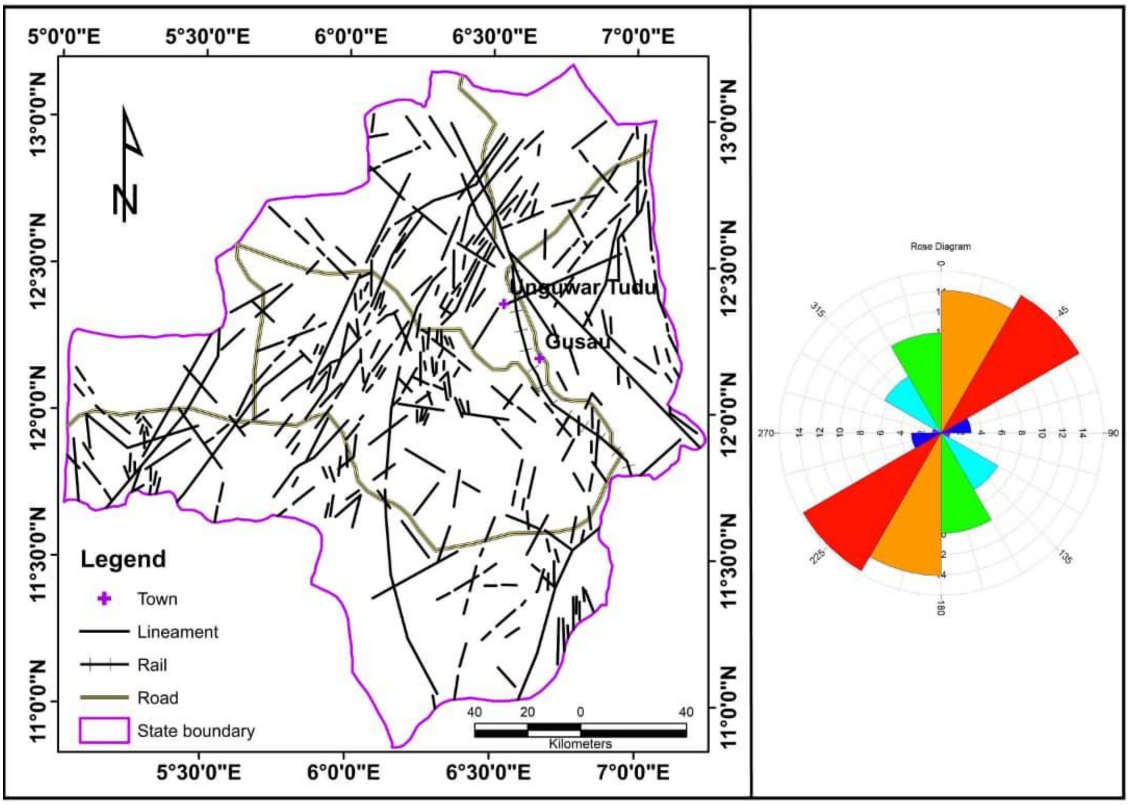

Figure 6. Lineament Map of the Study Area

5. Evaluation of Dar Zarrouk Parameters within the Sedimentary Section of the Study Area

The reflection coefficient (Rc) is a measure of the degree of fracture in an area. It could also indicate the density of formation in the aquifer. Areas of low reflection coefficient value have high water potentials (table 5). The reflection coefficient (Rc) values obtained from sedimentary rock formation of the studied area range between 0.01 to 1.00 with mean value of 0.65 which suggest excellent groundwater potential compare to the aquifers of the studied basement complex (table 6).

Low values of resistivity contrast indicate high groundwater potentials. The values of resistivity contrast obtained from the VES data within the Gundumi formation range from 0.01 to 30.73, this suggest an excellent level of groundwater potential.

Low value of coefficient anisotropy (λ) may be indicating high-density water-filled aquifer. In this work the value of coefficient anisotropy obtained from sedimentary rock unit (Gundumi formation) range from 0.44 to 3.79, this values implies moderate density-filled aquifer.

Table 5. Evaluation of Dar-Zarouk Parameters

VES Locations	Reflection Coefficient (Rc)	Resistivity Contrast (Fc)	Longitudinal Resistivity (ρ_L)	Transverse Resistivity (ρ_l)	Coefficient Anisotropy (λ)
1	0.137	0.759	113	131	1.077
2	0.069	1	144.68	189	1.143
3	0.28	0.563	32.68	43	1.145
4	0.878	15.45	38.1	201	2.296
5	0.389	0.439	41.6	45	1.038
6	0.7	0.176	72	78.89	1.047
7	0.121	0.784	94.83	125	1.147
8	0.842	11.64	36.73	238.8	2.549
9	0.177	1.434	41.23	265.39	2.535
10	0.0095	1.019	58.2	155	1.632
11	0.796	8.77	10.82	38.2	1.879
12	0.734	6.53	38.08	160.88	2.055
13	0.671	5.096	73.65	83.2	1.062
14	0.988	16.05	106.81	2798	5.12
15	0.999	0	61.43	98.5	1.27
16	0.923	0.03	76.39	160.42	1.449
17	0.956	45	22.25	306	3.687
18	0.937	30.75	37.78	1507	6.318
19	0.348	0.50	6.7	703	10.24
20	0.783	0.12	52.2	285.11	2.337
21	0.93	0.04	46	477	3.205
22	854	0.08	27	386	3.786
23	0.871	0.07	71.32	146.59	1,433
24	0.82	0.10	85.6	83.79	0.989
25	0.987	0.01	40	346.75	2.946
26	0.806	0.11	44	94.21	0.743
27	0.869	0.07	81.421	192.21	0.994
28	0.974	0.01	69.98	100.58	1.199
29	0.692	0.18	66.11	75.7	1.07
30	0.619	4.25	105	267.5	1.595
31	0.495	2.96	89.44	354	1.989
32	0.482	2.814	71.44	289	1.56
33	0.838	0.088	28.1	274	3.12
34	0.495	2.963	89.44	354	1.989
35	0.262	0.584	92	22.31	0.492
36	0.781	8.16	88	119	1.164
37	0.495	2.96	43.21	78.51	1.347

38	0.838	0.088	62.41	94.71	1.231
39	0.84	11.51	178.21	394	1.486

6. Conclusion

Groundwater potential assessment was carried out in Zamfara State, Northwestern Nigeria. A total of one hundred and eighty-three (183) vertical electrical soundings (VES) were used to identify potential groundwater bearing zones capable of sustaining economic development and potential growth of the study area. Two hydrogeological units were investigated (basement rock units and sedimentary rock unit). The qualitative and quantitative interpretations have helped in the delineating aquifer zones in the study area.

Generally, the VES result from the basement rock units revealed, four to five geoelectric layers which correspond to lateritic top soil, weathered basement (clay), partially fractured layer, fractured layer and fresh basement. The weathered/fractured layer was identified as the water bearing layer within the basement rock units of the study area. South-northeastern zone tends to be the most prospective region with the best hydrogeologic conditions for borehole siting.

Hydro-resistivity parameters evaluated from the basement rock units showed that the sounded locations have good groundwater potential that can sustain households (domestic water use).

Consequently, three geoelectric layers were delineated from VES result from sedimentary formation (section of the study area), which includes sandy clayey top/gravel sandy top soil, second layer are mostly silty clay/compacted laterite/compacted sandstone/sandy gravels layers, the third layer were majorly sandstone in some instances silty clay. However, the aquiferous layer is saturated sandstone/sandy gravel layer.

The Dar Zarrouk results revealed excellent groundwater potential within this formation. The values of coefficient anisotropy obtained from sedimentary rock unit range from 0.44 to 3.79, this signifies moderate groundwater density. Though, the values obtained from basement rock units were much high. This is concluded that the aquifers of the Gundumi formation is more promising and it can be tap for both domestic and agricultural use.

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Conflict of interest

There is no conflict of interest.

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