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Dar Zarrouk Parameters for delineation of groundwater potentials in Ganye and Environs, Adamawa State, Northeastern Nigeria

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Abstract

Groundwater is the main source of water supply in areas in Nigeria including the research area. The research is aimed at delineating groundwater potentials in Ganye and environs using Dar Zarrouk parameters. Fourteen (14) vertical electrical soundings were conducted across the study area in order to determine Dar Zarrouk parameters to determine groundwater potentials in Ganye and environs. The area is underlain by migmatite-gneiss and Pan African granites. Weathered/fractured basement constitute the aquifer type in the area. The aquifer conductivity in the study area range between 0.00871 to 0.032032 Ω^{-1} with mean value of 0.019493 Ω^{-1}. The aquifer longitudinal conductance ranges between 0.22246 to 0.759252 with mean value of 0.432846. The transverse resistance range between 627.8721 to 1,857.282 Ωm^2 with average value of 1,235.854 Ωm^2. The aquifer hydraulic conductivity range between 6.9314 to 15.562 m/day with mean value of 9.738 m/day while the transmissivity across the study area range between 114.2152 to 378.774 m^2/day with mean value of 216.0487 m^2/day.

1. INTRODUCTION

Resistivity methods are used to provide useful information on the groundwater potential (Senthilkumar *et al.*, 2017). Groundwater delineation using geoelectrical resisvity soundings are sufficient to solve variety of problems related hydrological investigations in basement terrain such as the research area (Oyeyemi *et al.*, 2018). Geoelectrical survey is a powerful tool for delineating the subsurface geology and collecting more information about the subsurface layers and structures (Mohamaden, 2016). A series of measurements of resistivity are made by increasing the electrode spacing in successive steps about a fixed point. This method of vertical exploration is known as the expanding electrode method, "Resistivity sounding" or "Depth probing" or vertical electrical sounding (VES). The apparent resistivity values obtained with increasing values of electrode separation are used to estimate the thickness and resistivity of the subsurface formations. VES is mainly employed in groundwater exploration to determine the disposition of the aquifers (Benson *et al.*, 1997).

In Vertical Electrical Sounding (VES), variations of the apparent resistivity with depth are measured. This is achieved by a gradual and systematic increase in the electrode array. Vertical Electrical Sounding, also referred to as "depth sounding" is undertaken on the assumption that the earth is made up of layers of approximately constant resistivity separated from others of differing resistivity by a plane surface. Vertical electrical sounding is a geoelectrical method commonly used to measure vertical alterations of electrical resistivity. his method has been recognized to be more suitable for hydrogeological survey than the other resistivity methods (Ankidawa, 2014). Application of the vertical electrical sounding method with a Schlumberger array is popular because of its ease of operation, low-cost and its capability to distinguish between saturated and unsaturated layers (Ankidawa, 2014). Similar studies use geoelectric resistivity soundings for delineating crystalline basement terrain in Nigeria. Study by Oyeyemi *et al.* (2018) applied geoelectrical survey for delineating groundwater in the crystalline basement terrain in south western Nigeria. Their results delineated three lithologies which include weathered basement, fractured basement and fresh basement. Geoelectric investigation of groundwater potential of Rafin-Yashi, Minna, Nigeria, the results reveal three distinct geoelectric layers, top soil, weathered/fractured basement and fresh basement (Markus *et al.*, 2018). Study by Adejumo (2018) using geoelectric soundings in a Crystalline Basement Complex Terrain of Idi-Oro Apete, Southwestern Nigeria. The result reveal five geoelectric layer layers these are topsoil, compacted lateritic clay/clay formation, weathered basement, fractured basement and presumably fresh bedrock.

Globally geoelectric soundings are also applied for delineating groundwater. Study by Mohamaden (2016) using geoelectric resistivity soundings to delineate groundwater aquifer and subsurface structures in Dakhla

Oasis, Egypt. Their results identified three geoelectric layers that include superficial, thin thickness and Quaternary deposits. Study by Suneetha *et al.* (2017) applied geoelectric survey to evaluate groundwater around coastal Maharashtra India, their results reveal that the top layer comprises of laterites followed by asbortment of clay/clayey sand and granulites as basement rocks. Study by Shantharam and Elangovan (2018) using geoelectrical survey for delineating groundwater potential zones in Coimbatore. Their result indicates that Calc-granulite and limestone rock types are better aquifers than the other rock types.

2. THE STUDY AREA

The study area is located in Ganye and forms part of the southern Adamawa Basement Complex. It is situated 8° 20' 00" N and 8° 27' 00" N and longitudes 12° 01' 00" E and 12° 75' 00" E and covers an area of about 256 km^2 (Figure 1). The study area is bounded by Jada Local 75 Government Area to the northeast, Mayo-Belwa Local Government Area to the north, Taraba State to the west, Toungo Local Government Area to the south and to the east by the Cameroon Republic. The area is inhabited by the Chamba tribe and characterized by rural setting. The major crops grown include maize, sorghum, cowpea, cassava, potatoes, rice, yam, groundnuts and sugarcane which are produced in large quantities. The population of Ganye is about 15,178 (National Population Commission, 2006). The area has a landmass of about 256 km^2, and is characterized by undulating topography gently topography. The highest elevation in the area is in the southwest and ranges from 580 to 1280 meters above sea level. The southern hills range from 560 to 720 meters above sea level. The low-lands surrounding the hills in northern and northeastern part of the area is topographically flat and is compose of the tertiary to recent alluvium deposit which provide fertile land for agricultural purposes. Figure 1 is Topographical map of the study area showing locations of VES points.

The study area falls within the humid tropics affected by the southwest rain bearing winds and by the northeast trades (harmattan) winds. The northeast winds blow from Sahara Desert from November to April, and the dry and dusty laden cloudiest monsoon, which comes from the southwest, dominates the month of May to September (Kwache and Ntekim, 2015). The harmattan period which begins from the month of November is generally characterized by low humidity due to the onset of the tropical continental air masses of the dry dust laden northeast trade wind while during rainy season the humidity is high. The temperature of the area varies from time to time, the minimum average for the year being 24°C and 15.2°C while maximum is 39.7°C and 40°C (Adebayo and Tukur, 1999). The mean annual rainfall in the research area is between 700 mm to 796 mm as recorded in the year 2019. These data show that the wettest months are from April to October (seven months) and the dry season is between November to March (five months). The period of high rainfall is between July and September (with peak in August), while the period of low rainfall is between December and April (with lowest in March).

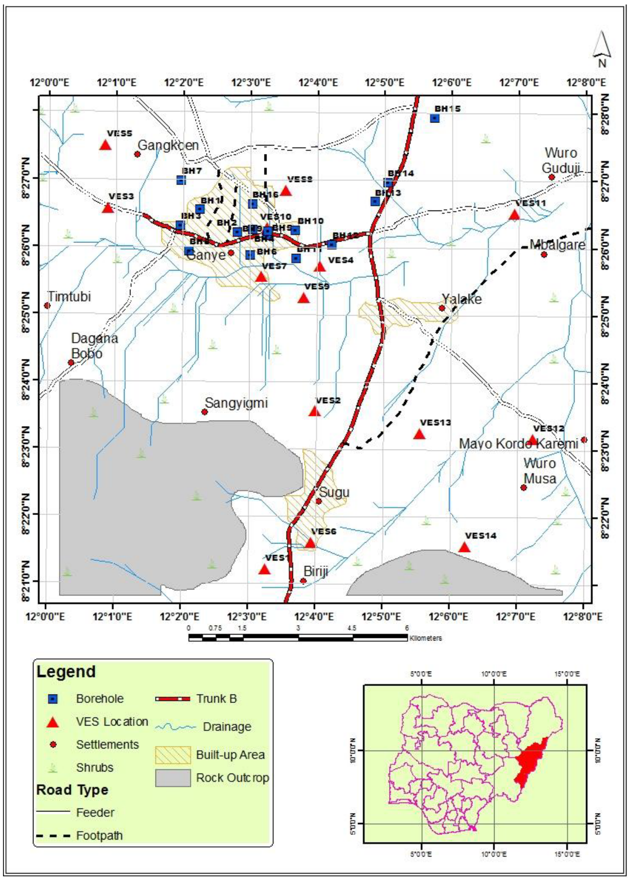

Figure 1: Topographical map of the study area showing locations of Borehole and VES points

2.1 Geology of the study area

Ganye, the study area is situated at the northern part of the geologically unexplored Adamawa Massif, northeastern Nigeria. The area is predominantly underlain by Granite gneiss and Granites (Figure 2). Minor rocks are migmatite gneiss, pegmatite, dolerites, mylonite and quartz vein. These rocks have experienced some tectonic deformations, evident by the presence of joints and faults. Granite gneiss outcrops in extreme northeast of the area and extends towards the east, southeast and central part and occupies about two-third of the entire area. The granite gneiss exhibits alternating features of dark and light minerals. The light minerals are mostly quartz and feldspar while the dark minerals are biotite and hornblende (Kwache and Bature, 2014). The granites are similar in mineral composition but vary texturally and structurally and include the migmatites, equigranular granites, porphyritic granites and fine-grained granites. Migmatites in the area consist of granitic materials alternating with biotite-enriched mafic materials. They are poorly foliated, mostly leucocratic, coarse-grained and show considerable variations in structure, texture and to a lesser extent, mineralogy. All phases of transition are observed between the variants which probably reflect the composition and

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physical conditions of the original country rock and various degrees of granitization. Biotite and iron ore minerals are the sole ferromagnesian minerals. Pegmatitic segregations, patches of granites and xenoliths of mafic rocks are very conspicuous in the migmatites. The granitic portion of the migmatite is often leucocratic and medium- to coarse-grained. Essential minerals occurring in equigranular granites include feldspar, quartz and biotite. Sericite and iron ore minerals constitute the alteration products.

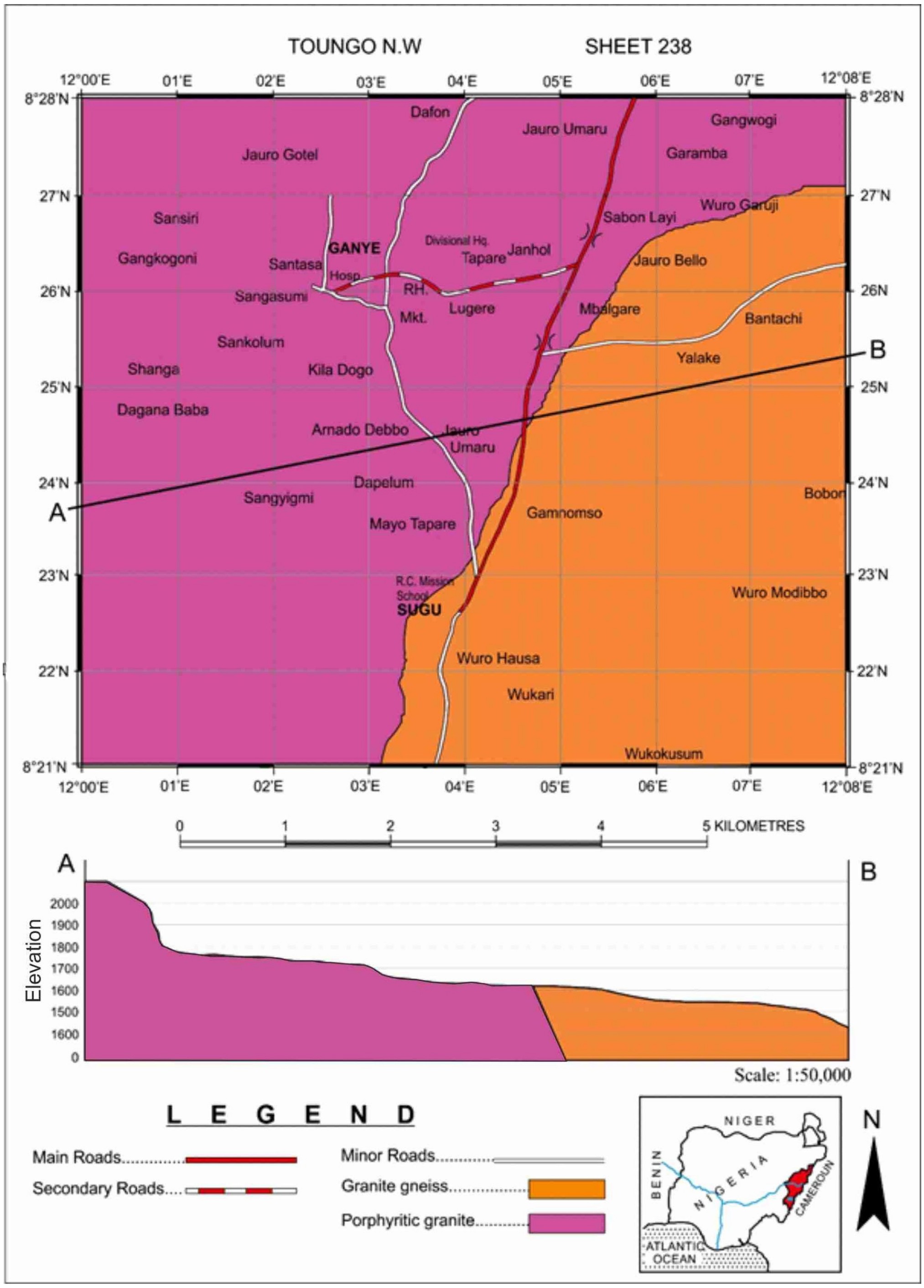

Figure 2: Geological map of the study area

3. MATERIALS AND METHODS

3.1 Electrical resistivity survey

Surface electrical resistivity surveying is based on the principle that the distribution of electrical potential in the ground around a current-carrying electrode depends on the electrical resistivities and distribution of the surrounding soils and rocks. The usual practice in the field is to apply an electrical direct current (DC) between two electrodes implanted in the ground and to measure the difference of potential between two additional electrodes that do not carry current. Usually, the potential electrodes are in line between the current electrodes, but in principle, they can be located anywhere. The current used is either direct current, commutated direct current (i.e., a square-wave alternating current), or AC of low frequency (typically about 20 Hz) (Zohdy *et al.,* 1974).

3.2 Field procedure

Electrodes were layout with non-conducting measuring tapes. The field procedure consists of expanding the current electrodes 'AB' while keeping the potential electrodes 'MN' relatively fixed. For each reading, the current was sent into the ground through A and B which setup the measured potential difference between the potential electrodes M and N, the magnitude of the potential difference developed is a measure of the electrical resistance and between probes. The resistance is in turn a function of the geometrical configuration of the electrodes and the electrical parameters of the ground (Dobrin, 1976; Ankidawa. 2014). The electrode separation (AB/2) was varied from 1 to 100 m. The SAS 1000 Terrameter was positioned half way between the potential electrodes M and N, and was connected to terminals P1 and P2 and to terminals M and N. The current electrodes A and B were connected to terminals C1 and C2 respectively, these cables were run in parallel adjacent to the SAS 4000 Terrameter and were arranged symmetrically with respect to the potential electrodes. Figure 3 shows topographical map of the area showing locations of VES points. In this array, four electrodes were connected to the Terrameter using the connecting cables and spread linearly, with the potential electrodes close to the sounding station and the current electrode at the end of the spread. The computed resistance for the investigated subsurface was displayed on the digital screen of the Terrameter. Record of the displayed value was taken at each sounding point while the coordinates and elevation of each of the sounding points was noted using a Global Positioning System (GPS). In each station, depth of investigation was systematically increased by expanding the current electrodes spacing progressively from 1 m to 100 m on both sides and taking apparent resistivity reading at each spread. The above processes were repeated for each of the sampled VES locations.

3.3 Geophysical (electrical resistivity) survey data processing

The field data for geoelectric soundings are represented in graphs, in which half of the current electrode separation, AB/2, is plotted on the abscissa (x-axis), while the corresponding apparent resistivity is plotted on the ordinate (y-axis). The scales of both axes are logarithmic. The curves are interpreted qualitatively in terms of the vertical distribution of the calculated formation resistivities. This is done using the traditional methods of auxiliary point techniques and curve-matching procedure employing albums of theoretical curves. Quantitative interpretation of the curves involved partial curve matching using two-layer Schlumberger master curves and the auxiliary K, Q, A and H curves. Output from the quantitative interpretation was modelled using computer iteration (Benson *et al.*, 1997). From this, estimates of layer resistivities and thicknesses were obtained which served as starting points for computer assisted interpretation. The conventional curves and auxiliary point diagrams (theoretical curves) used in the interpretation helped in obtaining a good fit between the observed field curves and the theoretical curves during total and partial matching.

3.4 Dar Zarrouk technique of determining aquifer hydraulic characteristics

The primary purpose of the resistivity method is to measure the potential differences on the surface due to the current flow within the ground. Since the mechanisms which control the fluid flow and electric current and conduction are generally governed by the same physical parameters and lithological attributes, the hydraulic and electric conductivities are dependent on each other. To obtain a layer parameter, a unit square cross sectional area is cut out of a group of n-layers of infinite lateral extent. The total transverse resistance R is given by:

$$R = \sum_{i=i}^{n} h_i \rho_i \quad (1)$$

For a horizontal, homogeneous and isotropic medium

$$\rho = \frac{(R_1 - R_2)}{(h_1 - h_2)} \quad (2)$$

where hi and ρi are respectively the thickness and resistivity of the ith layer in the section. The total longitudinal conductance S can be estimated using equation 3

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (3)$$

The longitudinal layer conductance Si can also be expressed by

$$S_i = \sigma_i h_i \quad (4)$$

where σi is the layer conductivity. Conductivity in this case is analogous to the layer transmissivity, T, given by:

$$S = K_i h_i \quad (5)$$

Ki is the hydraulic conductivity of the ith layer of thickness hi. R and S of equations 1 and 3 are called the Dar Zarrouk parameters, which have been shown to be powerful interpretational aids in groundwater surveys according to Ohm's law (Zohdy *et al.,* 1974):

$$j = \sigma E \tag{6}$$

where j is the current density; and σ is the electrical conductivity, which is the reciprocal of the resistivity, ρ. For aquifer material having unit cross-sectional and thickness h, the two fundamental laws can be combined to give probable relationship between electric and hydraulic characteristics of the formation, according to Niwas and Singhal (1981):

$$T = K\sigma R \tag{7}$$

$$T = \frac{KS}{\sigma} \tag{8}$$

where T is the transmissivity; R is the transverse resistance of the aquifer, K is the hydraulic conductivity and S is the longitudinal conductance. According to Heigold *et al.* (1979), hydraulic conductivity can be determined using:

$$K = 386.40R_{rw}^{-.93283} \tag{9}$$

where K = hydraulic Conductivity and Rrw = Aquifer Resistivity.

It has also been shown by Niwas and Singhal (1981) that in areas of similar geologic setting and water quality the product Kσ remains fairly constant. Thus, knowledge of K from some existing boreholes and of σ from VES sounding can be used to estimate Kσ for the same geologic zone. Hence, the aquifer hydraulic conductivity and transmissivity for the entire area can be estimated. This relationship forms the basis for the determination of aquifer hydraulic parameters used in this study.

4. RESULTS AND DISCUSSION

Aquifer systems in the area were delineated using the interpreted result from the geophysical (Electrical Resistivity) survey. Fourteen (14) VES Stations were surveyed within the study area using ABEM SAS 1000 Terrameter system. Quantitative interpretations of vertical electrical sounding data IX1D Interpex software often lead to the generation of geoelectric layers. The information from these geoelectric layers enhances the identification and interpretation of layer parameters which includes number of layers and their apparent resistivity, thickness and depth, curve type and root mean square error (Table 1). Three types of sounding curves have been identified, these are H-type, HK-type and KH-type of curve and the layers vary from three to four layers (Figure 3). H-type curves are characterized by high-low-high resistivity depicting a low resistivity value at the centre and constitute about 80% of the total curve type. HK-type curves are characterized by low-high-low resistivity depicting a high resistivity value at the centre. KH-type curves are characterized by low-high-high resistivity characteristics depicting a high resistivity value. Qualitative analysis of the curve types by inspection revealed that the area has VES 1, VES 2, VES 3, VES 4, VES 5, VES 7, 229 VES 9, VES 10, VES 12, VES 13 and VES 14 as H-type curves while VES 11 is Q-type. VES 6 is KH and VES 8 is HK-Type curve. Quantitative analysis of the curve revealed that 42.86% are 4 layered-curve constituting VES 1, VES 2, VES 6, VES 8, VES 10 and VES 13 while 57.14% are 3 layered-curve constituting VES 3, VES 4, VES 5, VES 7, VES 9, VES 11, VES 12 and VES 14. The aquifer resistivity in the study area ranges from 31.22 to 74.47 Ωm with an average of 51.94 Ωm. From the results obtained, aquifer thickness ranges from 15.85 to 34.79 m having an average 25.32 m. The high thickness at some VES points makes it prolific and desirable for groundwater tapping from the thick weathered basement. The VES with the greatest thickness of 34.79 m was observed at Gamnomso.

Geophysicist based on field experience devised a means of identifying aquifer type based on apparent resistivity of the layers penetrated. Apparent resistivity of the top soil does not have a specific range of values because of the different constituent materials, but it is believed that loose sandy soil has higher apparent resistivity values compared to water-logged moist clayey top soil with lower resistivity values ranging from 1 to 25 Ωm. Lateritic soil has very high resistivity of about >150 Ωm due to the presence of silicate materials. It is generally believed that weathered/fractured basement where water accumulates has lower resistivity values ranging from 25 to 120 Ωm while fresh basement has higher resistivity (>125). Due to the inhomogeneity of the subsurface layers penetrated by the current during electrical resistivity survey, the measured resistivity values are “apparent” i.e. not real. This inhomogeneity causes ambiguity in interpreted data which makes it very hard for geophysicist to have an absolute degree of confidence. Nonetheless, an electrical resistivity still serves the purpose of delineating areas of groundwater potentials. Geoelectric section constructed from the analysis of VES data coincide with the corresponding geological sections. Layers of different lithology may have the same resistivity and they form a single geoelectric layer. Anisotropy of the subsurface layers is another factor which will introduce errors in the estimates of true resistivity and depths in the interpretation of VES curves (Galin, 1979). To assess the accuracy of the VES interpretations, soundings were carried out in close proximity of existing wells. The results of the VES soundings were then correlated with the existing borehole lithologies. Figure 4 represents the correlated geoelectric sections beneath VES points with available borehole logs. Section along A-A^1 connects

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BH1 and BH7 with VES7 and VES14 respectively (Figure 5). Both VES7 and VES14 has 3 layers consisting of the overburden top soil with apparent resistivity of 130.27 Ωm and 386.56 Ωm respectively, weathered aquiferous basement with apparent resistivity of 31.29 Ωm and 68.39 Ωm respectively. The fresh basement has apparent resistivity of 131.83 Ωm and 226.1 Ωm respectively. Both boreholes are characterized by an average aquifer thickness of 22.57 meters. Section along B-B[1] links BH3 with VES7, VES9 and VES12 (Figure 6). All three VES points have three layers consisting of overburden top soil, weathered aquiferous basement and fresh basement.

Table 1: Geoelectric parameters and lithologic delineation at Ganye Area (model parameters)

VES	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Curve Type	RMS % error
1	1	238.7	0.651	0.651	Top soil	H- Type	0.31
	2	281.458	7.935	3.587	Lateritic soil	ρ1>ρ2< ρ3	
	3	50.899	20.165	22.751	Weathered basement		
	4	341.2	–	–	Fresh basement		
2	1	557.02	1.0118	1.0118	Top sandy soil	H- Type	0.82
	2	158.46	5.0062	5.0181	Lateritic soil	ρ1>ρ2< ρ3	
	3	65.502	25.3643	25.382	Weathered basement		
	4	246.92	–	–	Fresh basement		
3	1	156.94	6.0843	6.0843	Top soil	H- Type	0.46
	2	67.653	25.308	25.393	Weathered basement	ρ1>ρ2< ρ3	
	3	814.94	–	–	Fresh basement		
4	1	301.54	3.5333	3.5333	Top soil	H- Type	0.58
	2	68.122	22.36	22.893	Weathered basement	ρ1>ρ2< ρ3	
	3	492.22	–	–	Fresh basement		
5	1	437.16	1.1506	1.1506	Top soil	H- Type	0.79
	2	114.8	13.981	15.132	Fresh basement	ρ1>ρ2< ρ3	
	3	435.07	–	–	Fresh basement		
6	1	14.544	0.1822	0.1822	Top soil	KH- Type	0.63
	2	104.37	3.966	3.2044	Lateritic soil	ρ1<ρ2> ρ3	
	3	74.465	24.9654	18.169	Weathered basement	ρ1>ρ2< ρ3	
		203.04	–	–	Fresh basement		
7	1	130.27	5.782	1.782	Top soil	H- Type	0.48
	2	31.219	23.329	30.11	Weathered basement	ρ1>ρ2< ρ3	
	3	131.83	–	–	Fresh basement		
8	1	31.692	1.6322	1.6322	Top soil	HK- Type	0.92
	2	235.28	5.7501	5.3832	Lateritic soil	ρ1>ρ2< ρ3	
	3	33.633	18.673	19.056	Weathered basement	ρ1<ρ2> ρ3	
		128.483	–	–	Fresh basement		
9	1	11.164	6.5203	2.5203	Top soil/Clayey	H- Type	0.05
	2	38.987	20.0454	20.565	Weathered basement	ρ1>ρ2< ρ3	
	3	246.57	–	–	Fresh basement		
10	1	455.58	3.4091	3.4091	Top soil	H- Type	0.85
	2	154.77	5.4407	5.8498	Lateritic soil	ρ1>ρ2< ρ3	
	3	68.865	15.3205	18.17	Weathered basement		
	4	165.96	–	–	Fresh basement		
11	1	285.98	5.0955	1.0955	Top soil	H-Type	0.15
	2	57.21	15.7	15.845	Weathered basement	ρ1>ρ2< ρ3	
	3	221.544	–	–	Fresh basement		
12	1	140.22	7.3397	1.3397	Top soil	H-Type	1
	2	33.245	24.123	24.3735	Weathered basement	ρ1>ρ2< ρ3	
	3	640.45	–	–	Fresh basement		

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13	1	343	3.1237	3.1237	Top soil	H-Type	0.65
	2	382.17	3.5867	5.7104	Lateric soil	ρ1>ρ2< ρ3	
	3	44.901	34.085	34.796	Weathered basement		
	4	278.11	–	–	Fresh basement		
14	1	386.54	5.9827	5.9827	Top soil	H-Type	1.02
	2	68.385	21.83	21.812	Weathered basement	ρ1>ρ2< ρ3	
	3	226.1	–	–	Fresh basement		

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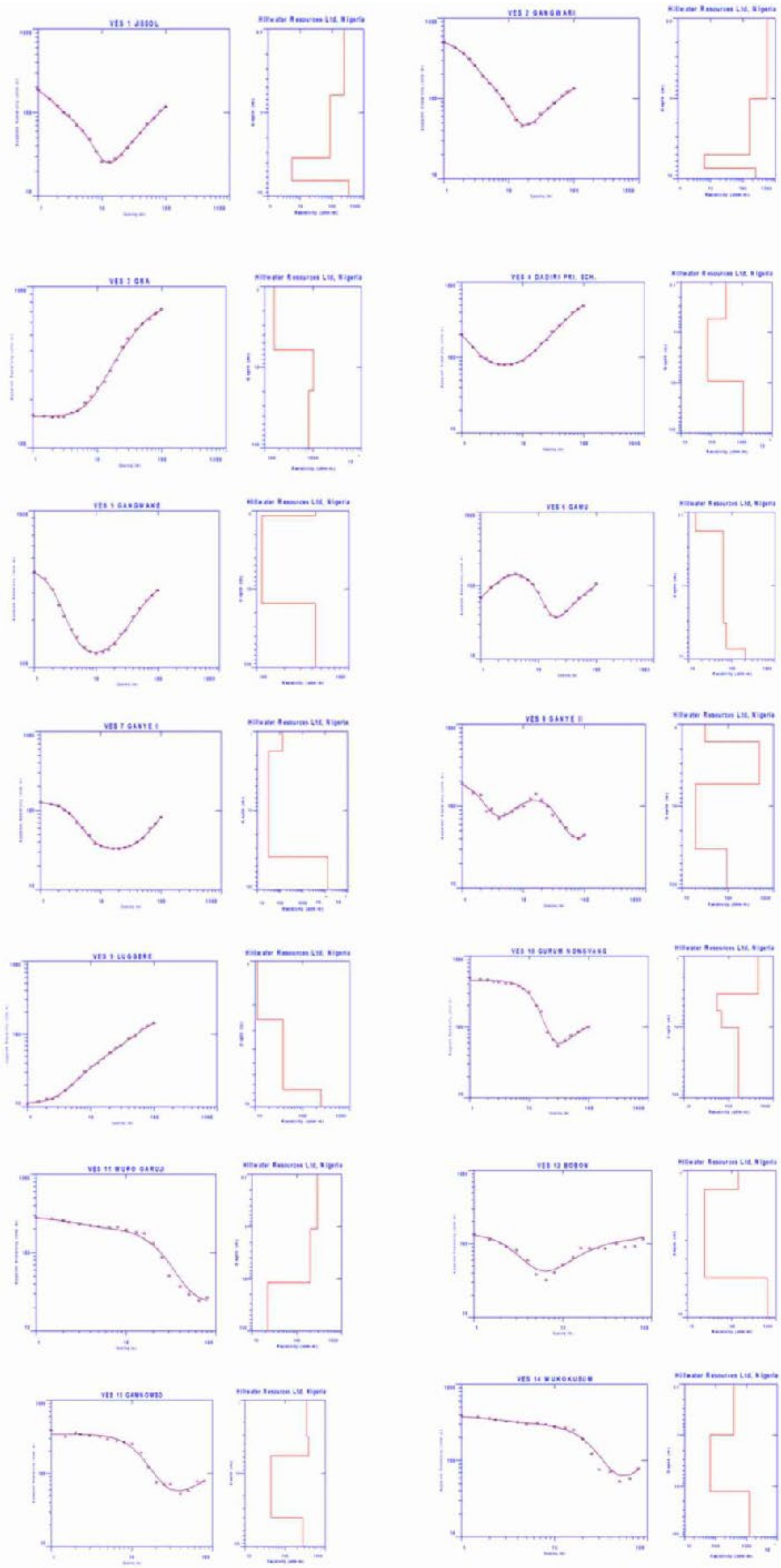

Figure 3: Different curve type from interpreted VES data of the study area

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The overburden top soil has apparent resistivity ranging from 11.16 Ωm to 140.22 Ωm while the weathered aquiferous basement is ranged from 31.22 Ωm to 38.99 Ωm with an average thickness of 22.50 meters. Section along C-C^1 connects BH13, BH14 and VES15 with VES4 and VES9 respectively (Figure 7). Both VES9 and VES14 has three layers consisting of the overburden top soil with apparent resistivity of 301.54 Ωm and 11.16 Ωm respectively. The weathered basement has apparent resistivity of 68.12 Ωm and 38.939 Ωm respectively while the fresh basement has resistivity of 492.22 Ωm and 246.57 Ωm. The boreholes have an average aquifer thickness of 22.57 meters.

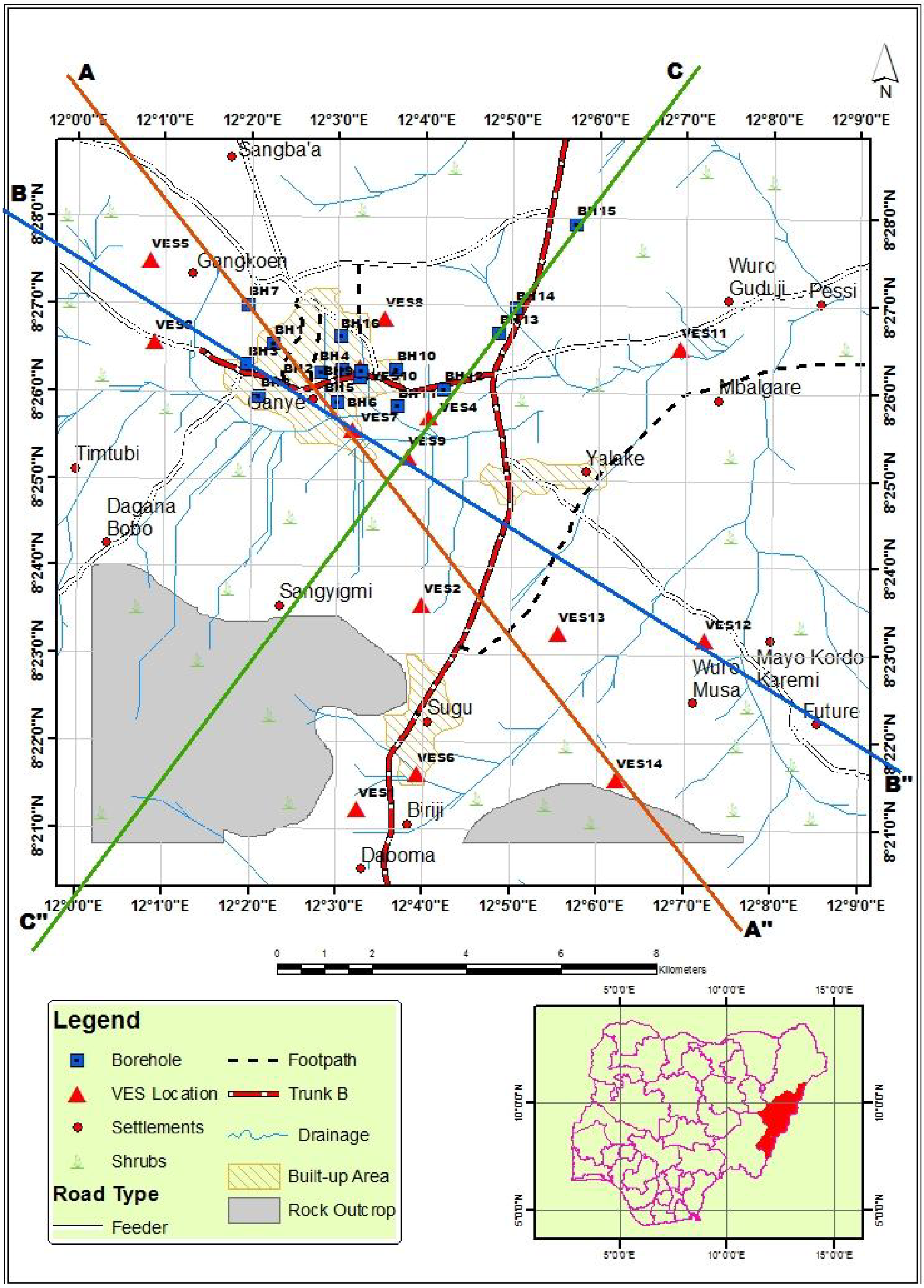

Figure 4: Map of the study area showing correlations between geoelectric and lithologic sections

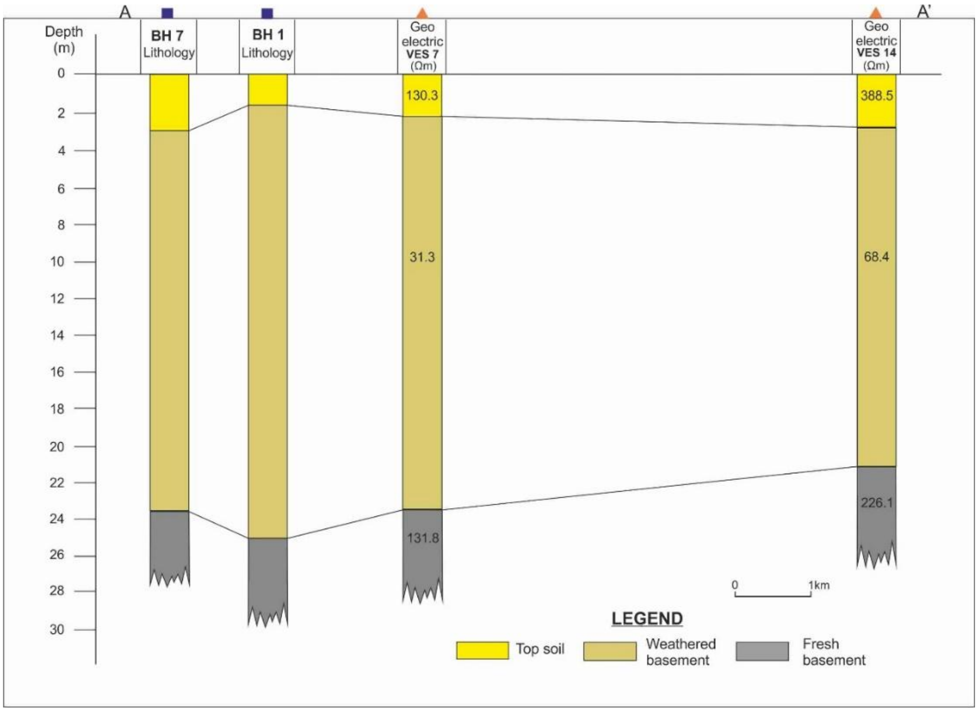

Figure 5: Correlation between borehole lithological section and geoelectric section along AA[1]

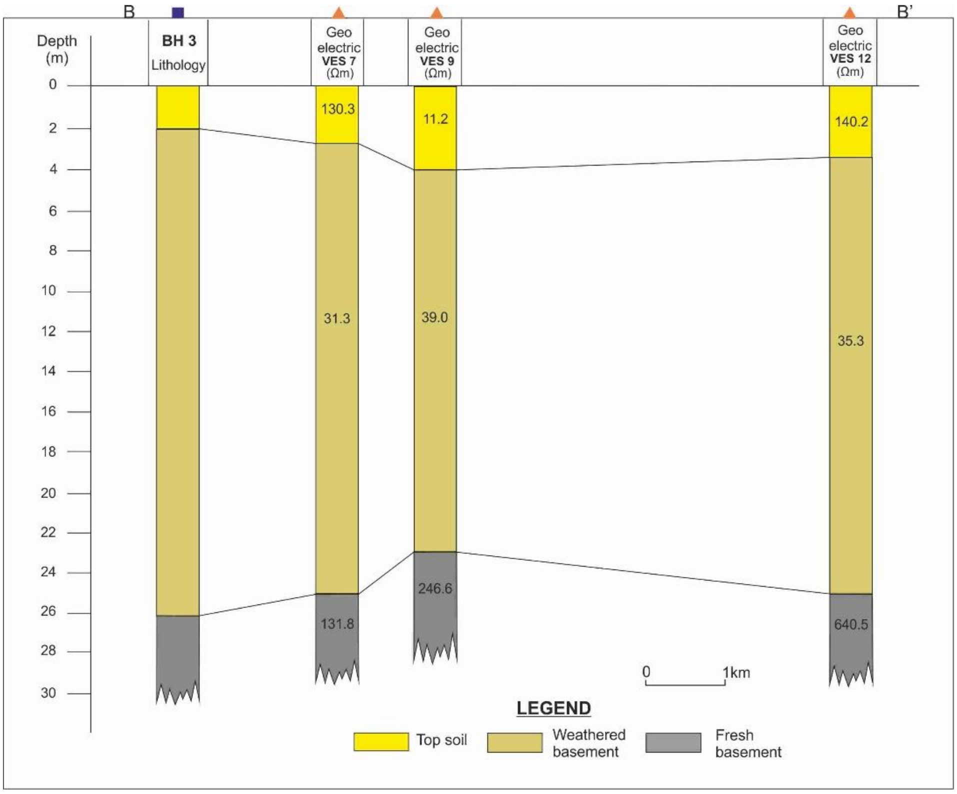

Figure 6: Correlation between borehole lithological section and geoelectric section along BB[1]

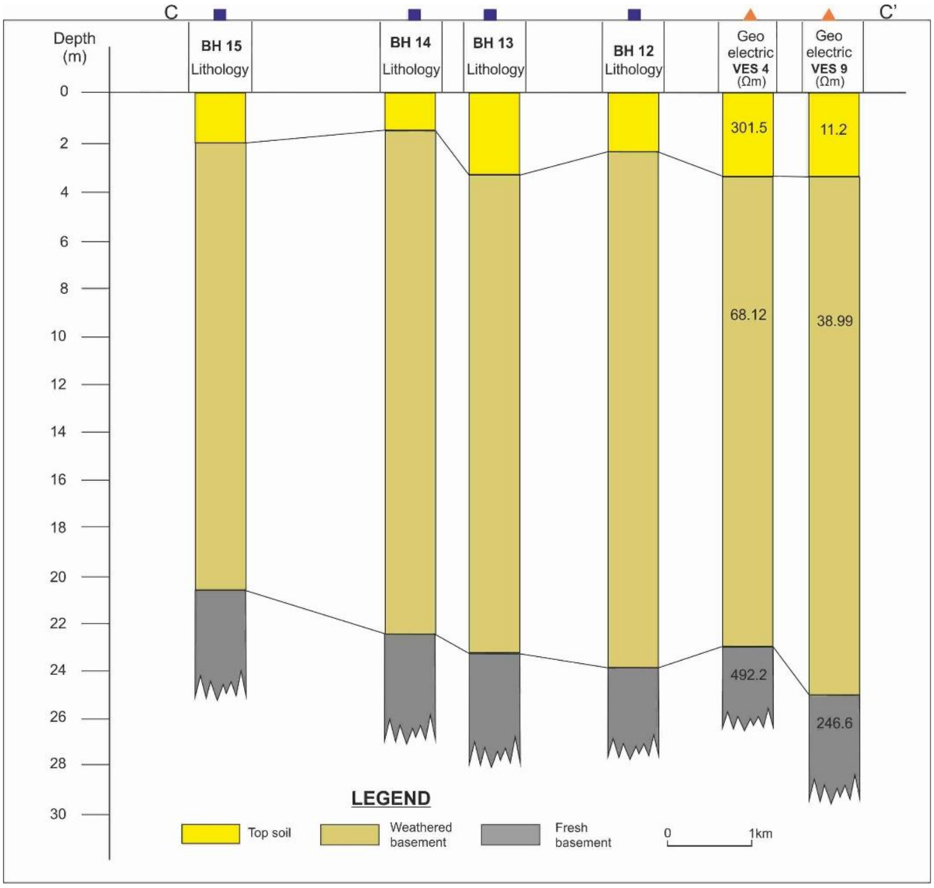

Figure 7: Correlation between borehole lithological section and geoelectric section along CC[1]

Table 2: Summary of Dar Zarrouk geoelectric parameters in the area

VES Stations	Aquifer Resistivity ρ (Ωm)	Aquifer Thickness (h) (m)	Aquifer Cond. σ = 1/ρ	Longitudinal Conductance S = σh (Ω)	Transverse Resistance R = hρ	Hydraulic Conductivity K (m/day)	Transmissivity Tr = KS/σ (m^2/day)	Groundwater Potential
VES 1	50.9	20.17	0.019646	0.39626	1026.653	9.8846	199.3724	Moderate
VES 2	65.5	25.36	0.015267	0.387171	1661.08	7.8125	198.125	Moderate
VES 3	67.653	25.31	0.014782	0.374132	1712.222	7.5807	191.867	Moderate
VES 4	68.12	22.36	0.01468	0.328244	1523.163	7.5319	168.413	Moderate
VES 5	114.8	13.981	0.008711	0.121777	1604.904	4.6287	64.708	Moderate
VES 6	74.47	24.94	0.013429	0.334919	1857.282	6.9314	172.8691	Moderate
VES 7	31.22	23.33	0.032032	0.747307	728.3626	15.562	363.0615	Moderate
VES 8	33.63	18.67	0.029735	0.555152	627.8721	14.55	271.6485	Moderate
VES 9	38.99	20.045	0.025649	0.514134	781.5546	12.675	254.0704	Moderate
VES 10	68.87	15.32	0.014521	0.222462	1055.088	7.4553	114.2152	Moderate
VES 11	57.21	15.7	0.017479	0.27442	898.197	8.8637	139.1601	Moderate
VES 12	33.25	24.12	0.030075	0.725409	801.99	14.705	354.6846	Moderate
VES 13	44.9	34.09	0.022272	0.759252	1530.641	11.111	378.774	Moderate
VES 14	68.39	21.83	0.014622	0.319198	1492.954	7.0414	153.7138	Moderate
Min.	31.22	13.981	0.008711	0.222462	627.8721	6.9314	114.2152	
Max.	114.8	34.09	0.032032	0.759252	1857.282	15.562	378.774	
Mean	58.42	21.80	0.019493	0.432846	1235.854	9.738086	216.0487	

According to Bouwers (1978) standards for hydraulic conductivity for soil materials include; clay soils (surface) range from 0.01 to 0.2 m/day, deep clay beds range between 10^{-8} to 10^{-2} m/day, Loam soils 0.1 to 1 m/day, fine sand 1 to 5 m/day, medium sand 5 to 20 m/day, coarse sand 20 to 100 m/day, gravel 100 to 1,000 m/day. The longitudinal conductance (Ohm) is used in classifying aquifers protective capacity (Okonkwo and Ugwu, 2015, Ankidawa and Seli, 2018). According to Braga *et al.* (2006), longitudinal conductance S>1.0 indicates high aquifer protection while longitudinal conductance S<1.0 indicates probable risks of contamination. The values of longitudinal conductance range from 0.22246172 to 0.75925248, with an average value of 0.48 which is below S<1.0. These suggest that the aquifers in the study area are liable to probable risks of contamination. Study by Ankidawa and Seli (2018) on the floodplain of River Benue obtained longitudinal conductance S<1.0. Figure 8 shows the distribution of longitudinal conductance across the study area. Longitudinal conductance is high in the south eastern part of the study area and low in the north western part of the study area (Figure 8). The longitudinal conductance increases from north western to the south eastern part of the study area. These suggest that the aquifers in the north western part of the study area are liable to probable risks of contamination.

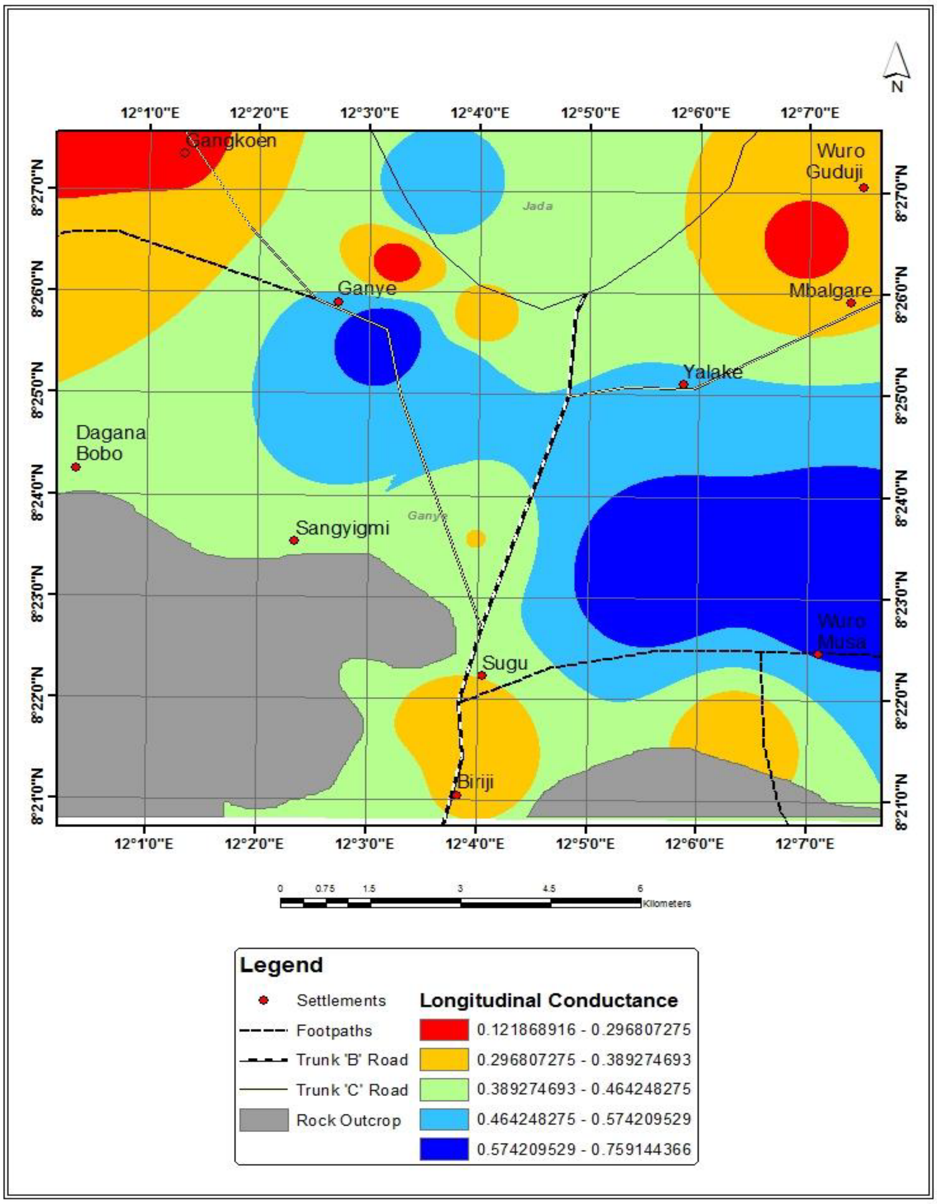

Figure 8: Aquifer longitudinal conductance (ohm) across the study area

The transverse resistance range between 627.8721 to 1857.2818 Ωm^2 with mean value of 1132.87947 Ωm^2 (Table 2). Transverse resistance is being used to classify groundwater zones (Toto *et al.*, 2008; Nejad, 2009). Transverse resistance is high in the southern and west eastern parts of the study area and low in the north, east and northeastern parts of the study area (Figure 9). This suggests that aquifer yield is high in the southern and west eastern parts of the study area. Similar findings were observed by Ankidawa and Seli (2018) on the floodplain of River Benue northeastern part of Nigeria. According to Ezeh (2012) low transverse resistance indicates inadequate aquifer thickness or mixed of finer sediment in the formation. This suggest that aquifers in the north, east and northeastern parts of the study area are probable having mixed of sediments.

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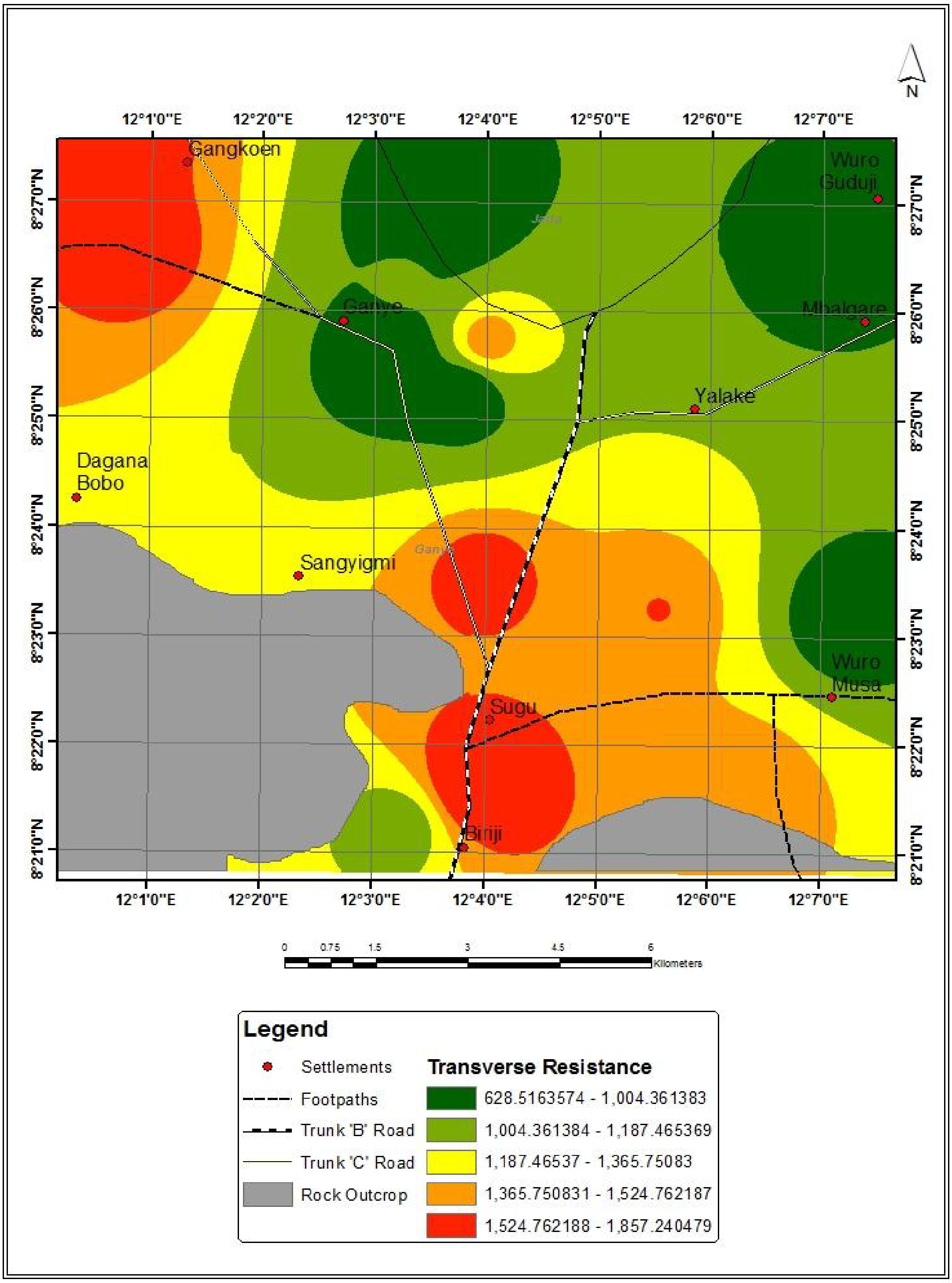

Figure 9: Aquifer transverse resistance (Ωm^2) across the study area

The result of the hydraulic conductivity range from 6.9314 to 15.562 m/day with an average of 9.738 m/day (Table 2). This suggests that the sediments in the study area are of medium sand (Table 3). The formation of the study area allows free flow of groundwater to recharge the aquifers. The hydraulic conductivity is low in the north western part of the study area and high in the south eastern part of the study area.

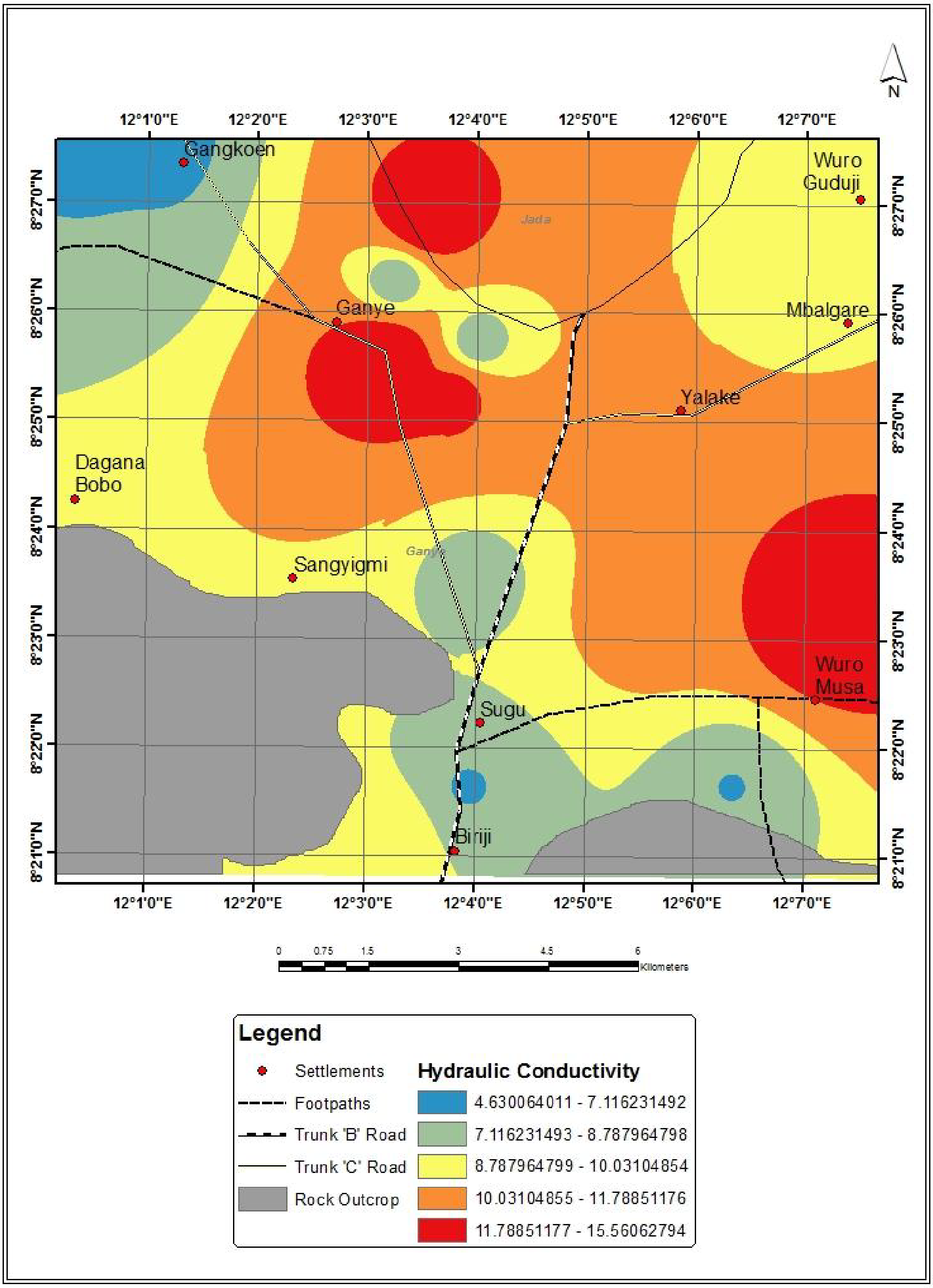

Figure 10: Aquifer hydraulic conductivity (m/day) across the study area

Transmissivity values according to Offodile (1992) for classification of well potential include: >500 m^2/day is high potential, 50 to 500 m^2/day is moderate potential, 5 to 50 m^2/day is low potential, 0.5 to 5 m^2/day is very low potential and <0.5 m^2/day is negligible potential. The transmissivity values range from 114.215 m^2/day to 378.774 m^2/day with average value of 236.336 m^2/day (Table 2) indicate moderate potential. The areas with high transmissivity can be attributed to having thick weathered basement. Areas of low potential in the area constitute 14.29% while 85.71% is of moderate potential and covers the north, eastern, western and southern parts of the study area (Figure 11). The aquifer in the study area can therefore be delineated as moderate potential and is good for productive boreholes having moderate transmissivity.

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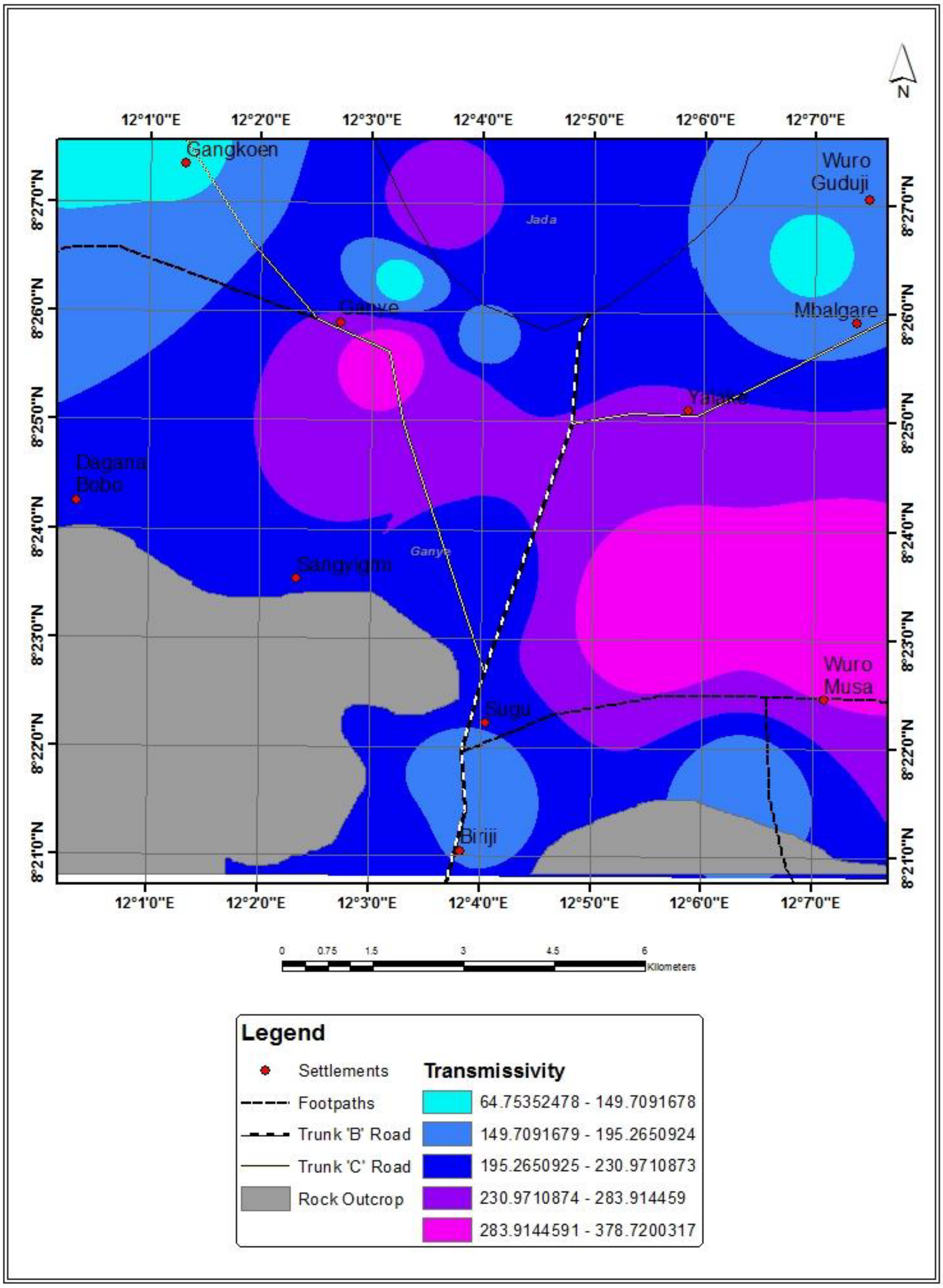

Figure 11: Aquifer Transmissivity (m^2/day) across the study area

4.1 Hydraulic head distribution

The northern, north west, central and southeastern part of the research area constitutes the recharge areas (Figure 12). The recharge areas include Gotel, Santasa, Ganye, Dafon, Mbalgare and Janhol (Figure 12). The flow is from the northeast around Wuro Garuji towards Ganye, from east around Wuro Musa to Yalake, from west, southwest and south towards Sugu, and from northwest aroud Gangkoen towards Ganye (Figure 12). The northwest, north eastern and central part of the research area constitute the discharge areas. The discharge areas include Gomnoms, Tapare, Lugere, Gangwogi, Sabon layi, Wuro Garuji, Garamba and Wuro Kusum (Figure 12). Studies by Kwami *et al.* (2019a), Kwami *et al.* (2019b) show similar patern of groundwater flow. Ankidawa *et al.* (2020) estimated hydraulic conductivity in Otukpo area which is similar to what was observed in the present study.

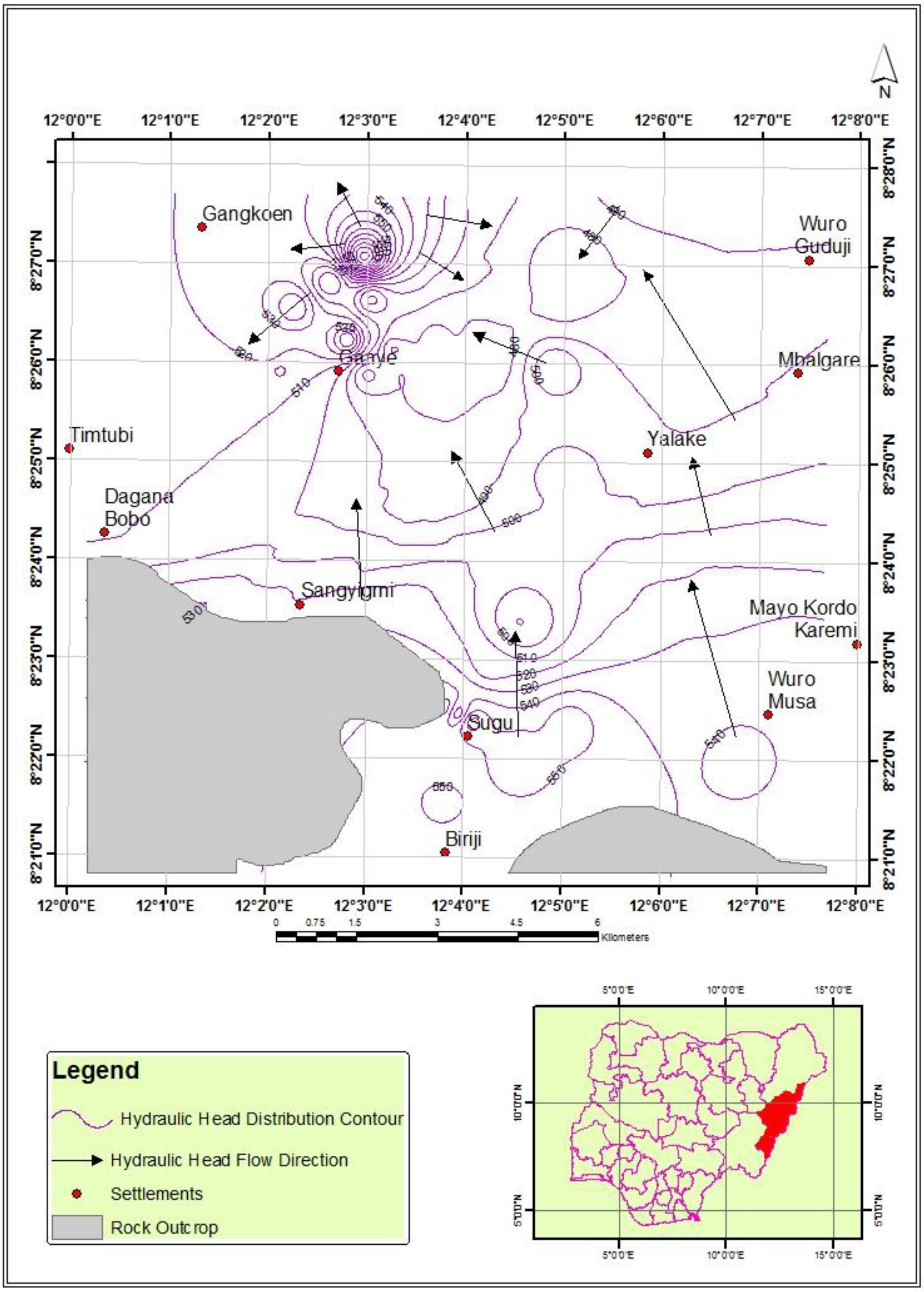

Figure 12: Hydraulic head distribution in unconfined aquifer in the study area

5. CONCLUSION

The study area is underlain by migmatite-gneiss complex rocks and granite rocks. The area was subjected to orogenesis during the Pan African orogeny which involved uplift, cooling, fracturing, faulting and high level magmatic activity which gave rise to the emplacement of Pan African granites revealed by geologic structures. The electrical resistivity survey shows that the major aquifer systems in the area are the weathered/fractured basement of varying thicknesses. The longitudinal conductance reveals that aquifers in the area are liable to probable risks of contamination. The transverse resistance result reveal that aquifer potential is high in the north western and southern parts of the area. The hydraulic conductivity result shows permeability of medium sand which allows free flow of groundwater to recharge the aquifers. The transmissivity result reveals moderate aquifer potential which is good for boreholes having moderate transmissivity. The hydraulic head results show that the flow is from the southern part towards northern part of the area.

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