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Aquifers Characterization and Classification Using Electromagnetic and Galvanic Resistivity Methods in Basement Complex, Katsina-Ala, Central Nigeria

Bem S. Terhemba
Assistant Lecturer, Department of Physics, Federal University, Dutse, Jigawa State, Nigeria
Dr. Obiora Daniel
Senior Lecturer, Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria
Mbah David
Student, Department of Physics, University of Nigeria, Nsukka, Nigeria
Dr. Chukudebelu J. U.
Senior Lecturer, Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria
Dr. Ezema P. O.
Senior Lecturer, Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria

Abstract:
Integrated approach involving electromagnetic (EM) and vertical electrical soundings (VES) have been used in this research to map out, characterize and statistically classified estimated characteristic in order to develop underground water productivity map in a basement complex terrain of Katsina-Ala, Central Nigeria. 15 EM conductivity traverses were carried out using Geonics EM-34 from which qualitative interpretation of conductivity data revealed points of inflexions which were subjected to further investigation using VES. A total of 26 VES points were occupied in the present study using ABEM Terrameter SAS 300C for Schlumberger array at half current spacing of 65 m to 160 m, from which geo-electric parameters were determined. A χ transform equal to 10.7762 $\Omega m^2/day$ was estimated from the result of borehole pumping test conducted carried out in the area which effectively transform geo-electric data into hydraulic parameters. Thus, hydraulic conductivity ranging from 0.0672 m/day to 0.4854 m/day with average of 0.2 m/day and transmissivity ranging from 0.8621m^2/day to 12.9520m^2/day with average value of 4.7133m^2/day was estimated. Statistical classification Transmissivity values estimated revealed three classes; very low, low and intermediate classes with a variation of 0.3264 which signified a fairly heterogeneous formation thus justifying the use of our χ transform in the area.

Keywords: *Electromagnetic, vertical electrical sounding, aquifers characterization, transmissivity classification, Katsina-Ala.*

1. Introduction

Groundwater systems globally provide 25 to 40% of the world's drinking water (United Nation Organization, 2006) and water supply is expected to become a crucial issue in many regions of the world including Nigeria. Access to clean water is a fundamental human right and a basic requirement for economic development. The recent socio-economic evolution of nations are based and strongly controlled by the availability of water which is obtained either as surface or subsurface water (Ibuot *et al*., 2013). Since groundwater normally has a natural protection against pollution by the covering layers, only minor water treatment is required (Reinhard, 2009). However, to enable a sustainable use of groundwater resources, detailed knowledge on the extent, hydraulic properties and vulnerability of groundwater reservoirs is necessary.

In recent years, there has been growing interest and awareness in the field of groundwater prospecting and management of groundwater resources. The use of geophysical methods for both groundwater resource mapping and for water quality evaluations has increase recently due to the rapid advances in microprocessors and associated numerical modelling solutions (Obiora *et al*., 2015a) and the useful information about the aquifer are interpreted by experienced geophysicists for hydrogeological studies (Niwas and Celik, 2012).To understand the physical processes in geo-hydrology requires detailed knowledge of aquifer characteristics such as permeability, hydraulic conductivity, transmissivity and Storativity. Conventionally, these parameters are obtained by in-situ measurements such as pumping test and down-hole measurements (Mohammed *et al*., 2011; Pantelis *et al*., 2007). However, in many circumstances, the availability of boreholes at sufficient points may be lacking, as drilling new boreholes and conducting in-situ tests is time consuming and costly. This situation has attracted the interest of geoscientist globally to device alternative methods that includes the use of surface geophysical data and theoretical models that are less tedious and cost effective for characterization and management of groundwater resources with tremendous success (Niwas and Muhammed, 2012). One of the advantages of these methods is that they provide specially distributed physical properties in regions that are difficult to sample using the conventional hydrogeological methods (Butler, 2005; K'Orowe *et al*., 2011).

From different geological settings, empirical geoelectrical studies have revealed that log-loglinear relationships bearing either positive or negative gradients exist between geoelectric parameters and hydraulic parameters; depending on mineralogy of rocks, grain size distribution and pore-fluid chemistry (Huntley, 1987; Odondi, 2009; Sosi *et al*., 2013). These correlation relations justify the use of geoelectric parameters for aquifer hydraulic sites characterization. Heigold *et al*. (1979) showed an inverse correlation between resistivity and hydraulic conductivity using data from Central Illinois. Mazac and Landa (1979) from their analysis of data from Czechoslovakia concluded that relations between aquifer transmissivity and one of Dar Zarrouk parameters are possible for both direct and inverse material-level correlations between resistivity and hydraulic conductivity (Kelly and Reinhard, 1985). Singh (2005) examined the correlation relationships for hydraulic permeability and transmissivity with electrical resistivity in a range of fractured and alluvial aquifers. Among his findings include: the exponential decrease of permeability with increase resistivity in hard rock, exponential increase of permeability with increase resistivity and transmissivity for weathered zones and alluvium aquifers. However, in case of fractured rock and sandwiched aquifers, transmissivity increases exponentially with increase in resistivity.

The physical conditions (tortuosity and porosity) controlling the electric current flow (electrical resistivity)also likewise control the lateral flow of the water (hydraulic conductivity) in porous media (De Lima and Niwas, 2000). Capitalizing on this analogy, a large number of empirical equations have been developed to convert geophysical quantities into hydraulic parameters. Niwas and Singhal (1981, 1985) have developed an analytical relationship between the hydraulic conductivity and electrical resistivity using Darcy's law of lateral flow of groundwater and Ohm's law of current flow in clean porous media.

It is worthy of mention that though a lot of work on aquifer characterization using empirical formulation, none of the estimated parameters have been quantitatively classified like it is established using measured values. In this research, inverse relationship existing between resistivity and hydraulic conductivity will be used to characterize aquifer in the study area and statically classified these properties in order to quantitatively develop the aquifer productivity map of the area for proper management of ground water resources using electromagnetic and galvanic resistivity methods. Electromagnetic method will be used in this present study on its account of good horizontal resolution of anomalies such as deep weathered zones, fractured zones and the vertical highly conductive dike; all which could hold water (Beeson and Jones, 1981; Jika and Mamah, 2012) and cost effectiveness in selecting borehole sites that will further be investigated using vertical electrical sounding (VES).

2. Geology of the Study Area

Katsina-Ala local government area has land mass of 2,402km^{2}and population of 224,718 at the 2006 census. It is bounded by latitudes 7^{o}09$^'$ and 7^{o}20$^'$ north of the equator and longitudes 9^{o}15$^'$ and 9^{o}30$^'$ east of the Greenwich meridian and has generally low lying to gently undulating terrain. The area is drained majorly by River Kastina-Ala. The geology of the study area is predominantly of the crystalline basement complex rocks of the middle Benue Trough, comprising of mainly quartzite, siliferous rocks, migmatite gneises, older granites and other undifferentiated basement rocks (Offodile, 2002). As shown in Fig.1, the north of Katsina-Ala is a complex sedimentary formation while the main town located along river Katsina-Ala bank comprise of alluvium deposit. These sediments comprise of sandstones, clays/sandy clays and Eze-Aku shale group. They are of Turonian age: a period of marine transgression in Nigeria when the sea covered large parts of the eastern and northern Nigeria (Reyment, 1965).The aquifer units in the area and other similar basement complex areas are believed to be derived essentially from the weathered and/ or fractured rocks (Offodile, 2002).

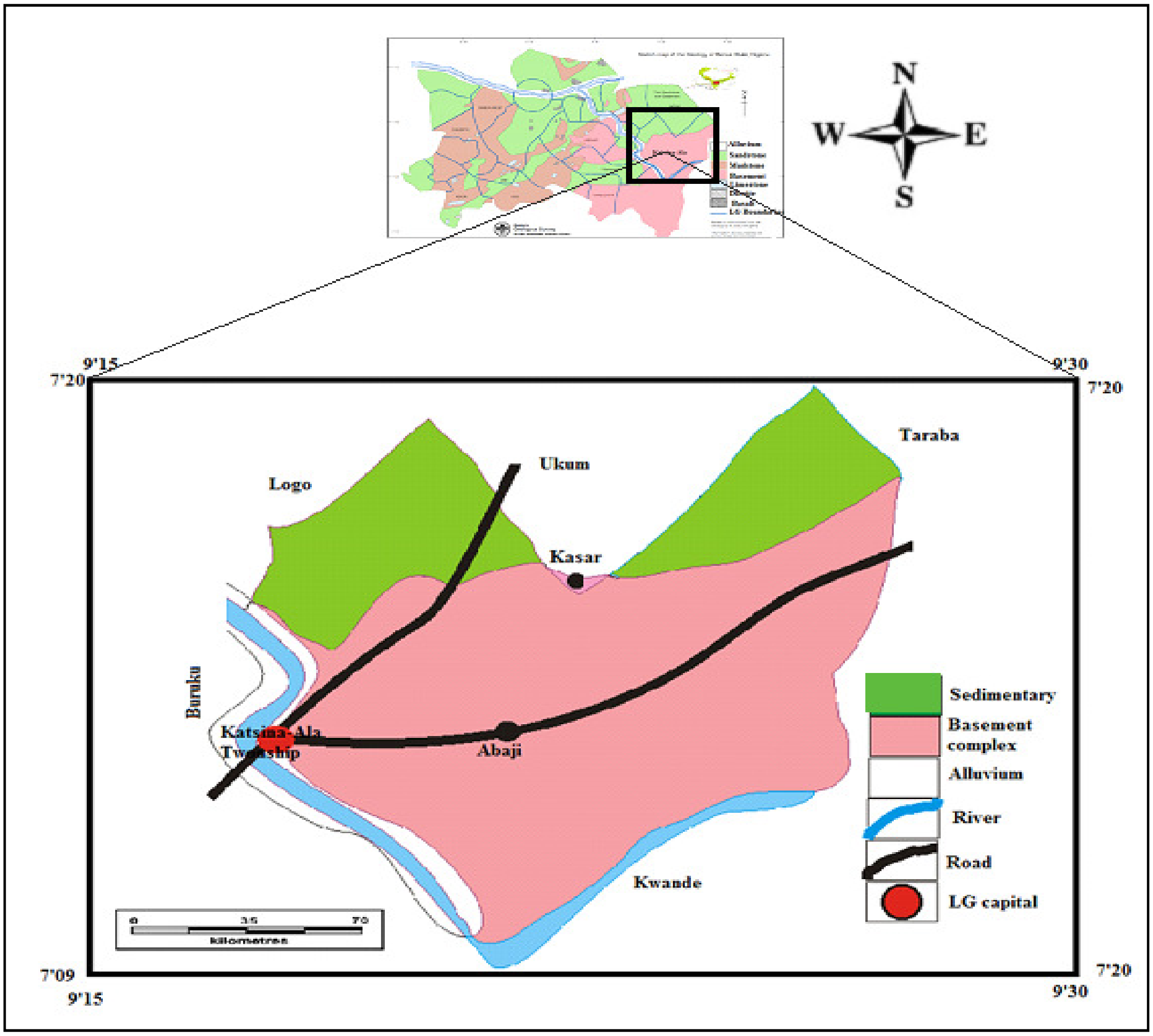

Figure 1: Geological map of Katsina-Ala (McDonald, 2001)

3. Materials and Methods

The rate of groundwater and electric current flow in the ground mainly depend on the hydraulic and electric conductivities of the formation. These processes are govern by Darcy's law of fluid flow and Ohms law of current flow stated respectively as

$$q = -K\frac{dh}{t} \qquad (1)$$

and

$$J = -\sigma\frac{dV}{t}, \qquad (2)$$

where q = specific discharge$\left(\frac{m}{s}\right)$, K = hydraulic conductivity$\left(\frac{m}{day}\right)$, J = current density $\left(\frac{A}{m^2}\right)$
t = thickness of aquifer(m), dh =difference of hydraulic heads(m), σ = electrical conductivity (Siemens/m) and dV = potential difference (volts).

Although these two fundamental laws are different, there exist analogy between them and similar other laws such as Fick's law of solutes diffusion and Fourier law of heat flow. The analogy between Darcy's law and Ohm's law form the bases for the resistance network models of aquifers (Karplus, 1958). By applying this model where groundwater system is simulated using the analogy between hydraulic parameters of groundwater flow and geo-electrical parameters of current flow, equations (1 and 2) can be combined using a common parameter aquifer thickness *t*. Subash *et al.* (2008) derived the inverse relation that exists between hydraulic conductivity K and aquifer resistivity ρ for a hard rock aquifer given by

$$K = \chi\sigma or \frac{\chi}{\rho}. \qquad (3)$$

Hydraulic transmissivity which is a parameter used to describe the ability of a confined aquifer to transmit water along it, assuming flow across the aquifer is negligible. For aquifer thickness t(x, y), the transmissivity is defined as

$$T(x,y) = \int_0^{t(x,y)} K(x,y,z)dt \qquad (4)$$

where K is the hydraulic conductivity, and z is the coordinate in the direction across the aquifer. The principal hydraulic conductivity in the z direction is zero, and therefore the transmissivity is a tensor defined in the aquifer (x, y) plane. The bulk transmissivity T is derived from eqn. (3 and 4) to be

$$T = \frac{\chi t}{\rho} = \chi C, \quad (5)$$

where χ = constant that relates resistivity and hydraulic parameters and C = longitudinal conductance.

The basic condition for the effective application of these equations is that the constant of proportionality be determined via pumping test result where it is assumed that the aquifer units in the area have similar geometry and type.

Geonics EM-34 designed to directly measure linear conductivity of the ground in both horizontal (HDM) and vertical dipole modes (VDM) was employed to measure ground conductivity using both dipole modes at constant inter-coil separation of 20m. This gave an effective depth of investigation of 15m in HDM and 30m in VDM. A total of 15 traverses were taken with traverse length ranging from 280m to 580m, along which qualitative interpretation reveal points of conductivity anomaly selected for vertical electrical soundings (VES).

The electrical resistivity of the ground is mostly measured via the use of galvanic contacts. This method is based on the principle that the distribution of electrical potential in the ground around a current-carrying electrode depends on the electrical resistivity. The usual practice in the field is to apply an electrical direct current or low frequency alternating current between two electrodes implanted in the ground and to measure the potential difference between two additional electrodes that do not carry current (potential electrodes).

Abem terrameter SAS 300C was used with Schlumberger array for resistivity soundings at points of inflexion recommended by EM method. During field work, half current electrode spacing of 65m to 160m were attained while the potential electrodes spacing was increased two times during the sounding to MN/2 equals to 1.5m and 5m. A total of Twenty six (26) soundings were occupied within the study area.

Finally, a single borehole pumping test was carried out in Abaji township area to determine the hydraulic conductivity and transmissivity values using 1HP Grundfos submersible pump installed at the depth of 57.18m. The Cooper-Jacobs straight line constant discharge method of pumping test was adopted for this measurement. Readings of draw - down were observed and recorded accordingly based on a pre-determined format of timing. A plot of draw-down against time gives the half log cycle ΔS from which hydraulic transmissivity (T) was determined. Transmissivity determined via pumping test was used to calculate the value of the constant of proportionality χ that effectively transform resistivity values to hydraulic parameters at locations where boreholes were not drilled.

All locations of data collected in the study area were represented on a Google earth map capture of the area using global position system (GPS) coordinates acquired during field work as shown in Fig. 2.

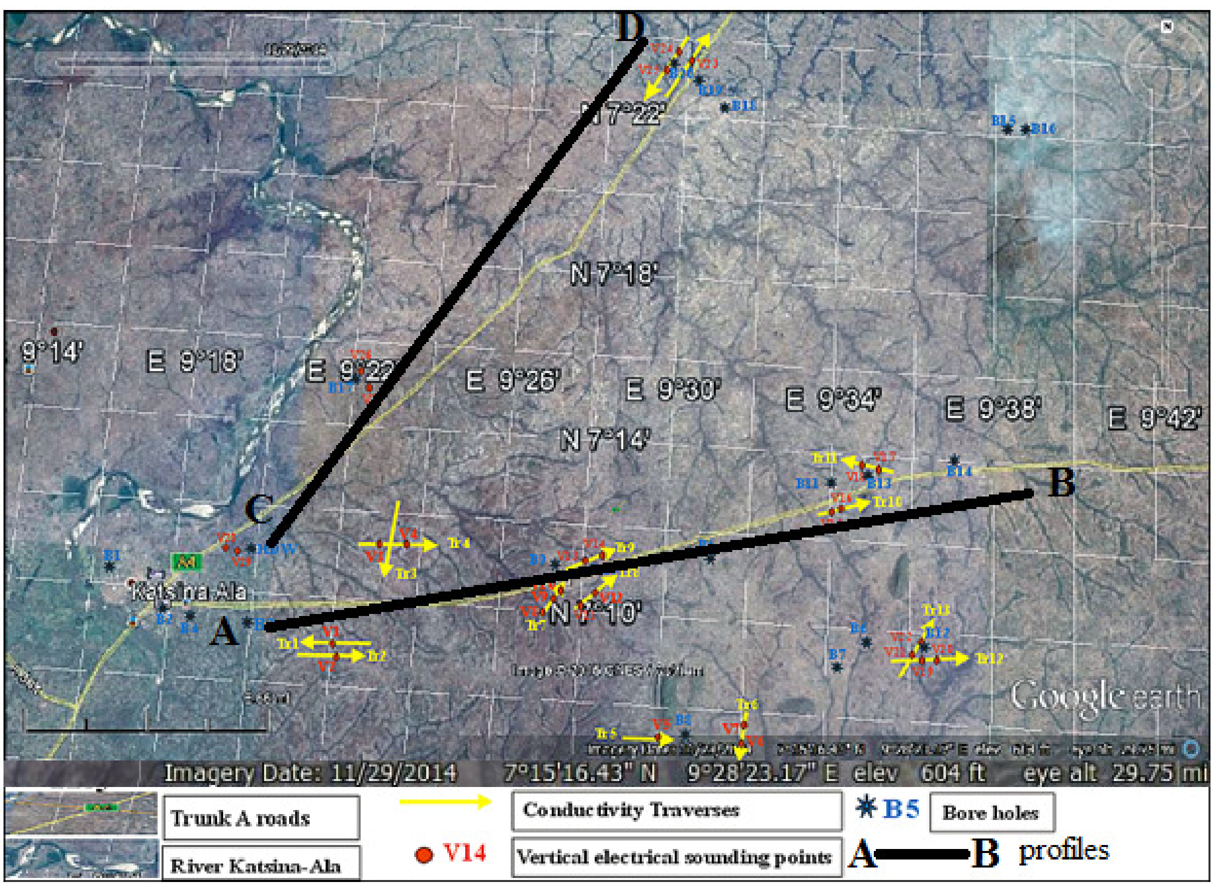

Figure 2: Google Earth map of Katsina-Ala showing conductivity profiles and VES points

4. Results and Discussions

4.1. Interpretation of EM Conductivity Results

EM data acquired in both HDM and VDM were qualitatively interpreted from the plots of both VDM and HDM as functions of horizontal distance (stations) using Grapher computer program. From the EM responses, regions of high conductivity anomalies were identified and subjected to further investigation using VES. The idea for selection of these points was based on the fact that EM-34 in HDM responds to near surface conductivity anomaly whereas in VDM, it responds to deeper conductivity anomaly. In basement complex where the rock units are highly resistive, regions of deep weathering, deep lying fractures and vertical dike intrusions are the considered aquifer units. Deep weathering is indicated by significant increase in both HDM and VDM forming an anticline shape-like signature. Deep lying fractures can be detected by spikes in VDM above HDM signature in hard rocks while for mudstones, fractured zones are often less conductive (hard mudstones) than the host rock (soft mudstones) and also in some cases characterized by high conductive noisy data (McDonald, 2005). Finally, vertical dike intrusion shows a false electrical conductivity anomaly. VDM is insensitive to this structure while HDM response gives negative values centred over the dike. Of course, the contribution of good ground controls such as prior information of the general geology cannot be over emphasized while interpreting EM as well as all geophysical surveys.

Four out of fifteen conductivity signatures derived from 1-D interpretation using Grapher are shown in figure 3 with the following deductions.

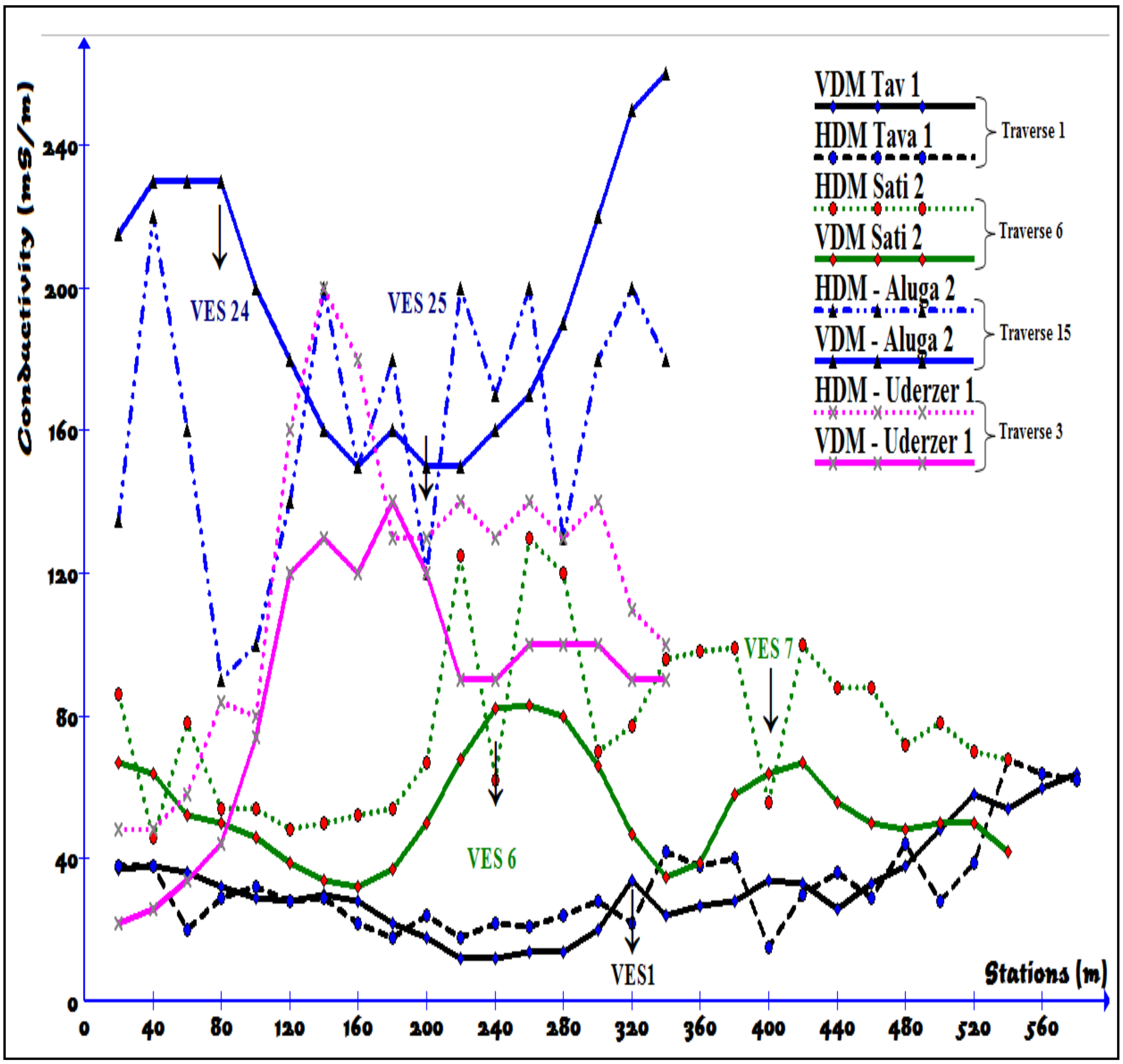

Figure 3: EM conductivity traverses 1, 3, 6 and 15 in HDM and VDM

1. The qualitative interpretation of EM data of traverses 1, 2, 10, 11, 12 and 13 show high degree of anomaly. With traverse 1 (black continuous and doted lines) representing this group consist of deep lying fractures marked by arrow at VES 1 (Fig. 4) and regions where there exist anomalous drops of conductivity values of HDM and increase in VDM above HDM.
2. Traverses 3, 4, 5, 6 and 9 show conductivity anomalies which could be as a result of deep lying weathered rock overlain by more resistive materials as indicated by drops in conductivity values of HDM particularly at traverse 6 (green lines in Fig. 4). Traverse 3 (purple lines) however, shows the presence of thick clay materials underlain by weathered rock as indicated by high conductivity values of HDM and VDM.
3. In traverses 14 and 15 (represented by traverse 15 with blue lines), the insensitivity of horizontal coil orientation at high conductivity with the noisy curves of HDM at high values of conductivity could be as a result of the presence of soft to moderately hard mudstone (McDonald *et al*., 2005). Further investigation on this traverse was occupied at the points marked by VES 24 and VES 25.Boreholes drilled in such formation could be abortive to very low yield.

4.2. Vertical Electrical Sounding (VES) Interpretation and Geo-electrical Sections

1-D quantitative interpretation of VES data was done using WINRESIT inversion software (Vander, 2004). Deductions and trend of geo-electric parameters estimated were considered along two lines; south-west to north-east (SW-NE) and south- west to north-west (SW-NW) designated as AB and CD on the Google earth map capture of the area shown in Fig. 3 above respectively. This establishes 3 to 5 layer types, H, KH, and Q curves with 53.85%, 42%, and 3.85% occurrences respectively. Figures 4 show four out of twenty-six VES curves representing the types of field curves in the study area.

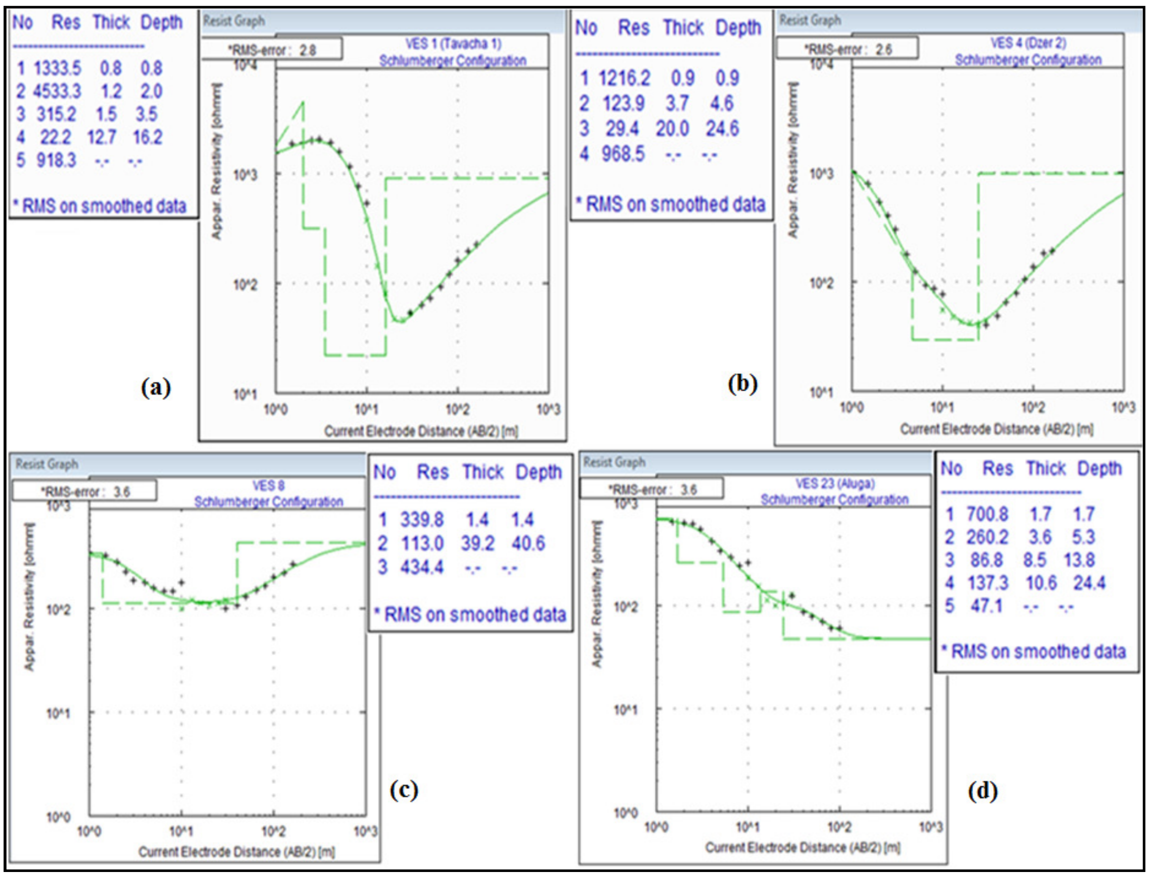

Figure 4: a, b, c and d showing 5, 4, 3 and 5 layers type KH, H, H and Q curves

The geo-electric layers of the study area along line AB comprises of top soil, sand/lateritic sand, sandy-clay, weathered basement and fractured/fresh basement rocks with resistivity and thicknesses ranges of 171 Ωm – 5991 Ωm, 985 Ωm - 6826 Ωm, 61 Ωm - 663 Ωm, 22 Ωm - 160 Ωm, 129 Ωm - 4022 Ωm and 0.6 m - 3.4 m, 1.1 m - 6 m, 1.3 m - 11.1 m, 9.4 m - 74 m and infinity respectively.

Along line CD, geo-electrical parameters revealed the presence of top soil, sand/lateritic soil, sandy-clay/mudstone, weathered layer and fractured basement with corresponding resistivities and thicknesses ranges of 701 Ωm – 5258 Ωm, 962 Ωm – 4322 Ωm, 41 Ωm – 233 Ωm, 42 Ωm – 69 Ωm, 73 Ωm – 245 Ωm and 0.5 m – 2.1 m, about 1 m, 1.2 m – 8.4 m, 10.6 m – 50.7 m and infinity. This is drawn into geo-electric sections along the two lines of investigations AB and CD as shown in figures (5a and 5b). The above geo-electrical sections compared favourably with information from literature such as Okafor and Mamah (2012) and BERWASSA boreholes log information (unpublished).From the interpretation, the aquifer units in the study area were delineated to be the weathered/fractured layers along profiles. VES points underlain by fractured basement may form good locations for geo-hydrological exploitation. Table 1 is the summary of results of VES data interpretation.

VES NO.	Northing (degree)	Easting (degree)	Layers thickness (m)				Layers Resistivities ρi (Ωm)					Curve type
			h 1 (m)	h 2 (m)	h 3 (m)	h 4 (m)	ρ 1 (Ωm)	ρ 2 (Ωm)	ρ 3 (Ωm)	ρ 4 (Ωm)	ρ 5 (Ωm)	
VES 1	7.16482	9.37823	0.8	1.3	1.5	12.7	1333.5	4533.3	315.2	22.2	918.3	KH
VES 2	7.16563	9.37973	0.9	1.6	4.6	15	936.1	2691.8	138.4	92.7	628.5	KH
VES 3	7.18583	9.39593	2.6	1.6	19.3	-	1031.7	212.9	40.5	301.4		H
VES 4	7.18642	9.39635	0.9	3.7	20	-	1216.2	123.9	29.4	968.5		H
VES 5	7.11818	9.50248	1	2	2.6	21.4	2472.2	4406.5	663.4	46	305.2	KH
VES 6	7.12108	9.54662	2.2	6	20.1	-	5990.8	1018	69	3777.9		H
VES 7	7.12108	9.54662	0.5	1.1	6.1	19.7	584.9	3147.7	397.3	54.9	3684.2	KH
VES 8	7.17838	9.46037	1.4	39.3	-		339.8	113	434.4			H
VES 9	7.18448	9.45833	0.6	1.3	11.1	28	263.4	783	121.9	81.2	940.9	KH
VES 10	7.18448	9.45833	0.8	2	12.1	-	404.6	985.1	151.2	801.1		KH
VES 11	7.18053	9.47069	0.7	1.3	4.5	30	1072.5	3486.8	91.6	32.7	558.6	KH
VES 12	7.18209	9.47069	0.7	2.9	5.7	74.5	1283.2	6825.7	165.8	40.5	128.7	KH
VES 13	7.18947	9.46668	2.2	6.4	48.6	-	1686.4	257	64.3	869.8		H
VES 14	7.19103	9.47892	0.7	1.8	5.8	22.3	700.4	2958.8	60.8	36.5	770.8	KH
VES 15	7.21668	9.56992	3.4	22.5	-		891.8	40.5	1378			H
VES 16	7.21668	9.56992	1.8	3.9	23.1	-	977.4	123.8	63.7	771.1		H
VES 17	7.22357	9.58187	1.9	1.3	10.3	-	171.1	149	47.9	1608.4		H
VES 18	7.22357	9.57598	0.6	3.4	11.7	-	819.1	305.2	53.9	1401		H
VES 19	7.15960	9.61222	1.6	1.7	9.4	-	1556.2	1147.8	70.4	4022.1		H
VES 20	7.15960	9.61222	2.1	1.2	11.2	-	2467.6	1490	96.8	2152.1		H
VES 21	7.16102	9.61305	0.7	1.3	11.9	-	1120.5	2344.8	71.8	1103		KH
VES 22	7.16102	9.61305	2.7	16	-		1318.3	160.3	1307			H
VES 23	7.39328	9.50697	1.7	3.6	8.4	10.6	700.8	260.2	86.8	137.3	47.1	Q
VES 24	7.39328	9.50697	2.1	0.7	1.2	40	5258.4	961.7	162.8	42	218.9	H
VES 25	7.39328	9.50697	0.5	0.8	5.8	50	1316.4	4321.5	40.7	41.6	73.3	KH
VES 26	7.26203	9.37275	0.8	2.8	29.2	-	1029.3	233.4	69.3	245.4		H

Table 1: Summary of result of VES data interpretation across the two lines AB and CD
Blue codes = Aquifer parameters

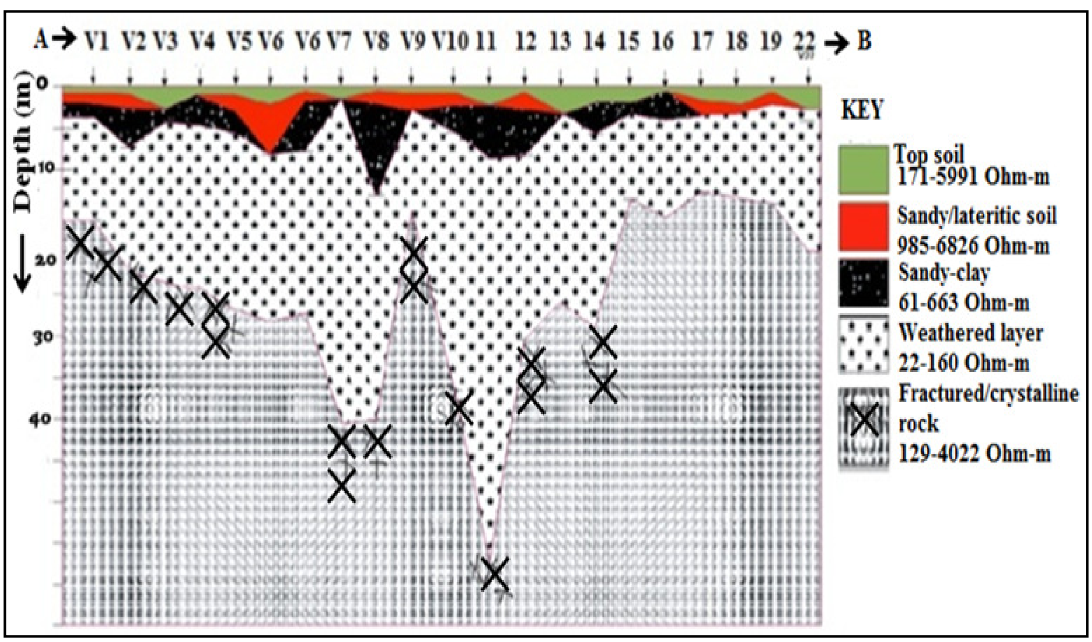

Figure 5a: Geo-electric section along AB in Katsina-Ala LG area

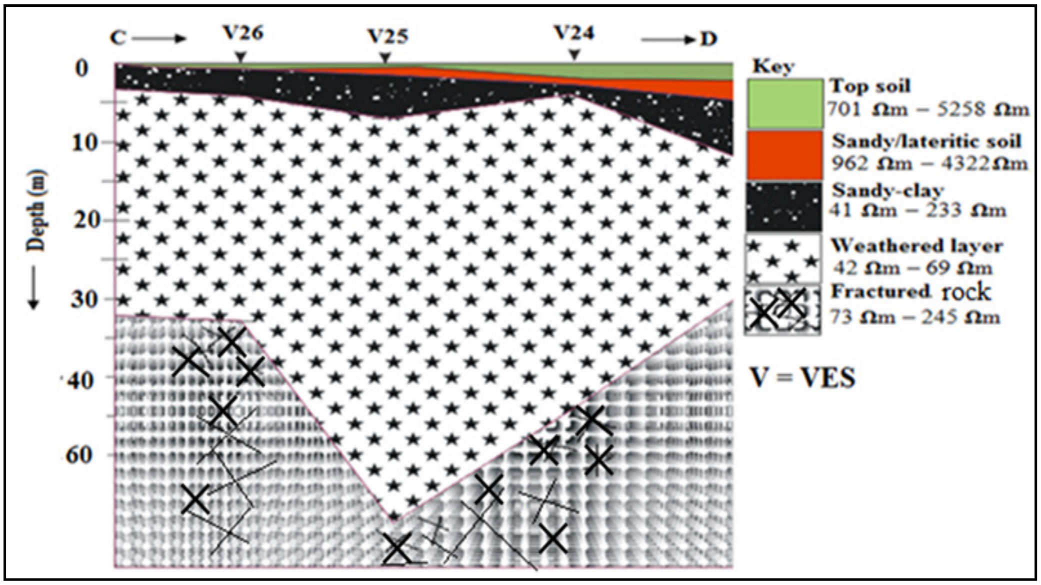

Figure 5b: Geo-electric section along CD in Katsina-Ala LG area

4.3. Aquifer Characterization

The constant of proportionalityχ was estimated to be $10.7761\Omega m^2/day$which effectively transformed geo-electric parameters to hydraulic parameters. The results of the estimate are as shown in table 2. Characterization of aquifer in the study area shows hydraulic conductivity ranging from 0.0672 m/day to 0.4854 m/day with average of 0.2 m/day and transmissivity ranging from $0.8621m^2/day$to $12.9520m^2/day$with an average value of $4.7133m^2/day$. These two parameters are important in determining the natural flow of water and its response to fluid extraction. The variation of transmissivity values depicts the variation of the aquifer bearing potential in the study area.

Hydraulic conductivity map of the area was developed as shown in figure 6. From conductivity map of the area, higher values were established towards south – west with yellow code and regions coded brown with hydraulic conductivity range of 0.28 to 0.49 m/day. The portions coded black are regions of least hydraulic conductivity ranging from 0 to $0.14m/day$. Cyan colour represents the dominant hydraulic conductivity range in the study area. The low hydraulic conductivity observed across the study area is an indication of low permeability (Obiora *et al*., 2015b).

VES No.	Thickness (m)	Resistivity (Ωm)	Overburden Thickness (m)	$S = h/\rho$ (Siemens)	T ($\frac{m^2}{day}$)	K (m/day)
VES 1	12.7	22.2	3.5	0.57207	6.1647	0.4854
VES 2	15	92.7	7	0.16181	1.7436	0.1162
VES 3	19.3	40.5	4.2	0.47654	5.1348	0.2661
VES 4	20	29.4		0.68027	7.3309	0.3665
VES 5	21.4	46	5.6	0.46522	5.0130	0.2343
VES 6	20.1	69	8.1	0.29130	3.1908	0.1562
VES 7	19.7	54.9	7.7	0.35883	3.8871	0.1963
VES 8	39.3	113	1.4	0.34779	3.7479	0.0954
VES 9	28	81.2	13	0.34483	3.7158	0.1327
VES 10	12.1	151.2	2.8	0.08003	0.8621	0.0712
VES 11	30	32.7	6.5	0.91743	9.8850	0.3295
VES 13	48.6	64.3	8.6	0.75583	8.1446	0.1676
VES 14	22.3	36.5	8.3	0.61096	6.5842	0.2953
VES 15	22.5	40.5	3.4	0.55556	5.9072	0.2661
VES 16	23.1	63.7	5.7	0.36264	3.9056	0.1691
VES 17	10.3	47.9	3.2	0.21503	2.3169	0.2249
VES 18	11.7	53.9	4	0.21707	2.3395	0.2
VES 19	9.4	70.4	3.2	0.13352	1.4386	0.1530
VES 20	11.2	96.8	3.3	0.11570	1.2468	0.1191
VES 21	11.9	71.8	2	0.16574	1.7856	0.1501
VES 22	16	160.3	2.7	0.09983	1.0755	0.0672
VES 24	39.9	42	4	0.95	10.2373	0.1242
VES 25	50	41.6	7.1	1.20192	12.9520	0.2590
VES 26	29	69.3	3.6	0.41847	4.5098	0.1555

Table 2: Aquifer characteristics estimated from surface geophysical data

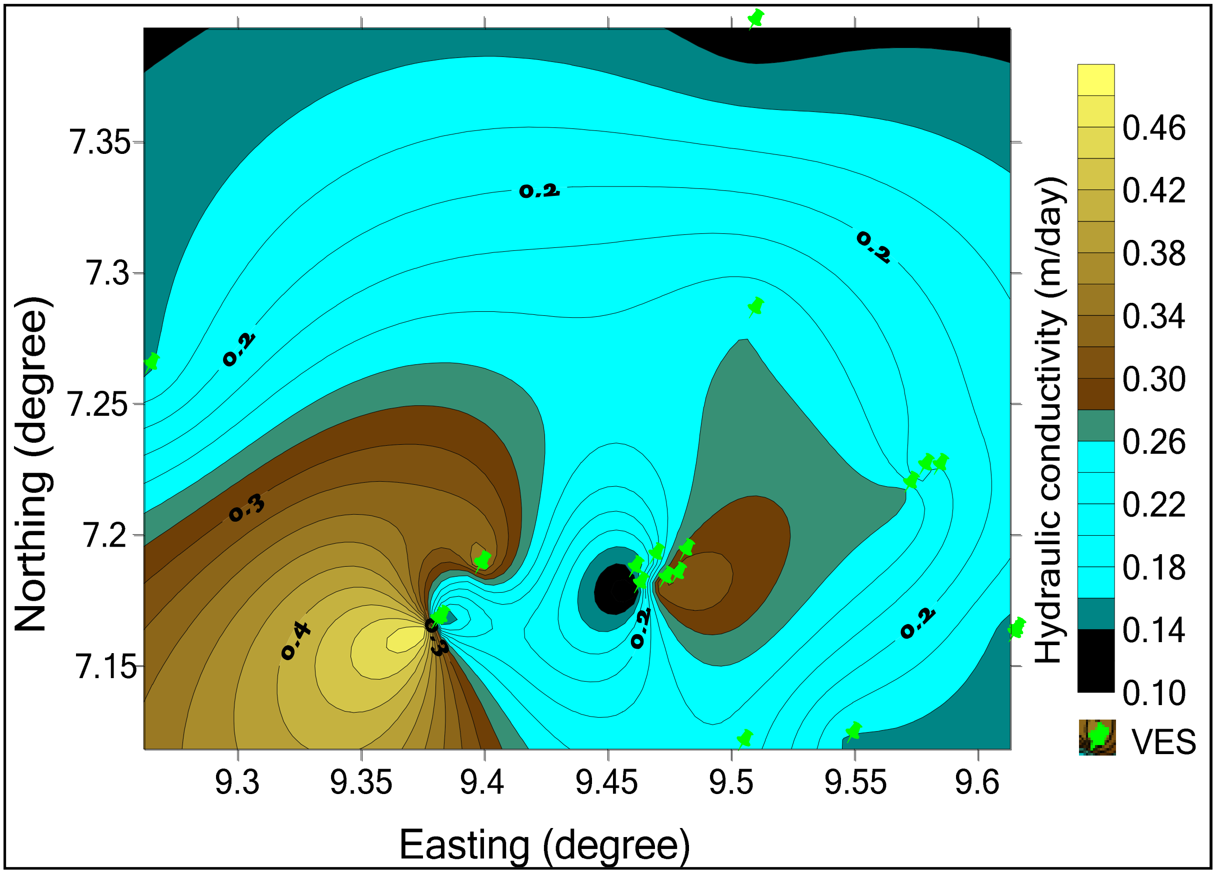

Figure 6: Hydraulic conductivity (m/day) maps of Katsina-Ala LGA

4.4. Transmissivity Analysis and Aquifer Productivity

Transmissivity values estimated were transformed into logarithmic transmissivity index *Y* (m^2/day) and analysed statistically. Logarithmic transformation has an advantage of shrinking a very large data to a representative one, thereby making it easy to be represented on maps. According to Krasny (1993), the coefficients of transmisssivity T (m^2/day) can be logarithmically transform using eqn. (8) with details of this transformation and classification as shown in Table 3.

$$Y = \log\left(\frac{T}{86400}\right) + 8.96. \qquad (8)$$

CLASSIFICATION OF T(m^2/day) BY MAGNITUDE					CLASSIFICATION OF T BY VARIATION			
T (m^2/day)	**Class of T mag.**	**Y (m^2/day)**	**Designation**	**Groundwater Supply Potential**	**Standard deviation of Y**	**Class of Y variation**	**Designation**	**Hydrological Environment**
>1000	I	7	Very high	Withdrawals of great regional importance	< 0.2	a	Insignificant	Homogeneous
1000 – 100	II	6	High	Withdrawals of lesser regional importance	0.2 - 0.4	b	Small	Slightly Hetero-geneous
10 – 100	III	5	Intermediate	Withdrawals for local water supply (small communities and plants)	0.4 - 0.6	c	Moderate	Fairly Hetero-geneous

1 - 10	IV	4	Low	Smaller withdrawals for local water supply (private consumption)	0.6 - 0.8	d	Large Very	Considerably Heterogeneous
0. - 1	V	3	Very low	Withdrawals for local water supply with limited consumption	0.8 - 1.0	e	Large	Very Hetero-geneous
< 0.1	VI		Imperceptible	Sources for local water supply are difficult	>1.0	f	Extremely Large	Extremely Heterogeneous

Table 3: Transmissivity classisifation (after Krasny, 1993)

This enabled us to classify the study area into three groups namely: Very low, low and intermediate class. Statistically, the mean value of Y (m^2/day) was calculated to be 4.5907 (m^2/day) and standard deviation $S = 0.3264$ indicating a slight variation in transmissivity. This variation reveals a slightly heterogeneous formation (Krasny, 1993). Negative and positive anomalies exist aside the background transmissivity with 4.2%, 8.3% and 87.5% occurrences respectively. 87.5% occurrence of background transmissivity which coincide to low transmissivity class indicates that the study area is hydrologically capable of sustaining only smaller local underground water supply. Positive anomalous region with 8.3% occurrence could be delineated as the most productive aquifer zone in the study area, but with groundwater potential that can only sustain local usage while the region with negative anomaly however can serve as prospective site for waste disposal since it is considered hydrologically unproductive.

Table 4 gives details of both classifications achieved in the study area along with groundwater prospects which aided in developing hydraulic productivity map of Katsina-Ala LGA as shown in Fig. 7

VES Points	T (m^2/day)	Y (m^2/day)	Statistical classification	Krasny classification	Ground water potential
VES 1	6.1647	4.8133	Background	Low	for smaller local water supply
VES 2	1.7436	4.2649	background	Low	for smaller local water supply
VES 3	5.1348	4.7340	background	Low	for smaller local water supply
VES 4	7.3309	4.8886	background	Low	for smaller local water supply
VES 5	5.013	4.7236	background	Low	for smaller local water supply
VES 6	3.1908	4.5273	background	Low	for smaller local water supply
VES 7	3.8871	4.6131	background	Low	for smaller local water supply
VES 8	3.7479	4.5973	background	Low	for smaller local water supply
VES 9	3.7158	4.5936	background	Low	for smaller local water supply
VES 10	0.8621	3.9590	negative anomaly	very low	Limited for local water supply
VES 11	9.885	5.0185	Positive anomaly	Low	for smaller local water supply
VES 13	8.1446	4.9346	Positive anomaly	Low	for smaller local water supply
VES 14	6.5842	4.8420	Background	Low	for smaller local water supply
VES 15	5.9072	4.7949	background	Low	for smaller local water supply
VES 16	3.9056	4.6152	background	Low	for smaller local water supply
VES 17	2.3169	4.3884	background	Low	for smaller local water supply
VES 18	2.3395	4.3926	background	Low	for smaller local water supply
VES 19	1.4386	4.1814	background	Low	for smaller local water supply
VES 20	1.2468	4.1193	Negative anomaly	Low	for smaller local water supply
VES 21	1.7856	4.2753	background	Low	for smaller local water supply
VES 22	1.0755	4.0551	Negative anomaly	Low	for smaller local water supply
VES 24	10.2373	5.0338	Positive anomaly	intermediate	for local water supply
VES 25	12.952	5.1358	Positive anomaly	intermediate	for local water supply
VES 26	4.5098	4.6776	background	Low	for smaller local water supply
		$\bar{Y}$ =4.590791292 S =0.326374177			
$\bar{Y} \pm S = BackgroundY$; $Y < \bar{Y} - S = Negativeanomaly$; $Y > \bar{Y} + S = Positiveanomaly$					

Table 4: Transmissivity transform and classifications in Katsina-Ala LGA

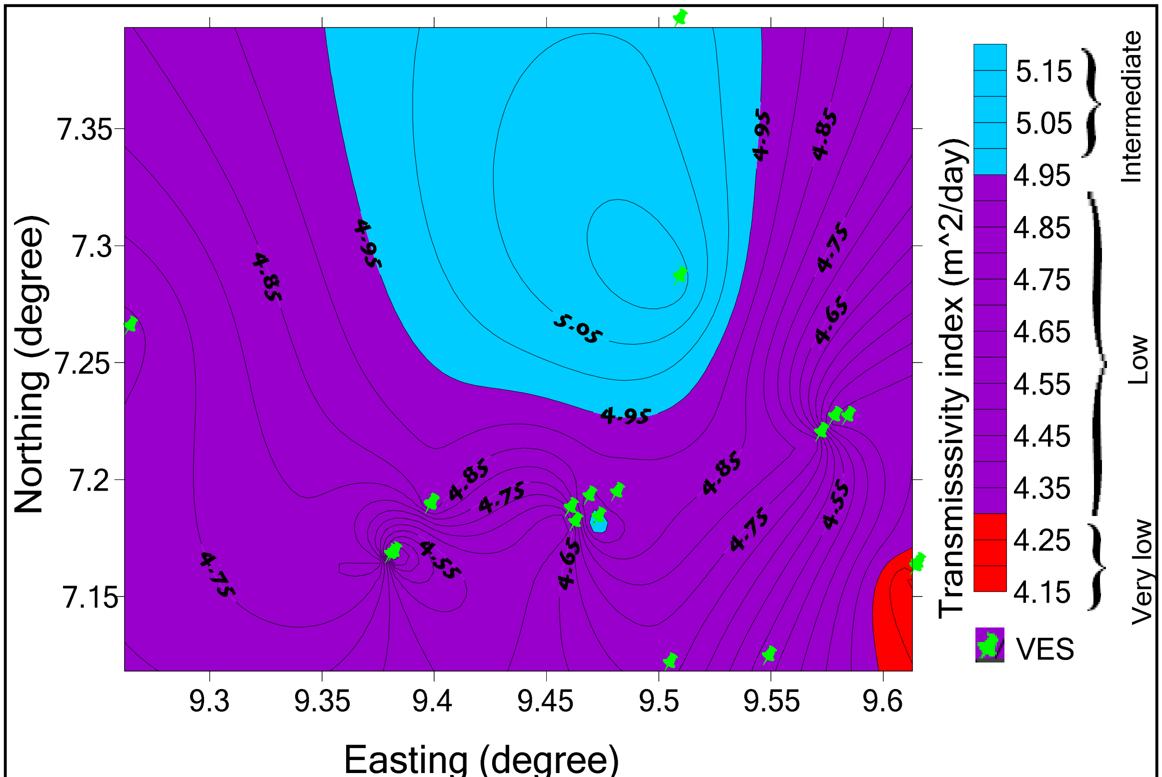

Figure 7: Transmissivity (m^2/day) distribution showing underground water productivity in Katsina-Ala LGA.

5. Conclusion

The importance of surface geophysical data in groundwater exploration, exploitation and management cannot be over emphasized. The results of this research work revealed the importance of using integrated geophysical methods to delineate aquifer zones, characterize and quantitatively classified the transmissivity values estimated from surface geophysical data in a hard rock terrain of Katsina-Ala, Central Nigeria. In an approach that proved to be cost effective, aquifer characteristics such as transmissivity and hydraulic conductivity that are traditionally determined using in-situ measurements such as pumping test were estimated and statistically classified. This classification which produced a slight variation of 0.3264 justified the fundamental assumption made in the development of the χ transform model adopted in this work. From this, we were able to develop the hydrological productivity map of the study area.

Transmissivity classification revealed three classes: very low, low and intermediate class with 4.2%, 87.5% and 8.3% occurrences respectively. 87.6% occurrence of background transmissivity corresponding to low class demonstrates that our study area is hydrologically capable of only supplying underground water for local sustenance. The negative anomaly with 4.2% occurrence in the study area however can serve as good site for waste disposal since such locations are considered to be hydrologically unproductive.

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