Aquifer Vulnerability Mapping in Katsina-Ala Area, Central Nigeria Using Integrated Electrical Conductivity (IEC)

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Abstract
The present demand for water are not only to detect and develop new groundwater systems to meet up with the millennium development goals, but also to protect existing water reservoirs against contaminants. This research work is aimed at mapping out aquifer vulnerability by integrated electrical conductivity (IEC) in Katsina-Ala area, Central Nigeria. With Schlumberger configuration, Twenty-Six (26) vertical electrical soundings (VES) were occupied in the present study using Abem terrameter SAS 300c at the peak of dry season (January to March) from which the VES data collected was interpreted for geo-electrical parameters. The parameters estimated for overburden was used to calculate the IEC and was indexed to generate a vulnerability map of the study area. The indexes revealed three strong regimes which include vulnerable ($\mathrm{IEC} > 0.1$ siesmen), highly vulnerable (IEC< 0.1 siesmen) and extremely vulnerable (IEC from 0 to 40×10^{-3}siesmens). The result will aid in the design of modalities for monitoring and protection of aquifer front against contaminants in the study area.
Keywords: Aquifer, Integrated electrical conductivity, Overburden, Vulnerability, Katsina-Ala

1. INTRODUCTION

Access to clean water is a fundamental human right and 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). The occurrence, movement and storage of groundwater are influenced by the lithology, thickness and structure of rock formations. To enable a sustainable use of ground water resources and the depending ecosystems requires aquifer protection and management of the resources.

This reasons among others prompt the united nation deliberation to trash a way forward, resulting into the popular Millennium Development Goals, specifically goal No.7 (MDGs 7) targeted at “Halving, by 2015 the population of people without access to safe drinking water and basic sanitation”. Year of reference: 1990 (WHO, 2004). To achieve this, yonder Water was the obvious resort especially in rural dwellings of developing nations of Africa and other parts of the world where surface water development was not feasible and considering the unreliability of alternative sources as well as the high cost associated with developing and managing these sources.

However, the present social demands are not only to detect and develop new groundwater systems to meet up with the targeted goal, but also to protect them. According to research, yonder water (groundwater) in most cases is prone to contaminations from sources (Nalbantcilar, 2011) like fertilizers, herbicides, pesticides, heavy metals, oil spillage, mining activities, sewage (latrines, underlined petroleum pipes and septic tanks) (Obiora et al., 2015) which are directly washed into groundwater systems. Aquifer protection is essential for a sustainable use of groundwater resources and protection of the dependent ecosystems. Protection of yonder water systems requires both proactive and reactive measures.

However, reactive approach of remediation of a site always tends to be difficult and impractical in several situations, from the standpoint financial, technical and operational (Braga and Francisco, 2014; Nalbantcilar, 2011). For this reason, it becomes imperative to establish tools for protection, planning and management of the rational use of yonder water resources.

In a proactive measure, by mapping areas of high and low vulnerability, it is possible to identify which areas are more susceptible to contamination, and thus work to prevent contamination in the first place which is cost effective and easily achievable.

The quantitative representation of aquifer protection against contaminants is called vulnerability. Groundwater vulnerability is defined as the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer (Lobo-Ferreira, 1999). Technically, it is feasible to assess the vulnerability of groundwater to other hazards, such as drought, over pumping, and subsurface disturbance in mines or injection wells (Liggett and Talwar, 2009) but our research is confined to groundwater vulnerability with regard to water quality degradation (contamination).

The main parameters to be considered in the natural vulnerability assessment involve the confinement degree (confined to unconfined), depth to groundwater table, the lithology and consolidation level of the strata above the saturated zone and the contaminants attenuation capacity and hydraulic accessibility of the unsaturated zone in case of unconfined aquifer (Foster and Hirata, 1987; Braga and Francisco, 2014).

Several methods have been developed in recent times to determine the vulnerability of aquifers. These methods are broadly categorized into index (and overlay) methods, statistical methods, and process-based computer methods (Harter and Walker, 2001).

In indexers-parametric methods, each parameter displays a range relating to its property, subdivided into discrete and ranks or classes with specific values as indices, which reflect their susceptibility level to contamination (Braga and Francisco, 2014; Harter and Walker, 2001). Statistical based approaches such as Logistic Regression (Heisel and Hirsch, 1992) involves the determination of the probability of a particular contaminant exceeding a certain concentration. They are often used in areas with diffuse sources of contamination, such as to detect nitrates over agricultural areas (Liggett and Talwar, 2009). Process-based computer models are anchored on recreating the flow and transport patterns within an unsaturated zone or aquifer itself and can be used as deterministic approaches to estimate time of travel, contaminant concentrations, and duration of contamination in a chosen layer (Liggett and Talwar, 2009). As much as they are strong economic tools for aquifer vulnerability mapping, process-base methods are capital intensive and require large data for simulations.

It is worthily mentioned that no single method chosen by a researcher is omnipotent hence are sites tired. That is to say, results obtained from a site with the use of a selected method cannot be used for making recommendations in other locations hence the need for such studies at every site of examination. The type of approach selected depends on the aim of the task at hand and the availability of data to achieve set objectives. It is against this backdrop that we aimed our research at using geophysical based approach of integrated electrical conductivity (IEC) described by (Röttger et al. 2005) to map the vulnerability of aquifer units in the basement complex terrain of Katsina-Ala area, central Nigeria. This will serve as tool for designing of modalities for protection, management and effective use of this cheap but scarce resource to enhance the socio-economic growth of the study location in line with MDGs.

2. SITE DESCRIPTION AND GEOLOGY

Katsina-Ala area, central Nigeria has land mass of $2{,}402\mathrm{km}^2$ and population of 224,718 at the 2006 census. It is bounded by latitudes 7°09' and 7°20' north of the equator and longitudes 9°15' and 9°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).

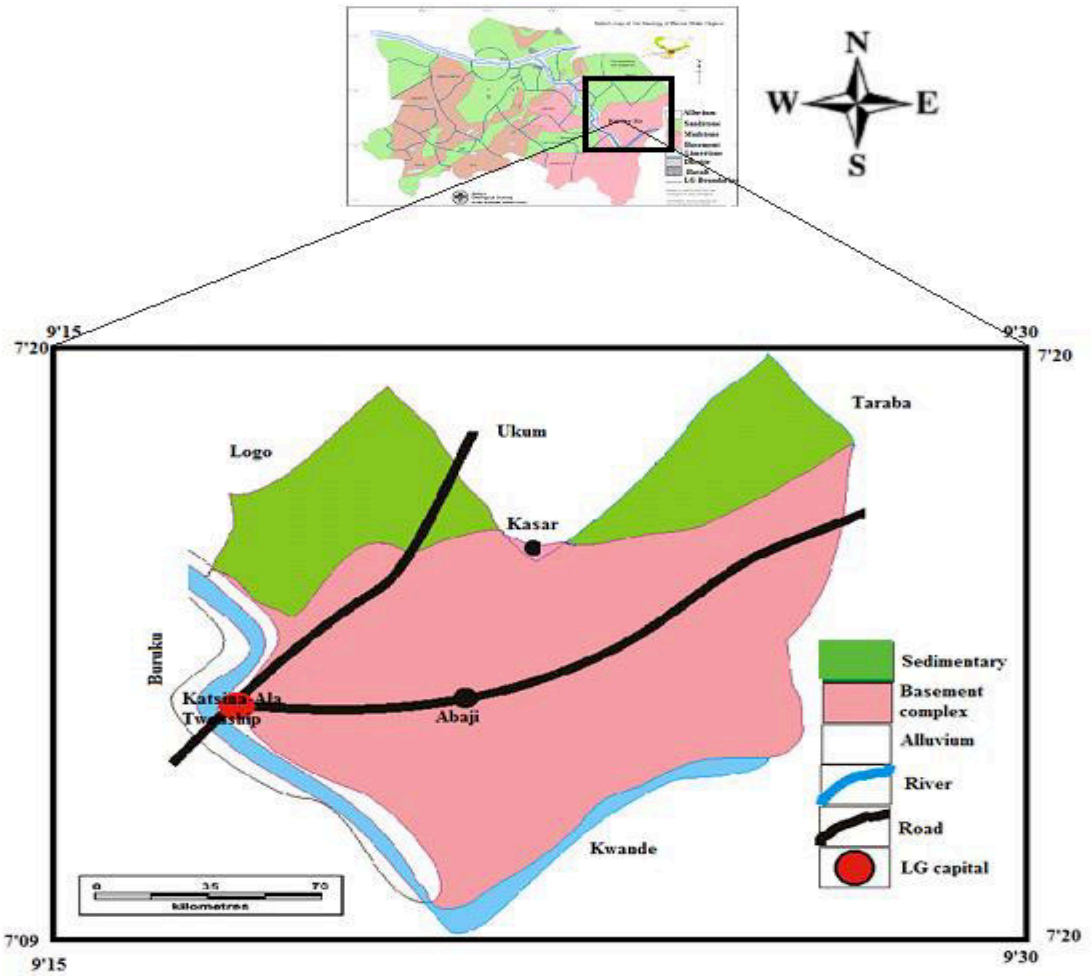

Fig. 1: Geological map of Katsina-Ala area, central Nigeria (modified from McDonald, 2001)

3. MATERIALS AND METHODS

The electrical resistivity of the earth's subsurface is mostly measured via the use of galvanic contacts. This method is based on the principle that the distribution of electrical potential in the subsurface around current-carrying electrodes 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 A and B (current electrodes) implanted in the ground and to measure the potential difference between two additional electrodes M and N that do not carry current (potential electrodes). This method which is useful in groundwater study due to its ability to map the subsurface electrical resistivity structure and the interpretation helps in revealing the geologic formations and physical properties of the geologic materials.

The Schlumberger configuration was employed for resistivity data acquisition in the present study using the Abem terrameter SAS 300C. It requires the gradual separation of current electrodes in near-logarithmic manner from a fixed point at equal intervals while keeping the potential electrodes at small separations or fairly constant until acquired data becomes relatively small before increment is made.

The quantity measured is in reality the apparent resistivity (ρa), a sort of an average resistivity of the material through which the current passes owing to the fact that the earth subsurface is not necessary horizontally stratified. Using the measured current, potential difference and the geometrical setup parameters of Schlumberger array, apparent resistivity is given as follows:

$$\rho_a = \frac{\Delta V}{I}\left(S^2 - P^2\right)\frac{\pi}{2P} = K\,\frac{\Delta V}{I} \quad , \qquad (1)$$

where S = AB/2, P = MN/2, and K is a geometrical factor.

During the measurement, the apparent resistivity obtained from eqn. (1) is plotted as a function of AB/2 on a bi-logarithmic scale and then inverted into a resistivity model. For a single sounding, it is done in 1-D way, traditionally by assuming that the Earth is made of horizontal, homogeneous and isotropic layers with constant resistivity. The apparent resistivity curve can be inverted to estimate the resistivity and thicknesses of the layers.

The resistivity soundings were carried out at strategic locations in the study area with dense population along major roads. This pattern is adopted following the linear settlement pattern along accessible roads of the inhabitants. The half current electrode spacing $(AB/2)$ of $65\ m$ to $160\ m$ were attained while the potential electrode spacing $(MN/2)$ was increased two times during the sounding from 1.5m to 5m. This extent of probes was attained bearing in mind that the ground water table in the study area was measured to be in the range of 5.5m to 13m. A total of Twenty six (26) VES soundings were occupied within the study area as shown in figure 2 on a Google earth map capture of the area using Global Position System (GPS) coordinates.

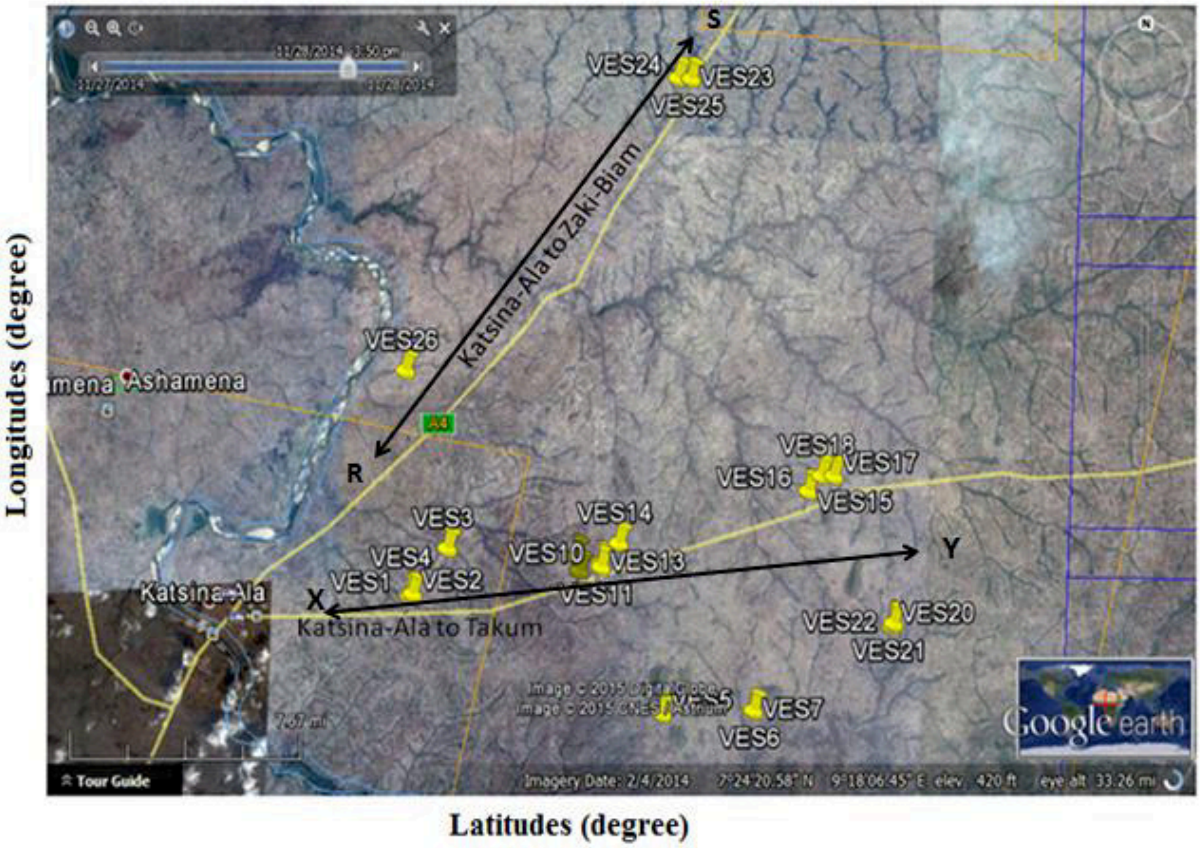

Fig. 2: Google earth map capture of Katsina-Ala area, central Nigeria showing VES points and settlement pattern.

The electrical resistivity contrasts existing between lithological sequences in the subsurface (Omusoyi, 2010) were used in the delineation of geoelectric layers, identification of aquiferous materials and finally, the geoelectric parameters of the overburden materials was used to quantitatively evaluate the susceptibility of aquifer material to contaminant load if found on the surface, and hence the vulnerability of the underlying aquifers, as demonstrated in Röttger et al. (2005).

In an unconfined aquifer such as our case study, the main protection of aquifer against contaminants is related to the presence of overlaying clay layers, whose protection capability comes down to the infiltration time lag of solutions, due to their low permeability. Kirsch et al. (2003) demonstrated that the protection degree of an aquifer or vulnerability may be considered directly proportional to the longitudinal conductance (S) of the overburden materials. This means that the higher the longitudinal conductance of overburden, the higher the degree of aquifer protection and vice vasa.

Aquifer vulnerability by electrical parameters can therefore be expressed as

$$IEC = \sum_i \sigma_i h_i, \quad (2)$$

$$IEC = \sum_i \frac{h_i}{\rho_i}, \quad (3)$$

where

$IEC =$ Integrated electrical conductivity, $h_i = ith$ Layer thicknesses, and $\sigma_i = ith$ Layer electrical conductivity or reciprocal of resistivity, ρ_i.

The above expression implies that the bigger the thickness of the layer, the larger the infiltration time of the contaminants (implying large filter) and the lower the resistivity/high electrical conductivity, the more clayey and less permeable the material will be (Braga et. al, 2006). Table 1 below gives the classification and rating of aquifer vulnerability using IEC-values.

Table 1: IEC/protective capacity rating (after Henriet, 1975)

Proctective capacity rating	Longitudinal unit conductance
Excellent	>10
Very Good	5 - 10
Good	0.7 - 4.9
Moderate	0.2 - 0.69
Weak	0.1 -0.19
poor	<0.1

Because water table is known to roughly follow the topography of a particular terrain, projects areas where topography seems to be of high influence, the vulnerability index is normalized by the thickness of the layers above the water table or depth of investigation. This will however lead to average conductivity of the layers above the reference depth hence revealing the geological conditions of the location as demonstrated by Röttger et al. (2005). Hence we have

$$IEC(norm) = \frac{\sum_i \sigma_i h_i}{\sum_i h_i}. \quad (4)$$

4. RESULTS AND DISCUSSION

Inversion of galvanic resistivity data acquired was done using WINRESIST inversion software by Vander (2004). These inversions revealed a sequence of 1-D resistivity depth models along two lines of investigation: South-West to South-East (SW-SE) and South- West to North-East (SW-NE) designated as lines XY and RS on the Google earth map capture of the area (Fig. 2) above respectively. This establishes 3 to 5 layer curve types, H, KH, and Q with 53.85%, 42%, and 3.85% occurrences respectively. Figure 3 shows four out of twenty-six VES curves which represent the types of field curves in the study area and Table 2 is the summary of VES interpretation results.

The geological interpretation of resistivity depth profiles supported by drilling results made available by BERWASSA boreholes log reports reveals top soil, sand/lateritic sand, sandy-clay, weathered basement and fractured/fresh basement rocks along line XY and top soil, sand/lateritic soil, sandy-clay/mudstone, weathered layer and fractured basement along line RS. From the interpretation, the aquifer units in the study area were delineated to be the weathered/fractured layers along profiles with resistivity and thickness ranges of 22.2 to 160.3 ohm-m and 9.4 to 74.5 m respectively. This indicates that the materials directory above the aquifer zone is the delineated vadose or unsaturated zone which was evaluated for natural yonder water protection using Integrated Electrical Conductivity, IEC. The resistivity of the topmost layer is observed to range from 171.1 to 5990.8 ohm-m, this layer is underlain by layer of resistivity range of 40.5 to 4533.3 ohm-m. The third layer is layer with relatively low resistivity values varying between 29.4 to 1378.0 ohm-m, this layer is dominated by medium resistivity materials and is highly conductive than the overlain layers. The fourth layer resistivity ranges from 22.2 to 3777.9 ohm-m and is undefined in some sounding points. The fifth layer resistivity is undefined in most of the sounding points.

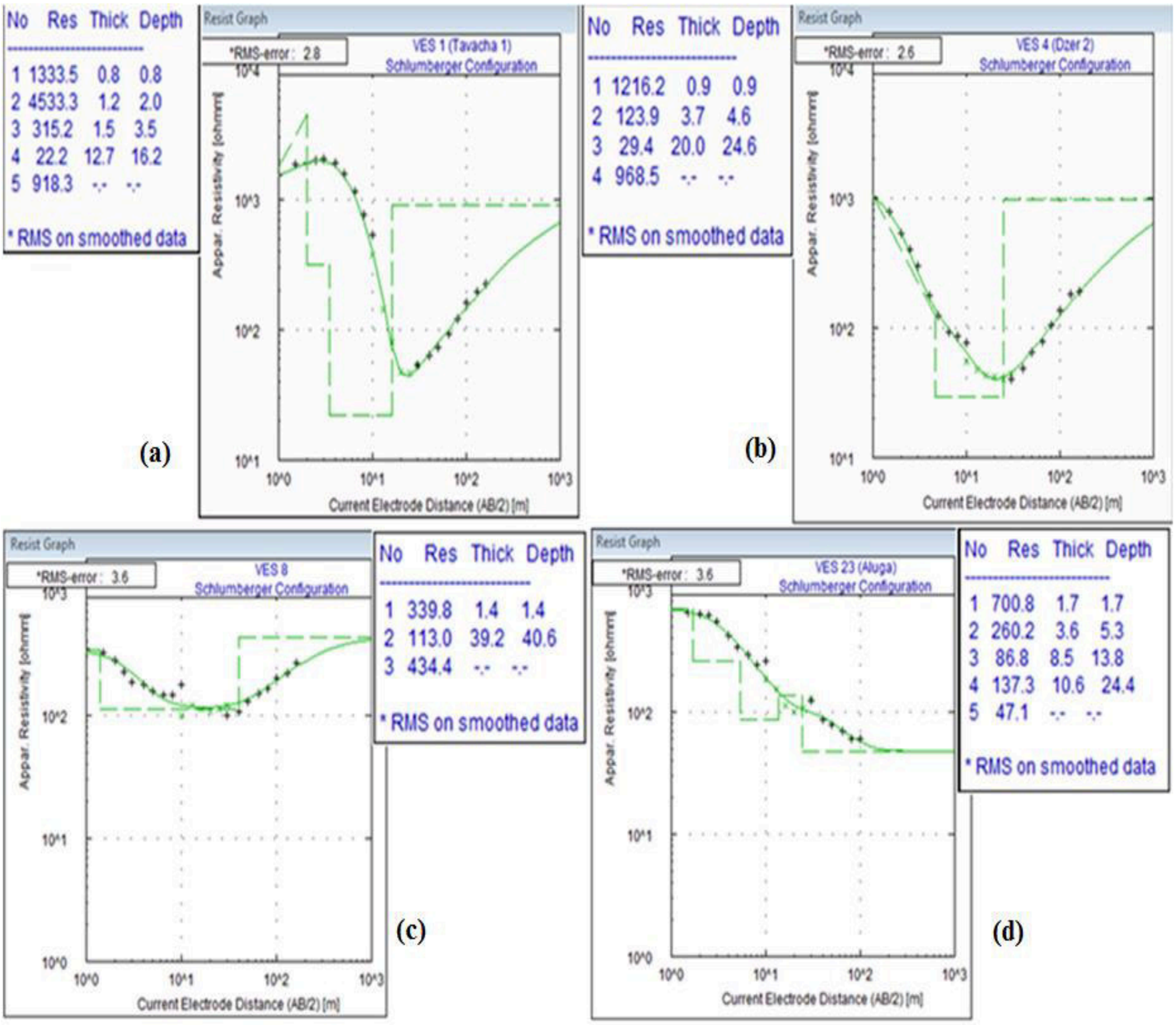

Fig. 3: Iterated field curves showing 5, 4, 3 and 5 layers type KH, H, H and Q curves (a, b, c and d)

Table 2: *Summary of result of VES data interpretation across the two lines XY and RS in Katsina-Ala, Central Nigeria.*

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

Blue codes = Aquifer parameters

4.1. Vulnerability from IEC values

The resistivity parameters of the vadose zone (Table 2) were used for evaluation of the IEC of the layers using equation (3) as shown in Table (3) with IEC ranging from 1.1791×10^{-3} to $190.2387 \times 10^{-3} siesmens$. The result was used to generate the aquifer vulnerability map of the area

(Figure 4) which gives the quantitative distribution pattern of the natural overburden protection of the aquifer in the area in both 2-D and 3-D. As suggested by Henriet (1975) that the protection degree of an overburden or vulnerability of aquifer may be considered directly proportional to the ratio between the thickness and resistivity or in other words, the total longitudinal conductance (S) of the overburden materials. Three classes of vulnerability (extremely, highly and vulnerable classes) were estabilisehed from the vulnerability map of the area. The South to North-West parts of the area which include the main Town and aluvium deposits of River Katsina-Ala are infered to be extremely vulnenarable as indicted by the red colour code with IEC values ranging from 0 to $40 \times 10^{-3} siesmens$. This is diagnostic of shallow aquifer or thin overburden thickness, an indication that the paculation time lag for contaminant if located on the surface will be very short. The middle part with yellow colour code is highly vulnerable. This is true due to its low values of IEC (less than 0.1 siesmens) which is a consequence of the geologic sequence that is highly resistive (lack of clay materials) and relatively thin. In the extreme North-Eastern part of the study area (brown colour), the vulnerability is less compared to the other zones, an indication that the zone is less permeable than other zones thereby, offering weak protection against contaminants that could be found on the surface. Longitudinal conductance values of the study area indicate that the entire subsurface is highly permeable, thus rendering the aquifer vulnerable to contamination from infiltration of surface contaminants. This reflects the absence or low volume of clay. The high resistivity values obtained is indicative of low concentration of conductive materials.

Table 3: Geo-electrical parameters of aquifer overburden materials and IEC in Katsina-Ala, Central Nigeria.

VES NO.	h_1 (m)	h_2(m)	h_3(m)	ρ_1(Ωm)	ρ_2(Ωm)	ρ_3 (Ωm)	$IEC = \sum_i \frac{h_i}{\rho_i}$ (siesmens) ($\times 10^{-3}$)
VES 1	0.8	1.3	1.5	1333.5	4533.3	315.2	5.6456
VES 2	0.9	1.6	4.6	936.1	2691.8	138.4	34.7928
VES 3	2.6	1.6	-	1031.7	212.9	-	10.0354
VES 4	0.9	3.7	-	1216.2	123.9	-	30.6028
VES 5	1	2	2.6	2472.2	4406.5	663.4	4.7776
VES 6	2.2	6	-	5990.8	1018	-	6.2611
VES 7	0.5	1.1	6.1	584.9	3147.7	397.3	16.5580
VES 8	1.4	-	-	339.8	-	-	4.1201
VES 9	0.6	1.3	11.1	263.4	783	121.9	94.9964
VES 10	0.8	2	-	404.6	985.1	-	4.0075
VES 11	0.7	1.3	4.5	1072.5	3486.8	91.6	50.0152
VES 12	0.7	2.9	5.7	1283.2	6825.7	165.8	35.3492
VES 13	2.2	6.4	-	1686.4	257	-	26.2073
VES 14	0.7	1.8	5.8	700.4	2958.8	60.8	97.0025
VES 15	3.4	-	-	891.8	891.8	-	3.8125
VES 16	1.8	3.9	-	977.4	123.8	-	33.440
VES 17	1.9	1.3	-	171.1	149	-	19.8294
VES 18	0.6	3.4	-	819.1	305.2	-	11.8727
VES 19	1.6	1.7	-	1556.2	1147.8	-	2.5092
VES 20	2.1	1.2	-	2467.6	1490	-	1.6564
VES 21	0.7	1.3	-	1120.5	2344.8	-	1.1791
VES 22	2.7	-	-	1318.3	-	1306.8	2.0481
VES 23	1.7	3.6	-	700.8	260.2	-	190.2387
VES 24	2.1	0.7	1.2	5258.4	961.7	162.8	8.4983
VES 25	0.5	0.8	5.8	13116.4	4321.5	40.7	143.0711
VES 26	0.8	2.8	-	1029.3	233.4	-	12.7737

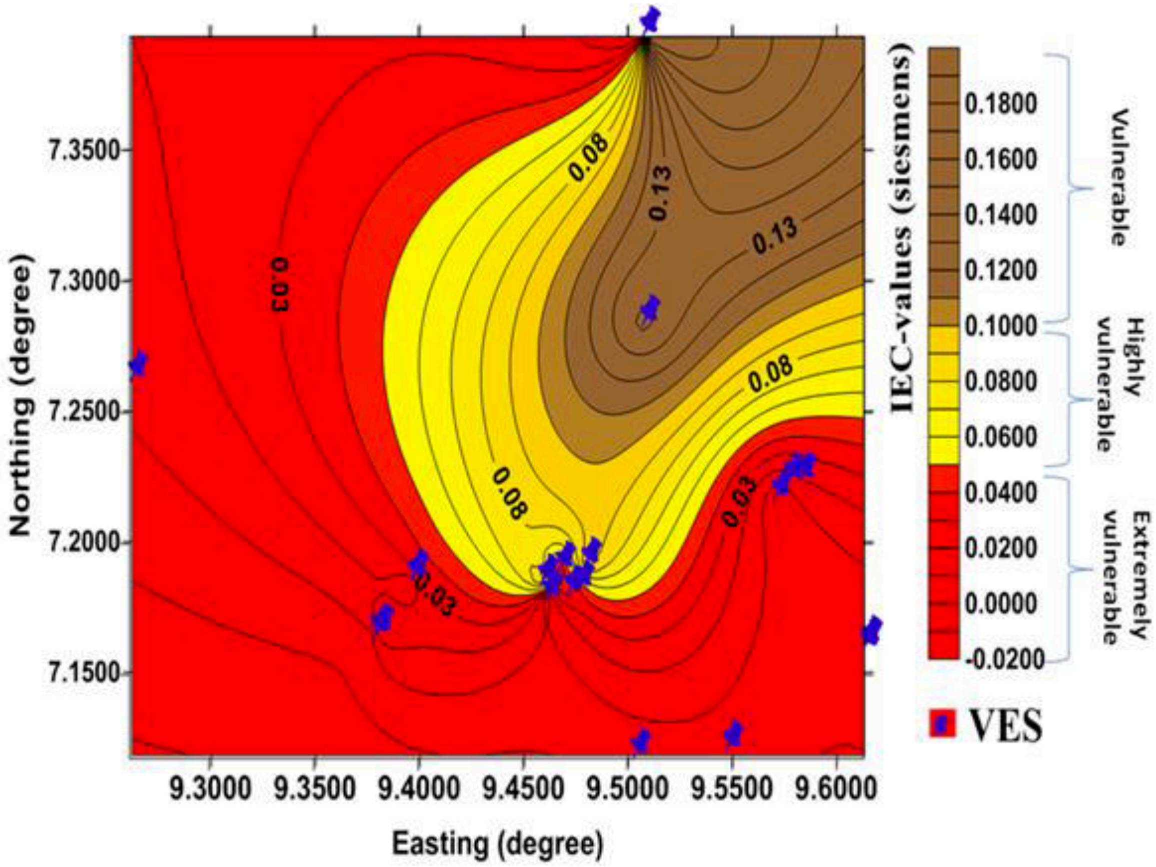

Fig 5a: Vulnerability map of Katsina-Ala, Central Nigeria using IEC.

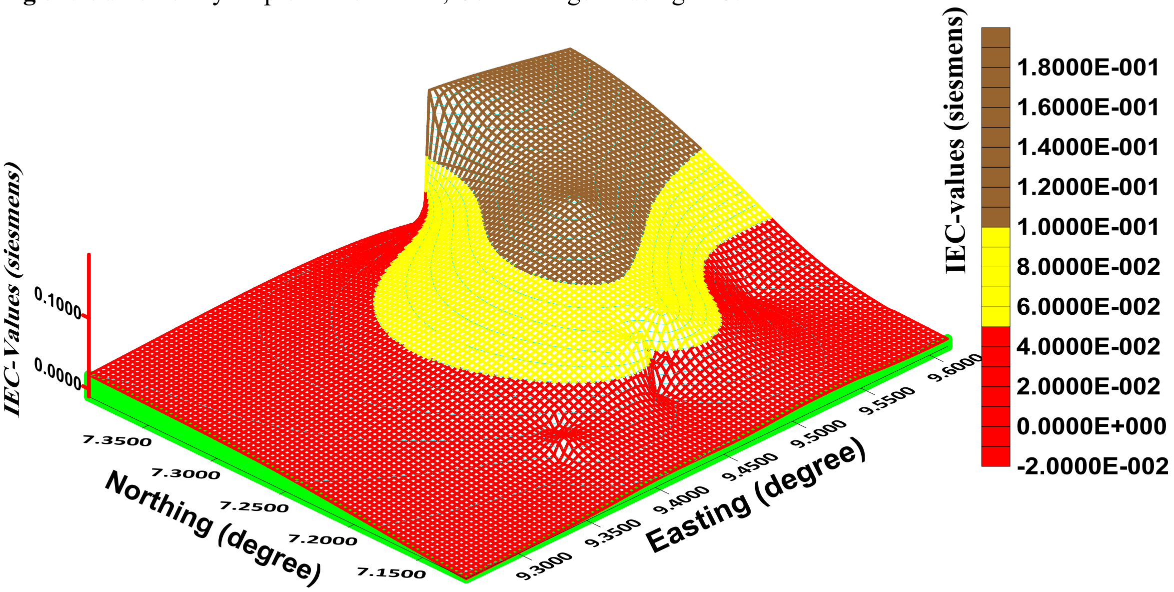

Fig 5b: 3-D vulnerability map of Katsina-Ala, Central Nigeria using IEC.

5. CONCLUSIONS

The importance of surface geophysical data in underground water exploration, exploitation and management cannot be over emphasized. The result of this research work enabled us to use electrical geophysical method to delineate aquifer zones and geo-electric parameters of overburden materials around Twenty Six VES points taken in Katsina-Ala area, central Nigeria. These parameters were used to map the vulnerability of the aquifer to contaminant load that could be found on the surface in the study area.

From the aquifer vulnerability map of the study area developed from integrated electrical conductivity IEC, three strong IEC regimes were identified as vulnerable, highly vulnerable and extremely vulnerable with IEC values across the entire study area ranging from 1.1791×10^{-3} to $190.2387 \times 10^{-3} siesmens$, and this was attributed to high permeability of the subsurface. These results will aid in the design of modalities for monitoring and protection of aquifer in the area against contaminants.

The possibilities of contaminant loads are inevitable in the study area due to the fact that the area is typically an agricultural area where activities involving the use of organic and inorganic fertilizers, insecticides, leachate from decomposed dump sites and other human activities capable of exposing contaminants load on the surface are rampart. As such, physico-chemical analysis of water from boreholes and wells should be carried out in the area to determine the amount and types of pollutants percolating into the aquifer, since the aquifer inferred in our research is on average considered vulnerable. This is important in determining the nature of water treatment and management that should be applied in the area.

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