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Original Article

Determination of hydraulic characteristics of an aquifer using vertical electrical sounding within the permanent site Adamu Augie College of Education Argungu, NW Nigeria

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Abstract

Twenty (20) vertical electrical soundings were acquired using ABEM SAS 300 terrameter in order to determine the hydraulic characteristics of the identified aquifers within Adamu Augie College of Education Argungu near Birnin Kebbi, Northwestern Nigeria. The data were interpreted and seven sounding curves were obtained (KH, HQ, HA, HK, AA, A, and Q). The generated geoelectric sections characterized the subsurface into six lithologic units (topsoil, clayey sand, sandstone, clay, shale and sand) with sandstone and sand constituting the major aquifers in the area. The resistivity layer parameters delineated across the entire area were used to determine the hydraulic characteristics of the identified aquifers. The delineated layers above the aquifers showed transverse resistance ranging from 333.06Ωm^2 to 23100.61Ωm^2, longitudinal conductance S from 0.025047 to 1.226506 mhos, hydraulic conductivity K from 0.44 m/day to 25.57 m/day, transmissivity T from 7.144 m^2/day to 465.374m^2/day, and coefficient of anisotropy from 0.98 to 1.0. The protective map shows that about 75% of the area falls within poor overburden protective capacity, 20% constitute moderate protective capacity, while the remaining 5% have good protective capacity rating. Therefore, the hydraulic characteristics of the area suggest that the materials above aquifers are less protected, and by implication vulnerable to infiltration.

Keywords: geoelectrical method, groundwater exploration, transmissivity, hydraulic conductivity, protective capacity, resistivity contrast

1. Introduction

The rapid increase in urbanization and industrialization has led to an increased waste generation. This has affected the drainage system, causing environmental pollution and contamination in the subsurface aquifers. This then necessitated evaluating the protective capacity of the overburden materials, in order to establish the level of safety for the hydrogeologic system within the study area. The electrical resistivity method is a unique geophysical tool used in contamination studies (Abiola, Enikanselu, & Oladapo, 2009; Adegoke, *et al.,* 1980). The resistivity method is used for electrical sounding and imaging providing information about vertical changes in subsurface electrical properties and, thus, it is useful in the determination of hydrogeologic conditions such as the depth to water table, depth to bedrock, and thicknesses of subsurface layers (Zohdy, 1974). Aquifer systems such as the Gwandu formation require a thorough understanding of the subsurface geology which cannot be obtain from surface geological mapping, except through geophysical techniques. Geophysical techniques in general and electrical methods in particular are most useful for aquifer parameter determinations. The electrical technique has been globally used as a preliminary tool in delineating deep aquifer systems, such as the one in the study area, because it yields a good correlation between a terrain's electrical resistivity and its geology and fluid content, with numerous successful case histories (Ammar & Kruse, 2016; Patra, Adhikari, & Kunar, 2016; Zohdy, Eaton, & Mabey, 1974). The aquifer parameters like hydraulic conductivity and transmissivity are extremely important for the management and development of groundwater resources (Djamel, 2017; Onawola, Olatunji,

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Ologe, & Jimoh, 2021). The subsurface characteristics like lithology, structure and texture control the occurrence and movement of groundwater, hence hydraulic conductivity, transmissivity and storability are commonly applied in groundwater modeling as they are considered the basic and the main aquifer parameters (Onawola, Olatunji, Ologe, & Jimoh, 2021). The main aim of this work was to determine aquifer hydraulic properties and to update our knowledge of the vulnerability of the near-surface aquifers within the study area.

1.1 Description of the study area and geology

The study area is located in the Northwestern part of Nigeria and lies in the northern part of Kebbi state (Figure 1). The area falls between latitudes 12.7355°N and 12.7603°N and longitudes 4.5254°E and 4.5439°E, covering in total about 2.265 Km^2. The drainage system in the area is river Rima. The area is accessible through Birnin Kebbi to Sokoto road. The study area Argungu is within Gwandu formation of Sokoto basin (Ologe, Abu, & Abdulsalam, 2018). The sediments are clays (coarse and medium-grained), sand, sandstones, limestone, shale, and mudstones (Adegoke, 1969) (Figure 2). Sand consists of non-aggregated particles of sand grains, while sandstone is a rock characterised by aggregated particles. Clay contains sand particles of both coarse and medium grains sizes (Ologe, & Ola-Buraimo, 2022). Sediments of the Sokoto Basin were accumulated during four main phases of deposition, the Gwandu formation being the youngest as it was deposited during post-paleocene (Ola-Buraimo, Ologe, & Benemaikwu, 2018). Recent research works on the textural characteristic and paleo environment of deposition of the sandstone and siltstone facies in Gwandu Formation are well articulated and widely discussed in the works of Ola-Buraimo, Oladimeji, & Imran, 2022; Ola-Buraimo & Usman, 2022.

The geology of Gwandu Formation and its stratigraphy where the study area is situated have been described as varying from one place to another. This was vividly described to be ambiguous in nature (Ola-Buraimo, Ologe, & Benemaikwu, 2018). Initially, Gwandu Formation was entirely described to have been deposited in a continental environment, but recent works have proven existence of fossils in the Gwandu Formation, which now indicate that parts of this formation were also deposited in a marginal marine environment (Ola-Buraimo, Ologe, & Benemaikwu, 2018; Ola-Buraimo & Usman, 2022). Other research evidence has shown that Duku Sandstone Type Locality is characterised by a herringbone structure, fine sized sand particles, well sorted and well-rounded grain shapes, indicative of transport and deposition by tidal waves in a tidal to intertidal marginal marine environment (Ola-Buraimo, Oladimeji, & Imran, 2022).

2. Methodology

Twenty resistivity soundings were carried out with the maximum separation of current electrodes being 100 m. Data were collected with an ABEM tetrameter. The electrode configuration was Schlumberger with Maximum half current electrode spacing (AB/2) of 100.0 m and potential electrode spacing (MN/2) of 12.0 m. The apparent resistivity was computed using equation (1) below:

$$\rho_a = \left(\frac{\Delta V}{I}\right) k \tag{1}$$

where k is a geometric factor and $\frac{\Delta V}{I}$ is the electrical resistance (in Ω) measured by the equipment. The apparent resistivity values obtained from equation (1) were plotted on a bi-log graph against the half current electrode separation spacing. From these plots, qualitative deductions, such as the resistivity of the first or top layer, the depth of each layer, and the curve signatures or types were made. The resistivities and thicknesses of the various layers were improved upon by employing an automatic iterative computer program following the main ideas of Zohdy, Eaton, & Mabey (1974). The WINRESIST computer software was employed for carrying out the iteration and inversion processes. The manually derived geoelectric parameters were subjected to an inversion

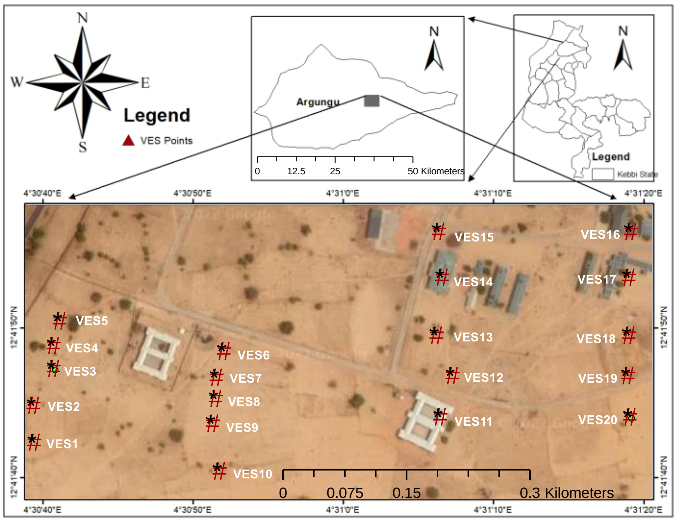

Figure 1. Location map of the study area (Adapted from Google Earth 2018)

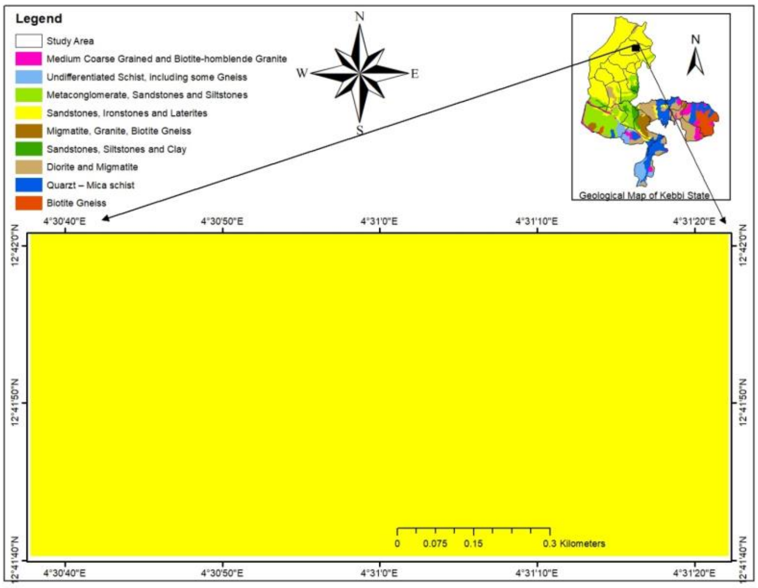

Figure 2. Geology map of the study area (Adapted from Google Earth 2018)

(Vander, 2004), which successfully reduced the interpretation error (rms error) to acceptable levels; The VES data presented as depth sounding curves were inverted with the aid of computer aided iteration curve matching techniques using Resist Version 1.0 (Vander, 2004). The algorithm takes the manually derived parameters as the starting geoelectric model, successively improving them until the error is minimized to an acceptable level. The hydraulic conductivity was estimated using the equation given by Heigold, Gilkeson, Cartwright, and Reed (1979). This was also corroborated by the work of Tijani, Oluchukwu, and Oladunjoye (2018).

$$K = 386.40Rrw^{-0.93283} \quad (2)$$

where, K is the hydraulic conductivity measured in m/day, and R_{rw} is the aquifer resistivity (Resistivity of the inferred aquiferous layer from the interpreted curves). The transmissivity was calculated using the formulae below:

$$T = K.b \quad (3)$$

where T is transmissivity, K is hydraulic conductivity and b is thickness of the aquifer measured in m^2/ day. Dar Zarrouk parameters are parameters related to the combination of resistivity of electric layer and thickness, these are vital for understanding and analyzing the geologic model (Zohdy, 1976) as witness in this research work. The total longitudinal conductance L_c of the overburden unit at each vertical electrical sounding station was obtained from the mathematical relation (Zohdy, Eaton, & Mabey, 1974) for longitudinal conductance L_c (mho), defined as:

$$h = h/\rho \quad (4)$$

where h is the thickness and ρ is the resistivity of the layer. The values of longitudinal conductance are used to evaluate the protective capacity of the aquifer (Kwami, *et al*., 2019).

3. Results and Discussion

Sounding curves (Figures 3 and 4) obtained in the study area are shown and they vary considerably throughout the study area. Typical forms of these curves are HA, KH, HA, HQ, AA, A, and Q types. Most of the sounding curves obtained were of the KH- type ($\rho1 > \rho2 > \rho3 < \rho4$). Such a steep rise in a sounding curve is a reflection of highly resistive sedimentary rocks at depth.

3.1 Generated geoelectric sections along profiles

The sounding data were analyzed with the aid of WinResist software to delineate the sub-surface layers with depths, thicknesses and their respective resistivity values. The geoelectric sections depict two-dimensional figures with varying resistivity and thickness of each geoelectric layer beneath each VES location connected along a profile (Adediran, Rotimi, & Ologe, 2021). The geo-electric section along profiles reveals three to four geo-electric layers which vary among topsoil, unconsolidated sandstone, clayey sand, clay, consolidated sandstone, and shale. The geo-electric section along profile one (Figure 5) consists of VES1-5 drawn in the NE direction. The section reveals four geo-electric layers which vary among topsoil, unconsolidated sandstone, clayey sand, consolidated sandstone, and shale. The first geo-electric layer represents the topsoil with resistivity and thickness ranging within 2739.8 – 33.3 Ωm and 0.3 – 0.9 m. The second identified layer beneath were VES 2, VES 3 and VES 5 denoting clayey sand with resistivity and thickness that ranged around 672.9 Ωm, 746.5 Ωm and 590.8 Ωm with 1.6 m, 3.5m and 1.7m respectively (Figure 5) while the geo-electric layer along VES4 is clay with resistivity and thickness of 23.4 Ωm and 2.3m. The third stratum beneath VES 1 to VES 5 is unconsolidated sandstone. The fourth geo-electric layer depicts consolidated sandstone (VES 7 and 10) and the remaining ones are clay. The SW geoelectric section was

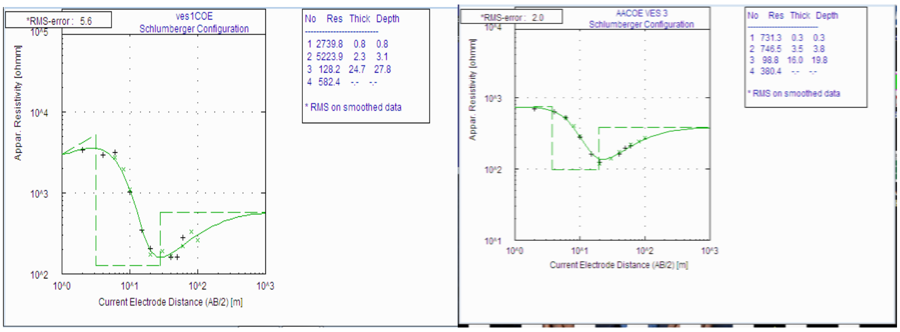

Figure 3. Typical sounding curves (VES 1 and 3) in the study area

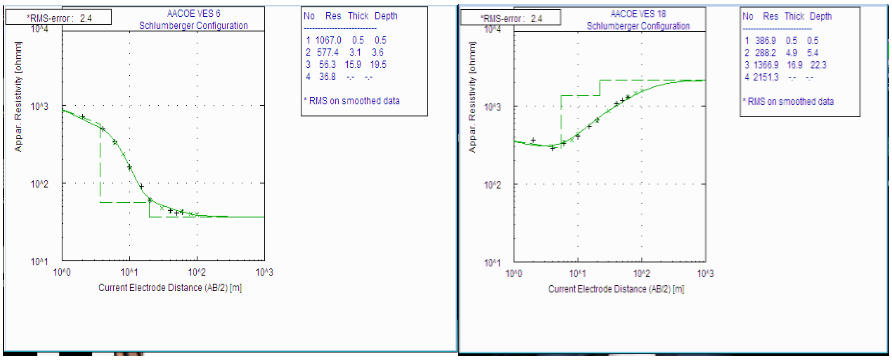

Figure 4. Typical sounding curves (VES 6 and 18) in the study area

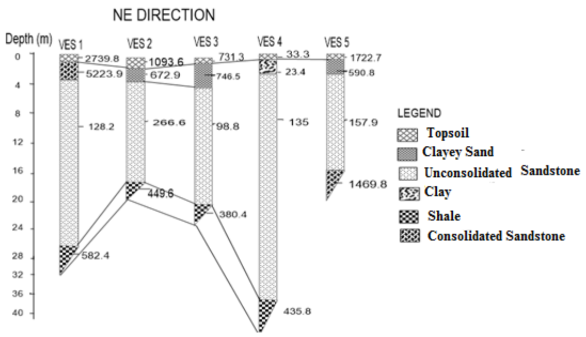

Figure 5. Geoelectric section profiles one

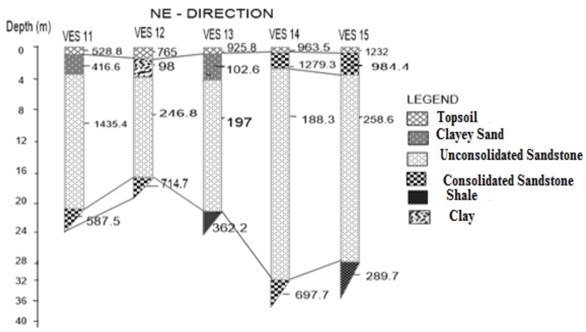

Figure 6. Geoelectric section along profile two

drawn through VES points 6, 7, 8, 9 and 10 (Figure 6). It depicts the area to be underlain by four geoelectric layers with three layers underlain in VES 10. These lithogic rock units consist of topsoil, clayey sand, clay, and shale. The unconsolidated sandstone and faulted consolidated sandstone units constitute the aquifer units in the study area. This was substantiated and corroborated in the work of Ologe and Ola-Buraimo (2022) that evaluated the aquifer characteristics within Birnin Kebbi Metropolis, Northwestern Nigeria using geoelectric survey. Figure 7 shows profiles of three cross sections drawn in the NE direction on VES 11 to 15. This section reveals four geo-electric layers which vary among topsoil, consolidated sandstone, clayey sand, unconsolidated sandstone and shale. The topsoil layer has resistivity and thickness ranges of 1232 – 765 Ωm and 0.3 – 1.3 m respectively. The claysand layer has resistivity between 984.4 Ωm and 1279.3 and thickness of 3.5 – 1.6 m. The third stratum is the unconsolidated sandstone which provides the

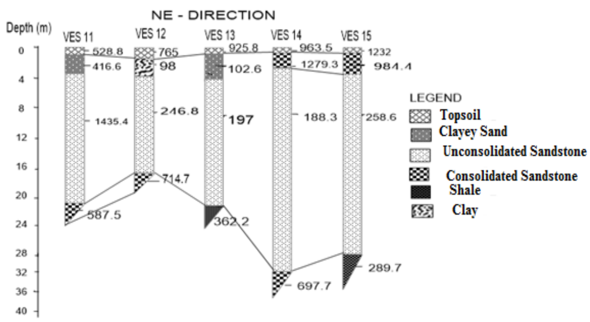

Figure 7. Geoelectric section profiles three

aquifer with shale as the last layer. Profile four was drawn on VES Points 16, 17, 18, 19 and 20 in the SW direction (Figure 8). The aquifer unit with resistivity values ranging in 181.2 – 1366.9 Ωm and thickness within 4.1-24.3m.

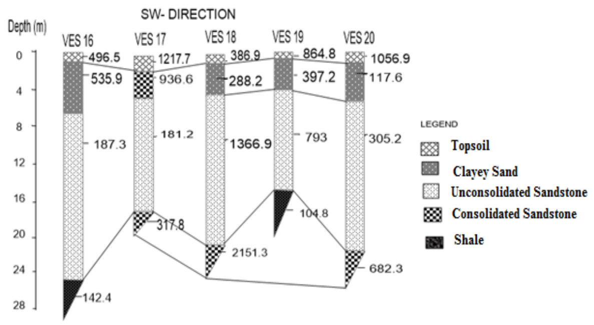

Figure 8. Geoelectric section profiles four

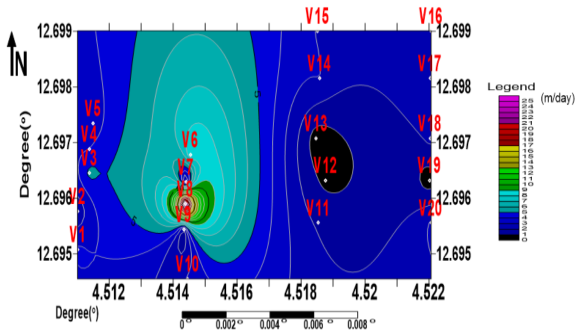

Figure 9. Hydraulic conductivity map

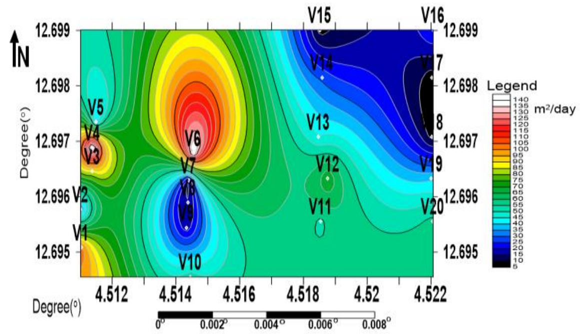

Figure 10. Transmissivity map

The Dukku sandstone was described to have good porosity and permeability serving either as hydrocarbon reservoir or water aquifer (Ologe & Ola-Buraimo, 2022). These geological features and paleo environment of deposition in the study area are factors responsible for low resistivity in some places, while high resistivities obtained in this research could be as a result of layers associated with continental deposits; characterised by ferruginisation, conglomeritic layer, and strongly consolidated poorly sorted sandstone (Ola-Buraimo, Ologe, & Benemaikwu, 2018). However, other areas of deposition of Gwandu Formation have been described to contain fine siltstone particles deposited in neritic marine and deeper middle neritic marine environments in Kola and Jodu areas respectively (Ola-Buraimo, Oladimeji, & Imran, 2022, Ola-Buraimo & Usman, 2022). This research output further substantiates the reason why there are different resistivity measures obtained in the study area, as shown in Figures 5-8. There is a direct relationship between the various aquifer layers varying from continental through marginal marine to middle neritic marine environments with increased porosity and permeability in the environmental trend. Thus, this is responsible for the variations from the very high resistivity values to the relatively low resistivity values obtained in this work.

3.2 Delineation of aquifer parameters

The second order geoelectric parameter, longitudinal conductance (Dar Zarrouk parameter), was generated from the primary/first order parameters (thickness and resistivity) of the geo-electric subsurface layers, which were used in the classification of the Aquifer Protective Capacity (Adeniji, Omonona, Obiora, & Chukudebelu, 2010; Agunloye, 1984). Longitudinal unit conductance ($S = h/\rho = h\sigma$). Other attributes used in the computation of the aquifer parameters include the following:

Transverse unit resistance ($T = h\rho$)

Longitudinal resistivity ($\rho L = h/S$)

Transverse resistivity ($\rho t = T/h$)

Anisotropy ($\lambda = \sqrt{\rho t / \rho L}$)

where h is the thickness of the layer (in metres) and ρ is the electrical resistivity of the layer in ohm-metres.

Hydraulic conductivity can be described as the relative ease with which a fluid flows through a medium (geological formation). The aquifer hydraulic conductivity map (Figure 9) was produced by contouring all hydraulic conductivity values in the range 0.44-26 m/day across the entire study area (Table 1). The highest hydraulic conductivity in the study area was in the N –S direction (Figure 9). Haley (2017) concluded in his study that hydraulic conductivity values need to be between 25 m/day and 100 m/day or more for an aquifer to be good.

Transmissivity as an aquifer parameter is defined as the permeability over the depth of the aquifer, or as the product of its hydraulic conductivity and the thickness of layer (Thomas, Fidelis, Ushie, & Okechukwu, 2018). Ariyo, Adeyemi, and Akintola (2017) reported in their study that transmissivity in the basement environment is generally low while in the sedimentary terrain it is always moderately high. The transmissivity values across this study area are detailed in Table 1 with 2D and 3D view shown in Figure 10.

The longitudinal conductance/protective capacity ratings are also presented in Table 1. The classification of the study area into various grades of protective capacity rating was strongly determined by the longitudinal conductances. The areas that are classified weak and poor are most susceptible to contamination, while the ones of good, very good and excellent classification indicate high protective capacity against contamination. The maximum longitudinal conductance S=1.22 gave a high protective rating, those with longitudinal conductance in the range of 0.2-0.4 are moderate and those with longitudinal conductance less than 0.1 to 0.19 are weak and poor indicating that the aquifers there are susceptible to contamination. The aquifer protective capacity map (Figure 11) was produced showing the protecting capacity ratings of the aquifer present in the area.

The coefficient of anisotropy that reveals degree of fracturing was also computed (Table 1). The coefficient of anisotropy across the entire area varies from 0.98 to 1.0 which indicates homogenous settings with no intense fracturing.

Table 1. Summary of the aquifer parameters

VES NO:	Aquifer resistivity	Thickness (h)	Transverse resistance Tr=ρh	Hydraulic Conductivity (K)	Transmissivity T=kh	Longitudinal Conductance (S)	Protective capacity	Anisotropy (λ)
VES 1	128.2	24.7	3166.54	4.18	103.246	0.217734	Moderate	1.0
VES 2	266.6	14.9	3972.34	2.11	31.439	0.069805	Poor	1.0
VES 3	98.8	16.0	1580.8	5.32	85.120	0.205906	Moderate	1.0
VES 4	135.0	36.7	4954.5	3.98	146.066	0.411231	Moderate	1.0
VES 5	157.9	11.6	1831.64	3.44	39.904	0.095023	Poor	0.99
VES 6	56.3	15.9	895.17	8.99	142.941	0.353062	Moderate	0.99
VES 7	598.4	13.3	7958.72	0.99	13.167	0.044201	Poor	0.99
VES 8	18.3	18.2	333.06	25.57	465. 374	1.226506	Good	1.0
VES 9	498.3	14.5	7225.35	1.18	17.110	0.063231	Poor	0.9
VES 10	174.9	17.1	2990.79	3.13	53.523	0.105545	Weak	1.0
VES 11	1435.4	17.9	25693.66	0.44	7.876	0.025047	Poor	0.98
VES 12	246.8	12.7	3134.36	2.27	28.829	0.128584	Weak	0.99
VES 13	197.0	16.2	3191.4	2.79	45.198	0.174056	Weak	0.99
VES 14	188.3	23.9	4500.37	2.92	69.788	0.177401	Weak	1.0
VES 15	258.6	24.8	6413.28	2.17	53.816	0.158763	Weak	1.0
VES 16	187.3	19.3	3614.89	2.93	56.549	0.158103	Weak	0.99
VES 17	181.2	13.0	2355.6	3.02	39.260	0.104451	Weak	1.0
VES 18	1366.9	16.9	23100.61	0.46	7.774	0.036344	Poor	0.98
VES 19	793.0	9.4	7454.2	0.76	7.144	0.030045	Poor	1.0
VES 20	305.2	13.7	4181.24	1.86	25.482	0.138803	weak	1.0

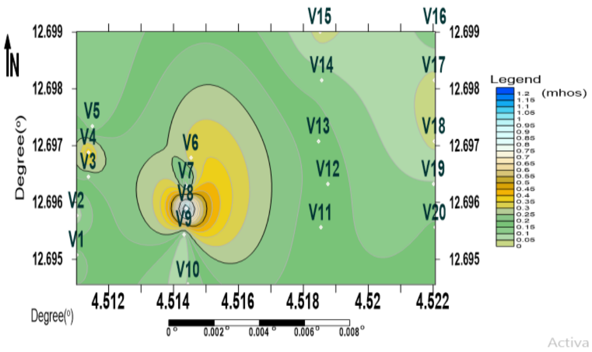

Figure 11. Aquifer protective capacity map

4. Conclusions

Geoelectrical investigation using Vertical Electrical Sounding (VES) was adopted within the permanent site of Adamu Augie College of Education Argungu, Kebbi State Northwestern, Nigeria to determine aquifer parameters in the area.

The interpreted results of the VES data were done using Winresist and suffer software packages and the results are presented as sounding curves, geo-electric sections, maps and a Table. The sections reveal three to six geo-electric layers which vary among topsoil, clayey sand, consolidated sandstone, clay, unconsolidated sandstone, and shale. The resistivity parameter of the geoelectric layers across the entire area were used to delineate the hydraulic characteristic parameters of the identified aquifers with the highest hydraulic conductivity and transmissivity values in the N –S direction in the study area.

It is observed that VES 8 has high protective rating to contamination, VES 1,3,4 and VES 6 are characterized by moderate aquifer protective capacity while VES 2,5,7,9,10,11,12,13,14,15. 2,5,7,9,10,11,12,13,14,15 and VES 20 are characterized by weak and poor protective capacity indicating that the aquifers in that area are susceptible to contamination. The overburden protective capacity map shows that about 75% of the area falls within poor overburden protective capacity, 20% constitute moderate protective capacity, while the remaining 5% have good protective capacity rating. Therefore, the hydraulic characteristics of the area are suggesting that the materials above aquifers are less protected, and by implication vulnerable to infiltration.

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