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GEO-ELECTRICAL SURVEY FOR DELINEATING GROUNDWATER POTENTIAL ZONES AROUND INDUSTRIAL AREAS, BAUCHI, NORTHEASTERN NIGERIA

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ABSTRACT

This present study uses Dar Zarrouk (D-Z) Parameters: Total Transverse Unit Resistance, T (Ωm2), and Total Longitudinal Unit Conductance, S (Ω−1) to suggest optimal locations for drilling of boreholes in Gudum environ, Bauchi State, Nigeria. The methodology adopted used and interpreted 20 Schlumberger Vertical Electrical Sounding (VES) curves with maximum current electrode spacing of AB/2 = 100 m. Aquifer parameter estimates from the (VES) curves were used to prepare contour maps of T (Ωm^2*), S (Ω−1), and aquifer thickness h (m). To effectively use these parameters, iso-thickness and iso-resistivity maps were compared with contour maps of transverse resistance. The agreement among these parameters provided the basis for identifying auriferous zones. It was observed that the Southern part of the study area, which is mainly underlain by the biotite hornblende granite, showed relatively higher T (Ωm2), h (m), and ρ (Ωm) values, implying high-yield auriferous zones. The overburden thicknesses at all VES stations range from 12.76 m to 44.57 m, with resistivity values from 104.0 Ωm to 371.1 Ωm. Also, the overburden thickness thematic maps confirm that the southern part of the study area has lower resistivity values, indicating that water wells sited in these areas yield more water.*

Keywords: Vertical Electrical Sounding, Resistivity, Dar Zarrouk parameters, Overburden thickness, Groundwater Potential.

INTRODUCTION

The demand for clean and portable water increases exponentially with increasing population and industrialization. Water is, therefore, a vital resource without which life would be impossible. Water occurs as surface water in streams and lakes, and as groundwater when it accumulates beneath the ground surface. The water needed to support domestic, agricultural, and industrial requirements in and around the study area is largely provided by the basement aquifers. These aquifers are usually located in weathered and fractured rocks, where porosity and permeability are sufficient to allow appreciable water storage (Dike, 1994). Recent hydrological surveys have shown that careful studies, backed by improved drilling techniques, can yield very favorable results even in problematic areas of the Basement complex (Dike*,* 1994).

Although various geophysical methods have been applied successfully to explore for groundwater in basement terrains, some of these methods are electrical, magnetic, and electromagnetic. Of all these methods, the electrical resistivity method has been the most widely used for groundwater exploration (Alile *et al,* 2008). It is used to evaluate the vertical variation of electrical resistivity below the earth's surface, since the electrical resistivity of most rocks depends on the amount of water in the pore spaces, the distribution of these pores, and the salinity of the pore water. This study aims to use the VES (Vertical Electrical Sounding) resistivity method to locate suitable aquifers, leveraging the resistivity contrast between dry, fresh, crystalline rocks and weathered or fractured, water-bearing zones.

The people in the study area typically depend on various water sources, such as streams and hand-dug wells, which are vulnerable to pollution, increasing the risk of waterborne diseases.

Hence, the need to provide portable water sources for Gudum, Bigi, and environs to reduce their adverse health exposure levels constitutes the objective of this study, through the determination of areas with thick Overburden, as this will greatly help in identifying the optimal drilling point within the area.

STUDY AREA

The study area is located at the outskirts of Bauchi town. It comprises the industrial layout area, Gudum, and Bigi (Fig. 1). The area lies between longitudes 9°49'52" and 9°51'44" and latitudes 10°15'21" and 10°17'22". The area is generally accessible via numerous tarred and untarred roads and footpaths linking most parts. The study area generally has a high relief. The Gudum Hill forms the prominent peak with an elevation of about 53 to 783m above mean sea level (Shemang & Umaru, 1994). The drainage system of Bauchi and environs has a dendritic pattern, with streams flowing radially from two main elongated water-sheds, one from Miri and the other to the north of Miri. The Tambari River flows from the south-west to the north-eastern part of the study area. All these streams are perennial, with their head courses and smaller tributaries being seasonal (Shemang & Umaru, 1994).

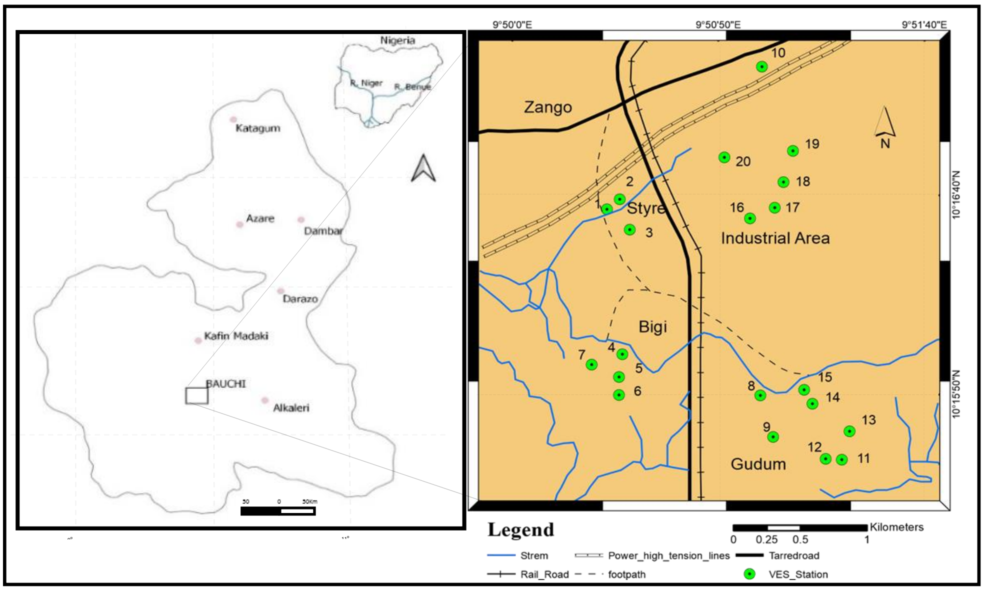


Fig. 1: Map of Bauchi State Showing the Location of the Study Area.

Geology of Bauchi State

Bauchi State is mainly underlain by crystalline rocks belonging to the Nigerian Basement Complex of Pre-Cambrian to Paleozoic age (Oyawoye, 1972). Minor Tertiary and Quaternary sedimentary deposits (Fig. 2). The Pre-Cambrian to Paleozoic Basement Complex rocks cover the southwestern part of the state. In contrast, the southeastern part is covered by the Paleocene Keri-Keri formation, and the Quaternary Chad formation covers most parts of the northern part of the state, with minor patches of Older Granites (Fig. 2).

Carter et al. (1963) divided the Basement Complex rock in northern Nigeria into three principal groups: the ancient metasediment, the gneiss-migmatite, and the older granite. According to Rahman (1981), Migmatite-gneiss found around Bauchi state comprises largely migmatitic granitic gneiss, basic schists and gneisses, relict metasediments, calcareous quartzite, and granitic rocks. Oyawoye (1962) described a variety of quartz monzonite series, which he named

Bauchite in 1975. The Precambrian-Paleozoic rocks occur mainly around Kafin Madaki, Bauchi town, and some parts of Alkaleri.

The Keri-Keri formation is a continental deposit and has been dated to the Paleozoic (Adegoke et al., 1993). Lithologically, it comprises well-developed medium- to coarse-grained sandstones, siltstones, and claystones (Dike, 1993). The Keri-Keri deposit represents deposits that follow the end of the Cretaceous compressional fold phase and affect the upper Benue trough. It has a distinct contact mainly with conglomerates and the Basement Complex (Dike & Egbuniwe, 1994). The Paleozoic Keri-Keri formation outcrops in some parts of Alkaleri, Mainamaji, Darazo, and Dambam (Fig. 2).

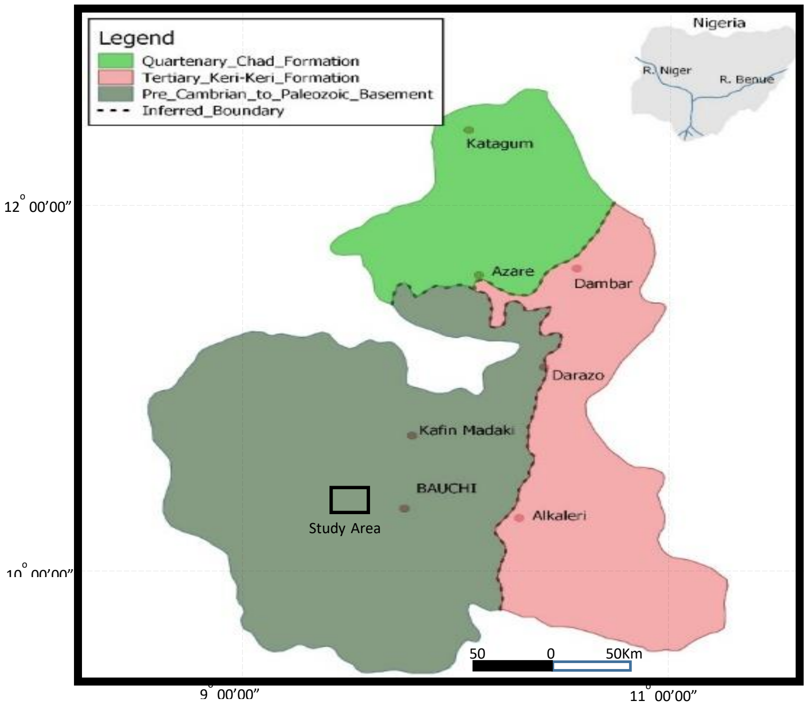


Fig. 2: Simplified geology of Bauchi State.

The Chad formation is a freshwater sedimentary sequence of Pleistocene age. It consists mainly of thick lacustrine and fluvial deposits (Carter *et al,* 1963). The Chad formation was deposited on top of Keri-Keri formation sediments, Cretaceous sediments, and the Basement Complex. The Paleocene Chad formation is observed mainly around Katagum, Gamawa, Azare, and some parts of Jamare (Fig. 2).

Geology and Hydrogeology of the Study Area

According to Likkason and Shemang (1995), the area around Gudum (part of the study area) is underlain by rocks of the Pre-Cambrian Basement Complex, comprising mainly of biotite-hornblende granite, fayalite-quartz monzonite (Bauchite) and undifferentiated migmatite and gneisses. Freshly broken surfaces of the Bauchite are greenish to bluish-green but become brownish upon weathering (Rahman, 1981). They are massive, homogeneous, and unfoliated with joints outcropping as smooth, rounded boulders derived from the massive foliated rocks by spherical weathering. Compositionally, Bauchite includes orthoclase, fayalite, ferrohedenbergite, and some biotite in its mineral assemblage with iron-titanium oxide, apatite, zircon, and rare epidote as accessory minerals (Rahman, 1981). Bauchite occurs towards the northern part of the study area (Fig. 2).

The Biotite-hornblende granite occurs as prominent hills with rugged surfaces with faint foliation defined by small streaks of biotite and hornblende alternating with feldspars and quartz (Eborall, 1989). They are characteristically porphyritic in texture, owing to perthite microcline in a groundmass of medium- to coarse-grained feldspars, quartz, biotite, and hornblende, and the contact between Bauchite and the hornblende granite is gradational (Eborall, 1989). Biotite hornblende granite occurs widely in the central portion of the study area (Fig. 2).

The migmatites and granites gneisses cover almost the entire northern part of the study area. They are variable in textures from medium to coarse grained (Fig. 2). According to Eborall (1989), the migmatites are composites of hornblende-bearing gneiss and granitic rocks, while the gneiss, composed of white plagioclase, some microcline quartz, and fairly abundant biotite and hornblende, is also present in varying amounts.

The study area consists of two main types of aquifers. The porous, broken, decomposed rock of the weathered basement and the fracture zones of fresh basement rocks (Umaru, 1987). The weathered basement is characteristically clay, brown to reddish brown, ferruginous, and lateritic. The decomposed material overlies the Crystalline rocks and is largely covered by a thin layer of superficial materials consisting mainly of sand, gravel, silts, and clays, locally intermixed with these materials (Shemang & Umaru, 1994). The fresh basement, though generally has a low percentage of joints and fractures, is in some places very highly fractured. The fracturing in the study area is mainly due to jointing, faulting, and shearing, probably associated with Pan-African Orogeny (Oyawoye, 1972). Generally, the groundwater potential of these crystalline rocks depends on the extent, pattern, size, opening, continuity, and hydrologic connectivity of the fractures (Dike et al., 1994).

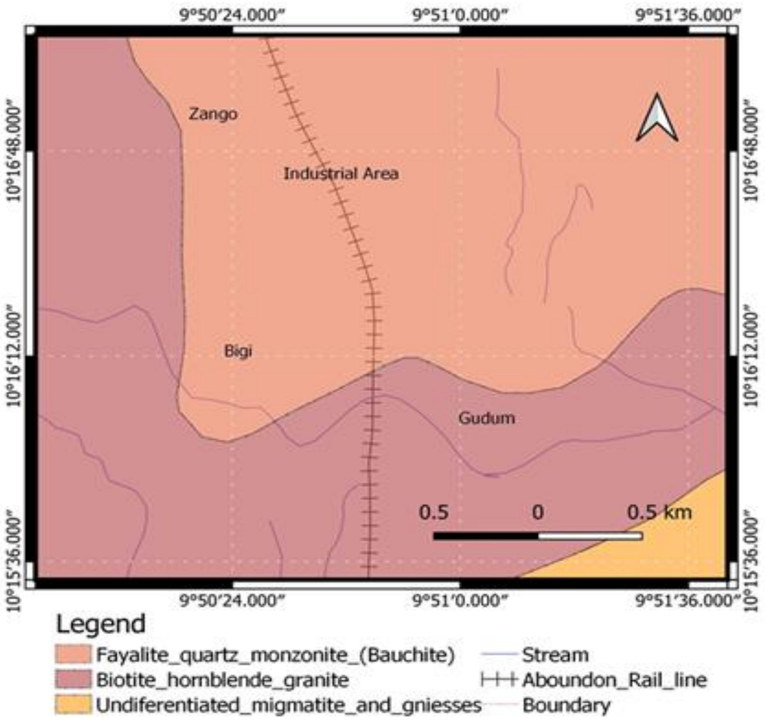
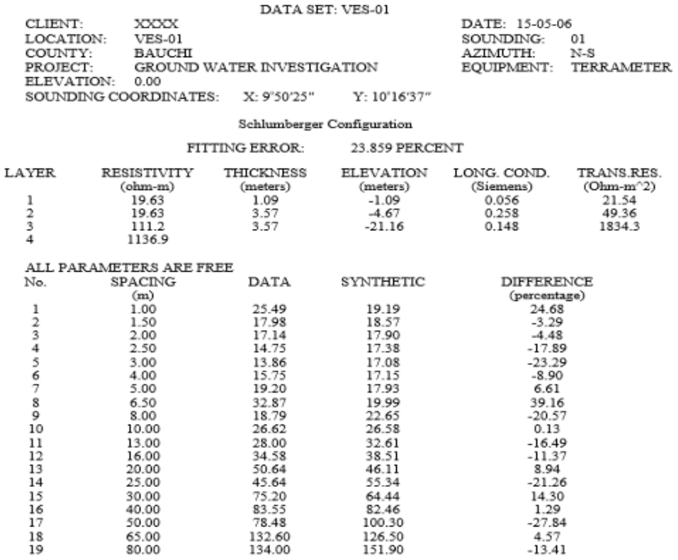


Fig. 3: Geologic map of the study area (Modified after Shemang and Umaru, 1994)

MATERIALS AND METHODS

The geophysical prospecting method adopted for this study is the Vertical Electrical Sounding (VES) technique of the Electrical resistivity method, deploying the Schlumberger array configuration (Fig. 3). The ABEM SAS-300C Terrameter, along with necessary accessories and equipment, was used. According to Salami and Ogbamikhumi (2017), in the array, the spacing between the potential electrode (MN) was recommended for reliable readings, not to exceed 40% of half the spacing (AB) between the current electrodes. The current survey comprises 20 VES stations (Fig. 1) acquired using the Schlumberger array, with a maximum current electrode separation (AB/2) of 100m. The apparent resistivity electrical response measured in the field was then plotted on a double-logarithmic graph sheet against half the current-electrode spacing (AB/2) to produce the observed field curve, which was initially interpreted by partial curve matching to estimate the layer's resistivity and thickness (Adam, 2006). These results serve as a starting point for the iterative computer-assisted interpretation that was later done. Geoelectric section and subsurface profile maps were generated using parameters such as overburden thickness, weathered/fractured zone thickness, Basement relief, and Clay thickness to aid our interpretation and evaluation of the groundwater potential of the study area.



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                              DATA SET: VES-01
   CLIENT:       XXXX                                      DATE:  15-05-06
   LOCATION:     VES-01                                    SOUNDING:    01
   COUNTY:       BAUCHI                                    AZIMUTH:     N-S
   PROJECT:      GROUND WATER INVESTIGATION                EQUIPMENT:   TERRAMETER
   ELEVATION:    0.00
   SOUNDING COORDINATES:    X: 9°50'25"       Y: 10°16'37"

                          Schlumberger Configuration

                  FITTING ERROR:         23.859 PERCENT

LAYER      RESISTIVITY    THICKNESS     ELEVATION    LONG. COND.    TRANS.RES.
             (ohm-m)       (meters)      (meters)     (Siemens)     (Ohm-m^2)
  1          19.63          1.09          -1.09         0.056          21.54
  2          19.63          3.57          -4.67         0.258          49.36
  3          111.2          3.57         -21.16         0.148         1834.3
  4          1136.9

   ALL PARAMETERS ARE FREE
   No.        SPACING         DATA        SYNTHETIC          DIFFERENCE
                (m)                                          (percentage)
    1          1.00           25.49         19.19               24.68
    2          1.50           17.98         18.57               -3.29
    3          2.00           17.14         17.90               -4.48
    4          2.50           14.75         17.38              -17.89
    5          3.00           13.86         17.08              -23.29
    6          4.00           15.75         17.15               -8.90
    7          5.00           19.20         17.93                6.61
    8          6.50           32.87         19.99               39.16
    9          8.00           18.79         22.65              -20.57
   10         10.00           26.62         26.58                0.13
   11         13.00           28.00         32.61              -16.49
   12         16.00           34.58         38.51              -11.37
   13         20.00           50.64         46.11                8.94
   14         25.00           45.64         55.34              -21.26
   15         30.00           75.20         64.44               14.30
   16         40.00           83.55         82.46                1.29
   17         50.00           78.48        100.30              -27.84
   18         65.00          132.60        126.50                4.57
   19         80.00          134.00        151.90              -13.41
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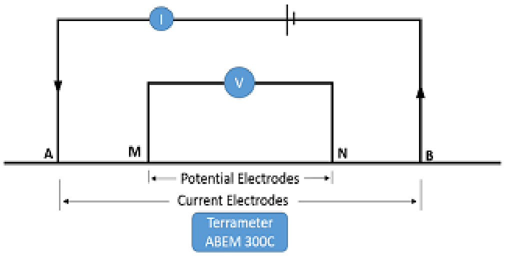

Fig. 4 Schlumberger configuration

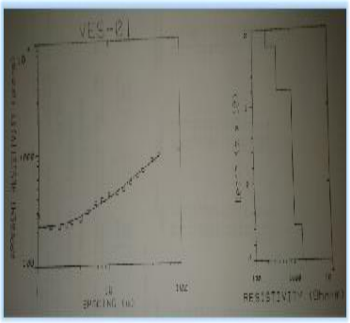

Fig.5: Resistivity A-type Curve

The first-order geoelectric parameters obtained from the iteration were used to calculate second-order geoelectric parameters or the Dar Zarrouk parameters (Mailet, 1947). The second-order parameters used in this study include total longitudinal conductance (ρl) and total transverse resistance (ρt) (Table 1). The variation of resistance and conductance in hard rock indicates the predominance of resistive and conductive zones, implying the groundwater potential in the formation above the bedrock. The ratio of the thickness to the resistivity of a layer defines the longitudinal conductance. At the same time, the transverse resistance is the product of the layer's thickness and resistivity. Both (mho) and (Ohm-m^2) were calculated using equations (1) and (2), respectively, from Mailet (1947), where h (m) is the thickness of the layer obtained from VES in each station, and (ohm-m) is the electrical resistivity of the layer obtained from VES in each station. N is the number of layers in the geo-electric profiles.

Table 1: Mathematical formulation of the second-order geoelectrical parameter employed (After Mailet, 1947; Lawal *et al*., 2021)

S/N	Parameter	Formula
1	Total longitudinal unit resistance	$S = \sum_{i=1}^{n} h1/\rho 1$
2	Total transverse unit resistance	$T = \sum_{i=1}^{n} h1\rho 1$
3	Longitudinal resistivity	$\rho l = {}^{H}/_{S}$
4	Transverse resistivity	$\rho t = {}^{T}/_{S}$

Geographic Information System (GIS) Techniques

The parameters calculated in Table 1 were converted to point data for each station, georeferenced, and then imported into the GIS environment. ArcGIS was used for data generation and spatial analysis, projected to the World Geodetic System 1984 (WGS 1984) coordinate system. The Spatial Analysis extension in ArcGIS was used to produce the thematic maps.

RESULTS AND DISCUSSIONS

Geoelectric Layer Characterization

The acquired field data were interpreted and presented using tables, figures, and subsurface maps (Table 2; Figures 6 and 7). Interpretation of the Vertical Electrical Sounding (VES) data, using a combination of partial curve matching and computer-assisted iterative techniques, revealed the presence of three to four geo-electric layers across the study area. These layers correspond to the topsoil, the weathered or decomposed layer, the fractured basement, and the fresh basement. This stratigraphic sequence is characteristic of Basement Complex terrains, where groundwater occurrence is primarily controlled by the extent of weathering and fracturing within the subsurface.

The interpreted VES results were further used to generate one-dimensional (1-D) geo-electric sections (Figure 4), which provide insight into the geometry and thickness variation of subsurface lithologic units along the profiles. The interpretation assumes horizontally stratified layers, and most VES stations exhibit acceptable fitting errors of less than 15%.

Transverse Resistance, Overburden Thickness, and Longitudinal Conductance

The computed data for each of these parameters are presented in Table 2. Figure 8b, the transverse resistance map, shows that the aquifer in the Southern part of the study area primarily exhibits higher transverse resistance values than in the Northern part. This indicates that the southern part has high transmissivity with good groundwater potential. The transverse resistance ranges from 3922.7 Ωm2 at VES-8 in the northern part of the study area to 20388.6 Ωm2 at

VES-5 in the southern part of the area. An isopach map of the aquiferous layer (Figure 7) shows that aquifer thickness is highly variable in the study area, ranging from 12.76 m at VES-8, north of the study area, to 44.57m at VES-6 in the Southern part of the study area, with average value 23.04 m (Fig. 6). Comparison of Figure 7 and Figure 8(a&b) shows that areas underlain by relatively thick aquifer materials have higher T-values than areas underlain by relatively thin aquifer materials. This relationship is expected because aquifer transmissivity is linear in aquifer thickness and Transverse resistance, assuming constant hydraulic conductivity. Although the contour maps shown in Figure 8(a & b) for the T and h values, respectively, point to intercalations of low

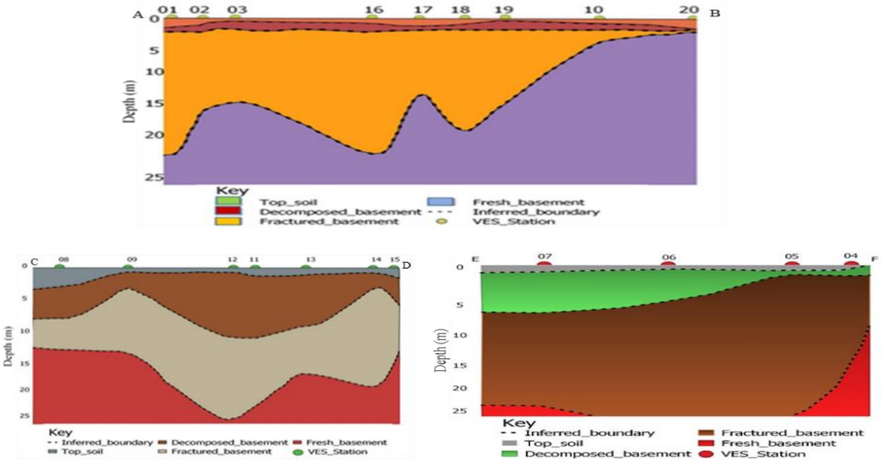

Fig. 6: VES profile A-B, C-D and E-F across the study

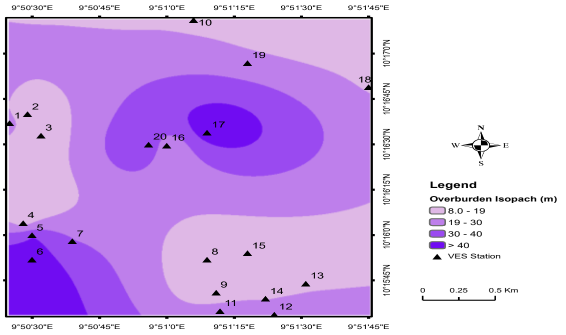

Fig. 7: Overburden isopach thematic

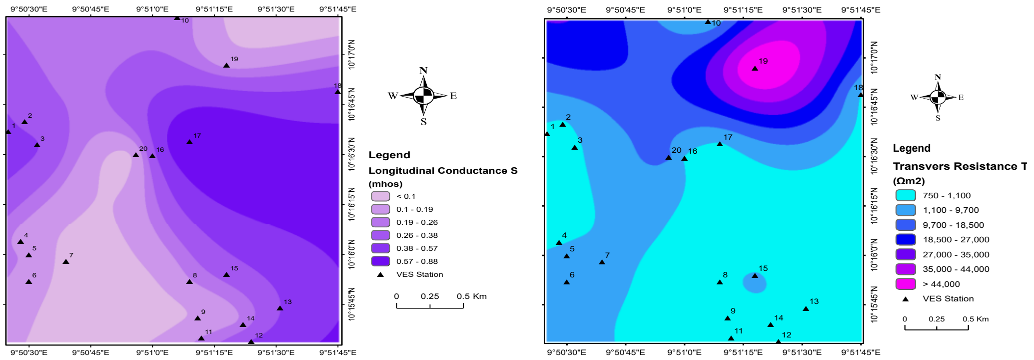

Fig. 8: Map of the study area showing variation in (a) Longitudinal Conductance and (b) Transverse Resistance

values of the parameters in the S-SE zone of the area generally show a relatively progressive decrease from South to North, indicating similar trend patterns in the distribution of these parameter values in the study area.

Resistivity Distribution

A total of twenty (20) VES stations were occupied using the Schlumberger array configuration (Figure 1). The interpreted resistivity values range from 7.2 Ωm to 52,925.2 Ωm, indicating significant lithological and structural variability within the subsurface. The iso-resistivity map (Figure 6) reveals distinct spatial variations in the resistivity of the weathered layer. Zones with relatively low resistivity are interpreted as areas of high conductivity, which may be attributed to increased moisture content, enhanced weathering, and possible groundwater saturation. Such zones are therefore considered to represent areas of relatively higher groundwater potential. Conversely, areas exhibiting high resistivity values are associated with fresh, unfractured basement rocks, which are typically characterized by low porosity and permeability and hence poor groundwater potential.

Aquifer Thickness (Isopach Analysis)

The isopach map (Figure 7) indicates that aquifer thickness varies considerably across the study area, ranging from 12.76 m at VES 8 in the northern region to 44.57 m at VES 6 in the southern region, with an average thickness of 23.04 m. The spatial distribution of aquifer thickness shows that the southern part of the study area is characterized by relatively thicker overburden, whereas the northern part exhibits shallow basement conditions. Thicker overburden zones generally indicate enhanced groundwater storage capacity due to greater weathering and fracturing, which increase both porosity and permeability.

Dar Zarrouk Parameters and Hydrogeological Implications

The computed Dar Zarrouk parameters, namely transverse resistance (T) and longitudinal conductance (S), are presented in Table 2 and illustrated in Figures 8a and 8b. The transverse resistance values range from 3922.7 Ωm² at VES 8 in the northern part of the study area to 20,388.6 Ωm² at VES 5 in the southern part of the study area. Higher transverse resistance values observed in the southern region suggest greater aquifer thickness and higher transmissivity, indicating more favorable groundwater conditions. This observation is consistent with hydrogeological principles, in which transmissivity is directly proportional to aquifer thickness under relatively uniform hydraulic conductivity. The longitudinal conductance map (Figure 8a) provides insight into the overburden's protective capacity. Areas with relatively high conductance values indicate clay-rich layers, which can serve as protective barriers against surface contamination, thereby enhancing groundwater quality.

Integrated Groundwater Potential Zonation

The integration of resistivity distribution, aquifer thickness, transverse resistance, and longitudinal conductance reveals a coherent spatial pattern in groundwater potential across the study area. A general south-to-north decreasing trend is observed in aquifer thickness, transverse resistance, and overall groundwater potential. The southern part of the study area is therefore identified as the most promising zone for groundwater development. This is attributed to the presence of thick weathered and fractured layers, moderate resistivity values indicative of saturation, and relatively high transverse resistance. In contrast, the northern part of the study area is characterized by shallow basement conditions, higher resistivity values, and relatively low groundwater potential, making it less suitable for sustainable groundwater exploitation.

CONCLUSION

This study has demonstrated the effectiveness of the Vertical Electrical Sounding (VES) method, integrated with Dar Zarrouk parameters, in delineating groundwater potential zones within the Basement Complex terrain of Gudum and its environs, Bauchi State. The geoelectrical interpretation revealed the presence of three to four subsurface layers: topsoil, weathered layer, fractured basement, and fresh basement, which are characteristic of crystalline basement environments. Groundwater occurrence in the study area is primarily controlled by the thickness of the weathered overburden and the degree of basement fracturing. The results show a clear spatial variation in hydrogeological conditions across the study area. The southern part is characterized by relatively thick weathered and fractured zones, moderate resistivity values, and high transverse resistance, all of which indicate favorable conditions for groundwater accumulation and transmission. In contrast, the northern part exhibits shallow basement conditions, higher resistivity values, and limited aquifer development, suggesting relatively poor groundwater potential.

The integration of resistivity data, aquifer thickness, and Dar Zarrouk parameters enabled the identification of zones with enhanced groundwater potential. Based on these criteria, VES stations 01, 05, 06, 07, 11, 12, 13, 14, 16, and 18 are recommended as the most suitable locations for borehole drilling within the study area.

RECOMMENDATIONS

Borehole development should be concentrated in the identified high-potential zones, particularly within the southern part of the study area. Future investigations should incorporate borehole logging and pumping test data to validate and refine the geophysical interpretations. Lastly, integrated hydrogeological studies combining geophysical, geological, and geochemical data are recommended to improve groundwater resource management in the area.

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