Delineation of aquifer potential zones using hydraulic parameters in Gombe and environs, North-Eastern, Nigeria

I.A. Kwami a,*, J.M. Ishaku b, S. Mukkafa c, A.I. Harun d, B.A. Ankidawa e

a Department of Geology, Gombe State University, P.M.B.0127, Gombe, Nigeria
b Department of Geology, School of Physical Sciences, Modibbo Adama University of Technology, P.M.B 2076, Yola, Nigeria
c Department of Environmental Management and Toxicology, Federal University Dutse, P.M.B 7156, Dutse, Jigawa State, Nigeria
d Department of Applied Geology, Faculty of Science, Abubakar Tafawa Balewa University, Bauchi, Nigeria
e Department of Agricultural and Environmental Engineering, School of Engineering and Engineering Technology, Modibbo Adama University of Technology, P.M.B 2076, Yola, Nigeria

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ABSTRACT

This research is aimed at delineating the groundwater potential zones in Gombe and environs using Dar Zarrouk parameters. The study area is located within longitudes 11°7′0″E to 11°14′0″E, and latitudes 10°15′0″N to 10°21′0″N, it is basically underlain by basement Complex rocks represented by Diorite and Granites, and Cretaceous sedimentary rocks represented by Bima, Yolde, Fika and Gombe Formations. Thirty two (32) vertical electric soundings (VES) using Schlumberger array method with the aid of ABEM Signal Averaging System (SAS) Terrameter was used for the data acquisition. The result of the interpretation shows four to six geo-electric layers. The geo-electric section revealed the major aquifers to be confined and semi confined and consist of Medium grain sandstones, with varying thicknesses. The aquifer hydraulic characteristics indicated that the transverse resistance, ranges from 235.2 Ωm² to 6317.87 Ωm² with an average value of 1789.50 Ωm². The Longitudinal conductance, S, ranges from 0.1415 Ωm to 31.933 Ωm with an average of 2.002 Ωm. The Hydraulic conductivity value range from 2.62m/day to 138.66 m/day with a mean value of 20.662 m/day. The transmissivity values obtained for the various layers range from 78.34 m²/day to 13284.02m²/day, with the average value been 893.57 m²/day. Four groundwater potential zones were delineated including medium grain sandstones, Sandstones, clayey sand and shaly sand.

1. Introduction

Increased demands for water by the world’s fast-growing population have stimulated the need to identify and establish the source of safe drinking water. Groundwater is that water found within the saturated voids beneath the ground (Abdulrahman et al., 2017). The source of groundwater is chiefly from precipitating atmospheric moisture which has percolated down into the soil and subsoil layers (Kwami et al., 2018).

The availability, quantity, and exploitability of groundwater depend on the porosity and permeability of the host rocks. Both parameters play important roles in ground water movement and recovery. The porosity of a geologic material is the amount of water (fluid) the material can hold. It is the volume ratio of the pore spaces to the total volume of soil, rock or sediment (Obiora et al., 2015). Geophysical investigations provide a rapid and cost-effective means of acquiring information on subsurface hydrogeology (Helaly, 2017). The application of electrical resistivity survey method using vertical electrical sounding was applied for the purpose of this research. Vertical electrical sounding is a geo-electrical method commonly used to measure vertical alterations of electrical resistivity. This method has been recognized to be more suitable for a hydro-geological survey of sedimentary basins than the other resistivity methods (Chambers et al., 2013).

The Dar Zarrouk Parameters derived from primary parameters (layer resistivity, and thickness) surface geo-electric soundings have proven to be important in understanding the spatial distribution of aquifer hydraulic parameters. Maillet (1947) first introduced the concept of Dar Zarrouk parameters, when the thickness and resistivity of subsurface layer is known, its transverse resistance and longitudinal conductance can be estimated. Nwosu et al., 2014 derived analytical relations between aquifer transmissivity and transverse resistance. Also, Heigold et al.
established the association of aquifer hydraulic conductivity with resistivity measurements.

2. Study area

The study area is located in Gombe State North eastern part of Nigeria, between longitudes 11°7′0″E to 11°14′0″E and latitudes 10°15′0″N to 10°21′0″N of the equator of the Greenwich meridian (Fig. 1). The topography of the area is generally hilly with some parts having elevations more than the other surroundings. The elevation of the study area ranges from about 400m to 600m above sea level and falls within the Upper Benue Basin. The outcrops generally consist of rocks which are made up of sandstones. Surface drainage systems in the study area comprises of numerous streams channels flowing in the direction of the river basin towards the southeast. The climatic condition in the study area is characterized by two seasons; a rainy season, which starts in May
Fig. 2. Geologic map of the study area (modified from Zaborski et al., 1997).
Table 1
Geoelectric parameters, lithologic delineation and aquifer systems in the study area.

| VES No. | Location                | Coordinates & Elevations | Layer No. | Resistivity (ohm-m) | Thickness (m) | Inferred Lithology          | Curve Type | Aquifer System |
|---------|-------------------------|---------------------------|-----------|---------------------|---------------|----------------------------|------------|----------------|
| VES01 METTAKO | N10° 15'50.7" E 11° 09'31.5" | ELEV. 477m                | 1         | 34.8                | 2.5           | Clayey Top Soil              | HKH        | Medium Grained |
|         |                         |                           | 2         | 14.0                | 14.0          | Clay                        | Sand       |                |
|         |                         |                           | 3         | 70.9                | 34.7          | Radish Brown Sand           |            |                |
|         |                         |                           | 4         | 27.3                | 20.2          | Medium Grained Sand          |            |                |
|         |                         |                           | 5         | 64.5                | ...           | Clay                        |            |                |
| VES02 JAURO ABDUL PANTAMI | N10° 16'26.5" E 11° 09'57.4" | ELEV. 462m                | 1         | 35.2                | 2.3           | Clayey Sand Top Soil         | KHK        | Medium Grained |
|         |                         |                           | 2         | 119.9               | 12.0          | Radish Brown Sand           | Sand       |                |
|         |                         |                           | 3         | 47.1                | 37.1          | Sandy Shale                 |            |                |
|         |                         |                           | 4         | 55.1                | 16.6          | Medium Grained Sand          | Stone      |                |
|         |                         |                           | 5         | 242                 | ...           | Compacted Sand Stone        |            |                |
| VES03 JEKADAFARI JANKAI | N10° 15'25.77" E 11° 09'41.5" | ELEV. 485m                | 1         | 8.0                 | 10            | Clayey Top Soil             | QH         | Silty Sand     |
|         |                         |                           | 2         | 41.3                | 11.0          | Clayey Sand                 |            |                |
|         |                         |                           | 3         | 89.5                | 51.9          | Silty Sand                  |            |                |
|         |                         |                           | 4         | 47.3                | ...           | Clay                        |            |                |
| VES04 GALDIMARI AREA II | N10° 15'25.77" E 11° 11'33.7" | ELEV. 432m                | 1         | 79.2                | 2.2           | Sandy Top Soil              | HKH        | Silty Sand     |
|         |                         |                           | 2         | 15.7                | 6.8           | Clay                        |            |                |
|         |                         |                           | 3         | 54.5                | 22.2          | Sandy Clay                  |            |                |
|         |                         |                           | 4         | 17.7                | 22.6          | Silty Sand                  |            |                |
|         |                         |                           | 5         | 21.4                | ...           | Sand Stone                  |            |                |
| VES05 BY PASS BARUNDE | N10° 15'50.2" E 11° 10'52.4" | ELEV. 435m                | 1         | 32.4                | 2.9           | Clayey Top Soil             | HKH        | Medium Grained |
|         |                         |                           | 2         | 4.2                 | 4.3           | Clay                        | Sand       |                |
|         |                         |                           | 3         | 67.7                | 23.5          | Radish Brown Sand           |            |                |
|         |                         |                           | 4         | 125                 | 60.5          | Medium Grained Sand          |            |                |
|         |                         |                           | 5         | 16.8                | ...           | Clayey Sand                 |            |                |
| VES06 AJIYA I | N10° 17'35" E 11° 10'32" ELEV. 450m |               | 1         | 29.0                | 2.1           | Clayey Top Soil             | HKH        | Medium Grained |
|         |                         |                           | 2         | 3.8                 | 7.3           | Clay                        |            | Sand Stone     |
|         |                         |                           | 3         | 490.6               | 63.1          | Silty/Sand Sand Stone       |            |                |
|         |                         |                           | 4         | 59.9                | 19.3          | Medium Grained Sand Stone   |            |                |
|         |                         |                           | 5         | 171.0               | ...           | Sand Stone                  |            |                |
| VES07 AJIYA II | N10° 17'42.2" E 11° 10'7.4" | ELEV. 469m                | 1         | 11.0                | 12.8          | Clayey Top Soil             | HKH        | Medium Grained |
|         |                         |                           | 2         | 53.7                | 10.0          | Clayey Sand                 | Sand       | Stone          |
|         |                         |                           | 3         | 93.5                | 36.4          | Silty Sand                  |            |                |
|         |                         |                           | 4         | 22.5                | 28.3          | Medium Grained Sand Stone   |            |                |
|         |                         |                           | 5         | 42.5                | ...           | Clay                        |            |                |
| VES08 KASUWAN KATAKO | N10° 16'52" E 11° 11'25" ELEV. 432m |             | 1         | 8.4                 | 5.3           | Clayey Top Soil             | HKH        | Medium Grained |
|         |                         |                           | 2         | 219.9               | 19.0          | Compacted Sand Stone        | Sand       | Stone          |
|         |                         |                           | 3         | 37.1                | 28.9          | Sand Stone                  |            |                |
|         |                         |                           | 4         | 20.8                | 15.8          | Medium Grained Sand Stone   |            |                |
|         |                         |                           | 5         | 38.1                | ...           | Sandy Silt                  |            |                |
| VES09 NEAR SPECIAL EDUCATION CENTRE | N10° 18'15.2" E 11° 09'29.3" | ELEV. 505m                | 1         | 84.8                | 0.7           | Lateritic Top Soil          | HKH        | Medium Grained |
|         |                         |                           | 2         | 39.6                | 2.3           | Clayey Sand                 | Sand       | Stone          |
|         |                         |                           | 3         | 114.1               | 7.2           | Sand Stone                  |            |                |
|         |                         |                           | 4         | 72.4                | 22.8          | Medium Grained Sand Stone   |            |                |
|         |                         |                           | 5         | 131.3               | ...           | Sand Stone                  |            |                |
| VES10 NEAR TASHAN GONA | N10° 17'05.2" E 11° 09'24.1" | ELEV. 491m                | 1         | 69.5                | 2.3           | Sandy Top Soil              | HKH        | Medium Grained |
|         |                         |                           | 2         | 7.7                 | 10.5          | Clay                        | Sand       | Stone          |
|         |                         |                           | 3         | 21.2                | 24.7          | Clayey Sand                 |            |                |
|         |                         |                           | 4         | 17.0                | 28.7          | Medium Grained Sand Stone   |            |                |
|         |                         |                           | 5         | 23.7                | ...           | Clay                        |            |                |
| VES11 MALAMKURI | N10° 16'15.8" E 11° 10'07.2" | ELEV. 459m                | 1         | 89.5                | 1.2           | Sandy Top Soil              | HKH        | Medium Grained |
|         |                         |                           | 2         | 11.3                | 17.2          | Clayey Sand                 | Sand       | Stone          |
|         |                         |                           | 3         | 106.4               | 31.8          | Silty Sand                  |            |                |
|         |                         |                           | 4         | 46.6                | 19.1          | Medium Grained Sand Stone   |            |                |
|         |                         |                           | 5         | 104.0               | ...           | Sand Stone                  |            |                |
| VES12 GABUIKKA PRL. SCH. | N10° 16'19.05" E 11° 09'49.21" | ELEV. 468m                | 1         | 15.1                | 2.4           | Clayey Top Soil             | HKH        | Shale Sand     |
|         |                         |                           | 2         | 2.0                 | 5.0           | Clay                        |            |                |
|         |                         |                           | 3         | 42.3                | 33.8          | Clayey Sand                 |            |                |
|         |                         |                           | 4         | 14.6                | 34.3          | Shale Sand                  |            |                |
|         |                         |                           | 5         | 17.6                | ...           | Clayey Shale                |            |                |
| VES13 RAFINSANYI | N10° 16'52.1" E 11° 10'44.1" | ELEV. 442m                | 1         | 80.7                | 4.6           | Sandy Top Soil              | HKH        | Medium Grained |
|         |                         |                           | 2         | 15.7                | 9.5           | Clay                        | Sand       | Stone          |
|         |                         |                           | 3         | 10.4                | 18.7          | Clayey Sand                 |            |                |
|         |                         |                           | 4         | 20.2                | 13.8          | Medium Grained Sand Stone   |            |                |
|         |                         |                           | 5         | 57.8                | ...           | Clayey Sand                 |            |                |

(continued on next page)
| No. | Location          | Coordinates & Elevations         | Layer No. | Resistivity (ohm-m) | Thickness (m) | Inferred Lithology           | Curve Type | Aquifer System         |
|-----|-------------------|----------------------------------|-----------|---------------------|---------------|-------------------------------|------------|------------------------|
| VES14 | KUMBIYA KUMBIYA  | E11°10'04.93" E 11°10'11.66" ELEV. 458m | 1         | 32.7                | 2.9           | Clayey Sand, Top Soil HKH      | Medium Grained | Sand Stone             |
|      |                   |                                  | 2         | 12.8                | 12.6          | Clay                           |            |                        |
|      |                   |                                  | 3         | 48.1                | 41.4          | Shale Intercalation            |            |                        |
|      |                   |                                  | 4         | 18.6                | 24.4          | Medium Grained Sand Stone      |            |                        |
|      |                   |                                  | 5         | 41.8                | ...           | Sand Stone                     |            |                        |
| VES15 | OPP. ALH. MANGA HOUSE | E11°10'38.0" ELEV. 442m | 1         | 56.6                | 1.6           | Sandy Top Soil QOQ             | Shale Sand  |                        |
|      |                   |                                  | 2         | 11.2                | 38.9          | Clay                           |            |                        |
|      |                   |                                  | 3         | 10.6                | 14.8          | Shale                          |            |                        |
|      |                   |                                  | 4         | 8.0                 | 29.4          | Clayey Sand                    |            |                        |
|      |                   |                                  | 5         | 23.2                | ...           | Sandey Shale                   |            |                        |
| VES16 | ARAWA             | E11°10'34.7" ELEV. 442m         | 1         | 27.8                | 6.8           | Clayey Top Soil HKH            | Medium Grained | Sand Stone             |
|      |                   |                                  | 2         | 17.4                | 14.7          | Clay                           |            |                        |
|      |                   |                                  | 3         | 64.7                | 42.3          | Clayey silt                    |            |                        |
|      |                   |                                  | 4         | 24.4                | 22.4          | Medium Grained Sand Stone      |            |                        |
|      |                   |                                  | 5         | 54.8                | ...           | Sand Stone                     |            |                        |
| VES17 | GSU ZOO           | E11°10'32.72" ELEV. 444m        | 1         | 91.0                | 5.9           | Sandy Top Soil HKH             | Medium Grained | Sand Stone             |
|      |                   |                                  | 2         | 29.2                | 8.1           | Clayey Sand                    |            |                        |
|      |                   |                                  | 3         | 215.9               | 22.8          | Compacted Sand Stone           |            |                        |
|      |                   |                                  | 4         | 39.0                | 35.0          | Medium Grained Sand Stone      |            |                        |
|      |                   |                                  | 5         | 62.6                | ...           | Sand Stone                     |            |                        |
| VES18 | YALANGURUZA      | E11°10'42.39" ELEV. 417m        | 1         | 31.8                | 1.3           | Top Soil, Sandy Clay HKH       | Sandstone   |                        |
|      |                   |                                  | 2         | 3.7                 | 16.1          | Clay                           |            |                        |
|      |                   |                                  | 3         | 177.6               | 107.5         | Sandy Clay Intercalation       |            |                        |
|      |                   |                                  | 4         | 16.5                | 24.2          | Shale                          |            |                        |
|      |                   |                                  | 5         | 36.1                | ...           | Sandstone                      |            |                        |
| VES19 | NEAR UBAN DOMA HOUSE | E11°10'39.55" ELEV. 427m | 1         | 20.0                | 5.8           | Clayey Top Soil HKH            | Silty Sand  |                        |
|      |                   |                                  | 2         | 5.3                 | 10.6          | Clay                           |            |                        |
|      |                   |                                  | 3         | 154.3               | 56.8          | Sandy Clay                     |            |                        |
|      |                   |                                  | 4         | 23.8                | 18.1          | Silty Sand                     |            |                        |
|      |                   |                                  | 5         | 59.3                | ...           | Sandiclsine                    |            |                        |
| VES20 | BAGADAZA          | E11°10'39.55" ELEV. 427m        | 1         | 82.3                | 1.4           | Sandy Top Soil HKH             | Medium Grained | Sand             |
|      |                   |                                  | 2         | 13.5                | 5.5           | Clay                           |            |                        |
|      |                   |                                  | 3         | 192.1               | 28.4          | Reddish Brown Sand             |            |                        |
|      |                   |                                  | 4         | 36.6                | 25.6          | Medium Grained Sand Stone      |            |                        |
|      |                   |                                  | 5         | 76.2                | ...           | Clay                           |            |                        |
| VES21 | JAURO JINGI      | E11°10'39.55" ELEV. 427m        | 1         | 40.1                | 3             | Clayey Top Soil HKH            | Shale sand  |                        |
|      |                   |                                  | 2         | 3.4                 | 5.3           | Clay                           |            |                        |
|      |                   |                                  | 3         | 78.8                | 25.3          | Silty Stone                    |            |                        |
|      |                   |                                  | 4         | 18.2                | 37.9          | Shaley sand                    |            |                        |
|      |                   |                                  | 5         | 17                  | ...           | Shale                          |            |                        |
| VES22 | NAYINAWA         | E11°10'39.55" ELEV. 427m        | 1         | 241.4               | 1.4           | Sandy Top Soil HKHA            | Sandstone   |                        |
|      |                   |                                  | 2         | 34.6                | 2.8           | Clayey Sand                    |            |                        |
|      |                   |                                  | 3         | 300.9               | 11.7          | Compacted Sand Stone           |            |                        |
|      |                   |                                  | 4         | 36.6                | 27.6          | Shale                          |            |                        |
|      |                   |                                  | 5         | 60.9                | 57.9          | Sand Stone Intercalation       |            |                        |
| VES23 | NEW GRA           | E11°10'39.55" ELEV. 427m        | 1         | 231.7               | 1.5           | Lateritic Sand Top Soil HKH    | Sandstone   |                        |
|      |                   |                                  | 2         | 45.3                | 28.0          | Sandy Clay                     |            |                        |
|      |                   |                                  | 3         | 233.4               | 75.2          | Sand, Silt                     |            |                        |
|      |                   |                                  | 4         | 61.6                | 18.7          | Sand Stone                     |            |                        |
|      |                   |                                  | 5         | 134.4               | ...           | Sand Stone                     |            |                        |
| VES24 | NEAR RUNDE       | E11°10'39.55" ELEV. 427m        | 1         | 227.4               | 6.3           | Sandy Top Soil HKH             | Silty Sand  |                        |
|      |                   |                                  | 2         | 114.4               | 17.8          | Radish Brown Sand              |            |                        |
|      |                   |                                  | 3         | 152.6               | 19.7          | Sandy Clay                     |            |                        |
|      |                   |                                  | 4         | 132.6               | 27.4          | Silty Sand                     |            |                        |
|      |                   |                                  | 5         | 212.0               | ...           | Sand Stone                     |            |                        |
| VES25 | LIJI             | E11°10'39.55" ELEV. 390m         | 1         | 173.9               | 9.1           | Sandy Top Soil HA              | Silty Sand  |                        |
|      |                   |                                  | 2         | 54.7                | 23.5          | Clayey Sand                    |            |                        |
|      |                   |                                  | 3         | 111.8               | 39.1          | Silty Sand                     |            |                        |
|      |                   |                                  | 4         | 208                 | ...           | Sand Stone                     |            |                        |
| VES26 | KABA             | E11°10'39.55" ELEV. 463m         | 1         | 36.7                | 4.9           | Clayey Top Soil HKH            | Medium Grained | Sand Stone             |
|      |                   |                                  | 2         | 2.0                 | 9.3           | Clay                           |            |                        |
|      |                   |                                  | 3         | 352.0               | 93            | Compacted Sand Stone           |            |                        |
|      |                   |                                  | 4         | 46.3                | 25.6          | Medium Grained Sand Stone      |            |                        |
|      |                   |                                  | 5         | 218.3               | ...           | Sand Stone                     |            |                        |
| VES27 | TUMPURE BASHAR   | E11°10'39.55" ELEV. 504m         | 1         | 521.0               | 7.1           | Top Soil Laterite HKQH         | Sandstone   |                        |
|      |                   |                                  | 2         | 197.8               | 19.5          | Lateritic Sand                 |            |                        |
|      |                   |                                  | 3         | 475.5               | 80.3          | Compacted Sand Stone           |            |                        |
|      |                   |                                  | 4         | 423.2               | 50.3          | Compacted Sand Stone           |            |                        |
|      |                   |                                  | 5         | 211.3               | 29.9          | Sand Stone Intercalation       |            |                        |

(continued on next page)
and ends in October and the dry season, which normally spans between October and April. Most of the streams are seasonal overflowing their banks during rainy season. The rainy season is the period when tropical maritime air mass travels northwards over the study area from the Gulf of Guinea.

The mean annual rainfall is 1015mm for Gombe where the study area is situated while the dry season is characterized by an arid wind or tropical continental air mass originating from the Sahara Desert. During the period, there is little cloud cover and the temperature ranges from 14°C–32°C. The study area is mainly classified as a Sudan savannah region, which is characterized by grasses, shrubs and trees with large trunks. The grasses dry and trees shade off their leaves during dry season and flourish again when wet season returns.

| Table 1 (continued) | VES No. | Location | Coordinates & Elevations | Layer No. | Resistivity (ohm-m) | Thickness (m) | Inferred Lithology | Curve Type | Aquifer System |
|---------------------|---------|----------|---------------------------|-----------|---------------------|---------------|-------------------|------------|----------------|
| VES28 ZAGAINA       | 6       | N10°19′15″ E 11°09′04″ ELEV. 502m | 1         | 378.5                 | ...        | Compacted Sand Stone | HKH        | Sandstone       |
|                     | 2       |          |                           | 95.1       | 8.2                  | Sandy Top Soil  | HKH        | Sandstone       |
|                     | 3       |          |                           | 280.2      | 38.5                 | Compacted Sand Stone | HKH | Sandstone |
|                     | 4       |          |                           | 119.6      | 22.5                 | Sand Stone      | HKH        | Sandstone       |
|                     | 5       |          |                           | 270.8      | ...                  | Compacted Sand Stone | HKH | Sandstone |
| VES29 ALKAHIRA      | 1       | N10°20′50″ E 11°09′44″ ELEV. 478m | 1         | 384.8                 | 3.2        | Top Soil Laterite  | HKH        | Sandstone       |
|                     | 2       |          |                           | 152.6      | 9.0                  | Sandy Clay      | HKH        | Sandstone       |
|                     | 3       |          |                           | 765.6      | 35.8                 | Loos Sand        | HKH        | Sandstone       |
|                     | 4       |          |                           | 105.2      | 54.3                 | Sand Stone      | HKH        | Sandstone       |
|                     | 5       |          |                           | 294.0      | ...                  | Compacted Sand Stone | HKH | Sandstone |
| VES30 LEGISLATIVE QTRS | 1   | N10°17′18″ E 11°07′31″ ELEV. 596m | 1         | 530.6                 | 3.9        | Top Soil Laterite  | HKQH Silty Sand | Silty Sand |
|                     | 2       |          |                           | 172.3      | 12.1                 | Lateritic Sand  | HKQH Silty Sand | Silty Sand |
|                     | 3       |          |                           | 631.6      | 38.9                 | Loos Sand        | HKQH Silty Sand | Silty Sand |
|                     | 4       |          |                           | 211.5      | 39.7                 | Sand Stone      | HKQH Silty Sand | Silty Sand |
|                     | 5       |          |                           | 84.4       | 58.8                 | Silty Sand      | HKQH Silty Sand | Silty Sand |
|                     | 6       |          |                           | 186.2      | ...                  | Shale           | HKQH Silty Sand | Silty Sand |
| VES31 BEHIND GRAVE YARD | 1   | N10°20′35″ E 11°08′12″ ELEV. 481m | 1         | 316.2                 | 14.6       | Top Soil Laterite  | AKQH Medium Grained Sand | Medium Grained Sand Stone |
|                     | 2       |          |                           | 504.0      | 10.1                 | Compacted Lateritic Sand | AKQH Medium Grained Sand Stone |
|                     | 3       |          |                           | 947.2      | 30.5                 | Loos Sand        | AKQH Medium Grained Sand Stone |
|                     | 4       |          |                           | 279.8      | 41.8                 | Sand Stone intercalation. | AKQH Medium Grained Sand Stone |
|                     | 5       |          |                           | 75.7       | 68.3                 | Medium Grained Sand Stone | AKQH Medium Grained Sand Stone |
|                     | 6       |          |                           | 253.0      | ...                  | Sand Stone      | AKQH Medium Grained Sand Stone |
| VES32 NASARAWO      | 1       | N10°16′45″ E 11°13′04″ ELEV. 395m | 1         | 26.3                   | 1.3        | Clayey Top Soil     | HKQH Shaley sand  | Shaley sand  |
|                     | 2       |          |                           | 4.7        | 4.4                  | Clay            | HKQH Shaley sand  | Shaley sand  |
|                     | 3       |          |                           | 100.1      | 14.9                 | Sandy Clay       | HKQH Shaley sand  | Shaley sand  |
|                     | 4       |          |                           | 16.7       | 17.9                 | Sandy Shale.     | HKQH Shaley sand  | Shaley sand  |
|                     | 5       |          |                           | 3.0        | 95.8                 | Shaley Sand      | HKQH Shaley sand  | Shaley sand  |
|                     | 6       |          |                           | 10.7       | ...                  | Shale           | HKQH Shaley sand  | Shaley sand  |

![Fig. 3. Cross section along Profile A-A’](image)

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2.1. Geology of the research area

The study area is underlain by Pre Cambrian Basement Complex rocks and Cretaceous sediments. The basement Complex rocks are represented by Diorite and Granites while the Cretaceous sediments are represented by Bima, Yolde, Fika and Gombe Formations (Fig. 2). Studies indicate that the rocks in the area were subjected to a wide range of tectonic disturbances involving Faulting. The orientation of the fault is mainly trending NW-SE.

The cross section A-B (Fig. 2) indicates (in younging order), the area constituted Basement rocks, Bima Formations, Yolde Formation, Fika Shales and Gombe Formation.

The Bima Sandstone, a continental Formation, is the basal part of the sedimentary successions in the study area. It lies unconformably on the
Table 2
Aquifer parameters of the study area (Dar-zarrouk parameter).

| VES No | Locations         | Layer Resistivity | Layer Thickness | Aquifer Conductivity | Longitudinal Conductance | Transverse Resistance | Hydraulic Conductivity (m/day) | Transmissivity (m²/day) |
|-------|-------------------|-------------------|----------------|--------------------|--------------------------|----------------------|---------------------------------|------------------------|
| 1     | METTAKO           | 27.3              | 20.2           | 0.036630037        | 0.73992674               | 551.46               | 17.67427124                     | 357.0202791            |
| 2     | JAURO ABUD        | 27.3              | 20.2           | 0.73992674         | 551.46                   | 17.67427124         | 357.0202791                    |
| 3     | JIKA             | 55.1              | 16.6           | 0.031814882        | 0.301207417             | 914.66              | 9.17991525                      | 152.3865932            |
| 4     | GALDIMALI AREA II| 89.5              | 51.9           | 0.011173184        | 0.579888267             | 464.055             | 5.838725201                     | 303.0298837            |
| 5     | BY PASS BARUNDE  | 17.7              | 22.6           | 0.056497175        | 1.276836158             | 400.02              | 26.47930715                     | 598.4097416            |
| 6     | AJIYA I           | 12.5              | 60.5           | 0.08              | 4.84                    | 756.25              | 36.62743871                     | 2215.9606427           |
| 7     | AJIYA II          | 59.9              | 19.3           | 0.031694491        | 0.32203673             | 1156.07             | 8.491805826                     | 163.9918524            |
| 8     | KASUWAN KATAKO    | 22.8              | 28.3           | 0.0444444444       | 1.25777778              | 636.75              | 21.61804253                     | 599.0556035            |
| 9     | NEAR SPECIAL      | 20.8              | 15.8           | 0.048076923        | 0.759615385             | 328.64              | 22.77760708                     | 359.8861919            |

A total of 32 vertical electrical soundings were carried out (Fig. 1). The electrode configuration used for the work was Schlumberger array. Field data acquisition was carried out rapidly since it requires mainly the movement (adjustment) of the current electrodes. Electrodes were laid out with non-conducting measuring tapes. The field procedure consists of expanding the current electrodes ‘AB’ while keeping the potential electrodes ‘MN’ relatively fixed. For each reading, the current was sent into the ground through A and B which set up the measured potential difference between the potential electrodes M and N, the magnitude of the potential difference developed is a measure of the electrical resistance between probes. The resistance is in turn a function of the geometrical configuration of the electrodes and the electrical parameters of the ground (Dobrin, 1976). The electrode separation (AB/2) is varied from 1 to 300 m. The SAS 4000 Terrameter was positioned half way between the potential electrodes M and N, and was connected to terminals P1 and P2 and to terminals M and N. The current electrodes A and B was connected to terminals C1 and C2 respectively, these cables were run in parallel adjacent to the SAS 4000 Terrameter and was arranged symmetrically with respect to the potential electrodes.

3. Materials and methods

3.1. Resistivity sounding

A total of 32 vertical electrical soundings were carried out (Fig. 1). The electrode configuration used for the work was Schlumberger array. Field data acquisition was carried out rapidly since it requires mainly the movement (adjustment) of the current electrodes. Electrodes were laid out with non-conducting measuring tapes. The field procedure consists of expanding the current electrodes ‘AB’ while keeping the potential electrodes ‘MN’ relatively fixed. For each reading, the current was sent into the ground through A and B which set up the measured potential difference between the potential electrodes M and N, the magnitude of the potential difference developed is a measure of the electrical resistance between probes. The resistance is in turn a function of the geometrical configuration of the electrodes and the electrical parameters of the ground (Dobrin, 1976). The electrode separation (AB/2) is varied from 1 to 300 m. The SAS 4000 Terrameter was positioned half way between the potential electrodes M and N, and was connected to terminals P1 and P2 and to terminals M and N. The current electrodes A and B was connected to terminals C1 and C2 respectively, these cables were run in parallel adjacent to the SAS 4000 Terrameter and was arranged symmetrically with respect to the potential electrodes.

3.2. Hydraulic parameters

The term “Dar Zarrouk” was introduced into the literature on electrical prospecting by Maillet (1947) for describing a relationship between the longitudinal unit conductance (Eq. 1) and transverse resistance (Eq. 2).

\[ S_i = \frac{h_i}{\pi i} \quad (1) \]

And the transverse unit resistance,

\[ T_i = \frac{h_i}{\pi i} \quad (2) \]

Where \( \pi i \) and \( h_i \) are the electrical resistivity and thickness of the ith layer, respectively.

DZ (Dar Zarrouk) curve for an \( n \)-layer section is a plot of the DZ...
resistivity.

\[
P_{mj} = \sqrt[3]{\frac{\sum_{i=1}^{j} T_i \cdot \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} S_i}}
\quad (3)
\]

Against the DZ depth

\[
L_{mj} = \frac{\sum_{i=1}^{j} T_i \cdot \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} S_i}
\quad (4)
\]

An n-layer DZ curve is composed of n branches, each of which terminates at a point whose coordinates, \(L_m\) and \(P_m\), represent the thickness and resistivity of a fictitious layer that replaces all the overlying layers. According to Eqs. (3) and (4), the coordinates of any given point on a DZ curve are a function of the thicknesses and resistivities of layers that exist above a given depth, D, but they are not related to the thicknesses and resistivities of layers beneath that depth. In contrast, on a VES (vertical electrical sounding) curve, the coordinates of a given point are calculated from an integral expression (Stefanesco et al., 1930) that involves all the thicknesses and resistivities in the section, and, therefore, they are not related to a particular depth.

The longitudinal conductance \(S\) is a measure of the impermeability of a rock layer (Billing, 1972). Electrical anisotropy is a measure of stratified rock which is generally more conductive in the parallel plane than in the perpendicular plane (Malick et al., 1973; Cihan et al., 2014). For a sequence of horizontal, homogeneous and isotropic layers of resistivity \(\sigma_i\) and thickness \(h_i\), Eqs. (5) and (6) defined the Dar Zarrouk parameters (longitudinal conductance \(S\) and transverse resistance \(R_T\)) as follows:

\[
S = \frac{h_1}{\sigma_1} + \frac{h_2}{\sigma_2} + \frac{h_3}{\sigma_3} + \ldots + \frac{h_n}{\sigma_n} = \sum_{i=1}^{n} \frac{h_i}{\sigma_i}
\quad (5)
\]

\[
R_T = \frac{e_1 h_1 + e_2 h_2 + \ldots + e_n h_n}{\sum_{i=1}^{n} e_i h_i}
\quad (6)
\]

Eq. (7) shows the relationship between aquifer transmissivity, and longitudinal conductance as proposed by Todd (1980).

\[
T_r = K \cdot R_T = K h
\quad (7)
\]

Where \(T_r\) = Aquifer Transmissivity, \(K\) = Hydraulic Conductivity, \(\sigma\) = Electrical Conductivity (reciprocal of resistivity), \(R_T\) = Traverse Resistance, \(S\) = Longitudinal Conductance and \(h\) = Aquifer Thickness.

The Hydraulic conductivity \(K\) was determined using Eq. (8) as given by Heigold et al. (1979).

\[
K = 386.40 \cdot R_{rw}^{0.928}
\quad (8)
\]

Where, \(K\) is the hydraulic conductivity and \(R_{rw}\) is the aquifer resistivity (Resistivity of the inferred aquiferous layer from the interpreted curves).
4. Result and discussion

Geo-electric parameters are interpreted from geophysical (electrical) resistivity survey data. Interpretations of vertical electrical sounding data using WIN-Resist2 software lead to the generation of geo-electrical layers. The information from these geo-electric layers enhances the identification and interpretation of layer parameters which includes number of layers and their apparent resistivities, thicknesses, depth, curve type and aquifer systems (Table 1).

About 11 curve types were identified in the study area (Table 1). Ground water is known to accumulate in the interconnected pores spaces within the Lithologic units. The shape of the VES curves (Appendix I) depends on the thickness of each layer, the number of layers in the subsurface and the ratio of the resistivity of the layer. The geo-electric characteristics give the respective layer resistivity values and thickness. The section gives a maximum of 9 layers with varying resistivity and thicknesses across each VES point. The first layer (Top soil) which composed of soil, loose sand and clay has resistivities ranges from 8 Ωm to 530.6 Ωm, and thickness varying from 0.7m to 14.6m. The second layer is composed of clay, clayey sand and sand silt intercalation in some places. This layer is characterized with resistivity values varying from 2 Ωm to 504 Ωm with thickness varying between 2.3m to 38.9m, the third layer which composed of clay sandstone intercalation, sandy clay, sandy silt and medium grained sandstones in some areas is characterized by resistivity values ranging between 10.4 Ωm to 947.2Ωm and thickness between 7.2m to 107.2m.

The fourth layer consists of Silty Sand and mostly medium grain sandstone with resistivity values ranging from 8 Ωm to 423.2Ωm and thickness ranging from 13.8m to 60.5m whereas the fifth layer consist of also clay and mostly sandstones characterized with resistivity values from 3 Ωm to 394 Ωm and thickness 29.9m-95.8m, also the sixth layer which is mostly clay has resistivity ranging from 10.7 Ωm to 378.5 Ωm.

The aquifer system comprises mostly of Medium grain sandstone accounting for about 16 VES locations, Sandstone 6 VES, Shaly and 4 VES points, and Silty Sand 6 VES points. This is inferred due to the high porosity and permeability characteristics of these Lithologic Formations attributed to their resistivity values.

4.1. Delineation of aquifer systems

A cross section of 3 bore holes with some VES points in the study area were used to correlate the borehole lithologic sections with the inferred lithologies observed from the Vertical Electrical Sounding interpretations (Fig. 1, above).

The profile A-A’ (Fig. 3) along East-West trends of the study area encountered 1 borehole (BH2) and 3 VES points (VES01, VES20 and VES05). The Lithologic log of the bore hole was correlated with the geoelectric sections, the aquiferous layer (medium grain sandstone) show thickness ranging from 20.2m to 60m with an average of 32.2m (Fig. 3). The second layer of the borehole lithologic section (reddish-brown sand) with thickness of about 4m appear in the sections of VES01 and VES20 and VES05 as third layer with 34.7m, 28.4m and 23.5m thickness.
Table 4
Protective capacity rating of aquifers in the study area using Oladapo and Akintorinwa 2007 rating.

| No. | VES locations | Longitudinal conductance | Protective capacity rating |
|-----|---------------|--------------------------|---------------------------|
| 1   | METTAKO       | 0.73992674               | Good                      |
| 2   | JAURO ABDUL PANTAMI | 0.30127047               | Moderate                  |
| 3   | JEKADAFARI JANKAI | 0.57988828               | Moderate                  |
| 4   | GALDIMARI AREA II | 1.27486158               | Good                      |
| 5   | BY PASS BARUNDE | 4.84                     | Good                      |
| 6   | AJIYA I       | 0.32200367               | Moderate                  |
| 7   | AJIYA II      | 1.25777777               | Moderate                  |
| 8   | KASUWAN KATARIO | 0.75961538               | Good                      |
| 9   | NEAR SPECIAL EDUCATION CENTRE | 0.31934712    | Moderate                  |
| 10  | NEAR TASHIN GONA | 1.68823592               | Good                      |
| 11  | MALAMKURI     | 0.40987124               | Moderate                  |
| 12  | GABUKKA PRL SCH. | 2.34931568               | Good                      |
| 13  | RAFINSANYI    | 0.63186837               | Moderate                  |
| 14  | KUMBIYA KUMBIYA | 1.31182704               | Good                      |
| 15  | OPP. ALIJ. MANGA HOUSE | 3.675            | Good                      |
| 16  | ARAWA         | 0.91802278               | Good                      |
| 17  | GSI ZOO       | 0.89743589               | Good                      |
| 18  | YALANGURUZA   | 1.46666667               | Good                      |
| 19  | NEAR UBAN DOMA HOUSE | 0.76505020   | Good                      |
| 20  | BAGADAZA      | 0.69453555               | Moderate                  |
| 21  | JAURO JINGI   | 2.08241758               | Good                      |
| 22  | NAYI NAWA     | 0.95073891               | Good                      |
| 23  | NEW GRA       | 0.30357143               | Moderate                  |
| 24  | NEAR RUNDLE   | 0.26666501               | Moderate                  |
| 25  | LIJI          | 0.34973164               | Moderate                  |
| 26  | KABA          | 0.55291576               | Moderate                  |
| 27  | TUNFURE BASHAR | 0.14150496               | Weak                      |
| 28  | ZAGAIMA       | 0.18812704               | Weak                      |
| 29  | ALKAHIRA      | 0.51615969               | Moderate                  |
| 30  | LEGISLATIVE QUARTERS | 0.69668246   | Moderate                  |
| 31  | BEHIND GRAVE YARD | 0.90224570            | Good                      |
| 32  | NASARAWO      | 31.93333333              | Excellent                 |

Table 5
Inferred aquifer potential rating using Transmissivity values.

| VES Locations | Transmissivity (m²/day) | Aquifer Potentials |
|---------------|-------------------------|--------------------|
| METTAKO       | 357.020791              | Moderate Potential |
| JAURO ABDUL PANTAMI | 152.386593               | Moderate Potential |
| JEKADAFARI JANKAI | 303.029837               | Moderate Potential |
| GALDIMARI AREA II | 598.409716               | High Potential     |
| BY PASS BARUNDE | 2215.960442              | High Potential     |
| AJIYA II       | 163.891852               | Moderate Potential |
| AJIYA II       | 599.055603               | High Potential     |
| KASUWAN KATARIO | 359.866199               | High Potential     |
| NEAR SPECIAL EDUCATION CENTRE | 162.237796  | High Potential     |
| NEAR TASHIN GONA | 789.076917               | High Potentials    |
| MALAMKURI      | 204.986212               | Moderate Potential |
| GABUKKA PRL SCH. | 1086.895932              | High Potentials    |
| RAFINSANYI    | 323.031865               | Moderate Potential |
| KUMBIYA KUMBIYA | 616.860816               | High Potentials    |
| OPP. ALIJ. MANGA HOUSE | 1632.882804              | High Potentials    |
| ARAWA         | 439.628951               | Moderate Potential |
| GSI ZOO       | 443.519138               | Moderate Potential |
| YALANGURUZA   | 684.143076               | High Potentials    |
| NEAR UBAN DOMA HOUSE | 363.562869               | Moderate Potential |
| BAGADAZA      | 344.263924               | Moderate Potential |
| JAURO JINGI   | 977.786270               | High Potentials    |
| NAYI NAWA     | 484.140856               | Moderate Potential |
| NEW GRA       | 154.709428               | Moderate Potential |
| NEAR RUNDLE   | 110.870346               | Moderate Potential |
| LIJI          | 185.509343               | Moderate Potential |
| KABA          | 276.425357               | Moderate Potential |
| TUNFURE BASHAR | 78.3379698               | Moderate Potential |
| ZAGAIMA       | 100.241985               | Moderate Potential |
| ALKAHIRA      | 272.671617               | Moderate Potential |
| LEGISLATIVE QUARTERS | 362.630576               | Moderate Potential |
| BEHIND GRAVE YARD | 466.209177               | Moderate Potential |
| NASARAWO      | 1328.02263               | High Potentials    |

Table 6
Aquifer classification based on Transmissivity values (Offodile, 1983).

| Transmissivity (m²/day) | Classification of well |
|-------------------------|------------------------|
| >500                    | High Potentials        |
| 50-500                  | Moderate Potential     |
| 5-50                    | Low Potential          |
| 0.5-5                   | Very low Potential     |
| <0.5                    | Negligible Potential   |

The profile B–B’ (Fig. 4) along NW-SE trends of the study area encountered 1 borehole (BH1) and 2 VES points (VES03 and VES13). The lithologic section of the borehole was correlated with the geoelectric sections, the aquiferous layer (medium grain sandstone) show thickness ranging from 10m to 51.9m, with an average of 25.2m (Fig. 4). The second layer of the borehole lithologic section (reddish-brown sand) with thickness of about 4m did not appear in geoelectric sections.

The third layer in the borehole lithologic section (Clayey Sand) with 10m thickness appeared as second layer in section of VES03 and 3rd layer in section of VES13 with thickness of 11m and 18.7m respectively. The 4th layer in VES 03 (Silty sand) with thickness of 51.9m did not appear in both VES13 and the lithologic section. The 5th layer in the borehole lithologic section (clay) with 7m thick did appear as 4th layer in section of VES03. The aquifer system delineated is semi confined to confined and have thickness ranging from 20.2m to 60m with an average of 32.2m.

The profile C–C’ (Fig. 5) along SW-NE trends of the study area encountered 2 VES points (VES10 and VES07) and 1 borehole (BH4) and the lithologic section was correlated with the geo-electric sections, the aquiferous layer (medium grain sand) show thickness ranging from 28.3m to 30m with an average of 29m (Fig. 5). The second layer of the borehole lithologic section (Clayey sand) with thickness of about 27m appear also as a second layer in VES07 and third layer in VES 10 geo-electric sections with thickness of 10m and 24.7m respectively. Clay appear as second layer in VES10 with 10.5m thickness. The third layer in the borehole lithologic section (Silty sand) with thickness of 27m appeared as a third layer in VES07 with thickness of 36.4. The 4th layer (clay) with 10m thickness did not appear in the geoelectric sections. Whereas the last layer in the bore hole (clay) did appear in both the VES10 and VES07. The aquifer system delineated is confined to semi confined to semi-confine and ranges in thickness from 28.3m to 30m with an average of 29m.

4.2. Dar-zarrouk parameters

Aquifer parameters such as Transmissivity, Hydraulic conductivity, longitudinal conductance, and transverse resistance were determined from the VES interpretation results using Dar Zarrouk Parameters (Table 2).

4.3. Transverse resistance and longitudinal conductance

The transverse resistance in the study area varies from 235.2Ωm² to 6317.87Ωm² with an average value of 1789.50Ωm². Thus indicating very low ground water development class (Ezeh, 2012). Ezeh (2012) went further to state that values of transverse resistance of less than 200,000Ωm² may not indicate absence of aquifer but may imply inadequate aquifer thickness or high mixed aquifer materials with finer sediments. The variation of transverse resistance in the study area is shown in Fig. 6 Thus areas of high transverse resistance occur in the western part of the
Fig. 8. Map of the study area showing variation in Transmissivity.

Fig. 9. Map of the study area showing variation in Hydraulic Conductivity.
study area.

4.4. Protective capacity

The values of the longitudinal conductance were used to evaluate the protective capacity of the aquifer using Oladapo and Akintorinwa 2007, protective capacity rating (Table 3). Values of longitudinal conductance in the study area ranges from 0.1415Ω to 31.933Ω with an average of 2.002Ω (Fig. 7). It revealed that in the study area Fifty percent 50% (VES 1, VES 4, VES 5, VES 7, VES7, VES10, VES12, VES 14, VES 15, VES 16, VES17, VES 18, VES19, VES21, VES 22, and VES 31) of the VES points have moderate protective capacity, Forty percent 40% (VES 2, VES 3, VES 6, VES 9, VES 11, VES 13, VES 20, VES 23, VES 24, VES 25, VES 26, VES 29 and VES 30) have Moderate Protective capacity, Six percent 6% (VES 27 and VES28) have Weak protective capacity, and Four percent 4% (VES32) have Excellent protective capacity (Table 4). Most of the VES points in the study area have values of Moderate to Good protective capacity, thus indicating that the aquifers are protected. This is a good indication that wells located at these points are not susceptible to contamination because of the presence of good natural filter to percolating fluids in the regions. Fig. 7 shows the variation of aquifer protective capacity within the study area, good to excellent protective capacity is dominant around the southern and northern parts of the area.

4.5. Transmissivity and hydraulic conductivity

The Transmissivity of the aquiferous layer in the study area were calculated and presented in Table 5. The Transmissivity values ranges from 78.34 m²/day to 13284.02m²/day, the average value been 893.57 m²/day. The Variation of the Transmissivity values in the study area was interpreted using Table 6 and it was observed that sixty nine percent (69%) of the VES points show Moderate Potential, thirty one percent (31%) show High Potentials (Table 5). Also the map of the study area showing variation in Transmissivity values is presented (Fig. 8). Fig. 8 shows that high aquifer potentials occur in the southern and northeastern part of the study area. The aquifer of the study area is generally of moderate to high potentials (Table 5).

The hydraulic conductivity values of the area range from 2.62m/day to 138.66 m/day at Tunfure Bashar and Nasarawo respectively, with mean value of 20.29 m/day, thus indicating hydraulic conductivity of fine, coarse sand and gravel (Bouwer, 1978). Fig. 9 shows map of the hydraulic conductivity values of the study area with variation of hydraulic conductivity values. Area with high hydraulic conductivity (around Nasarawo) would be highly susceptible to contamination because of the presence of good natural filter to percolating fluids in the regions. Fig. 9 shows the variation of aquifer protective capacity within the study area, good to excellent protective capacity is dominant around the southern and northern parts of the area.

5. Conclusion

The resistivity soundings results revealed that about11 curve types were identified in the study area namely HKH, HKH, HKH, HKH, QHA, QOH, HHHA, AH, HKOH, and AKOH with the lithologic layers varying from 4 to 6 consisting of varying resistivity and thicknesses across each VES point. The geo-electric sections revealed that the major aquifer systems in the area range from confined to semi-confined aquifers consisting of Medium grain sandstones with varying thicknesses. The longitudinal conductance computed indicates that the aquifers in the area have moderate to good protective capacity whereas transverse resistance indicates very low ground water development class. Hydraulic conductivity and transmissivity values moderate to high aquifer potentials. Four groundwater potential zones were delineated including medium grain sandstones, sandstones, clayey sand and shaly sand.

Declarations

Author contribution statement

I.A. Kwami: Conceived and designed the experiments; Performed the Experiments; Analyzed and Interpreted the data; Wrote the Paper.

J.M. Ishaku: Conceived and designed the experiments; Analyzed and Interpreted the data.

S. Mukkafa: Performed the Experiments.

B.A. Ankidawa and I. A. Haruna: Contributed reagents, materials, analysis tools or data.

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