ORIGINAL ARTICLE

Evaluation of groundwater potential of bedrock aquifers in Geological Sheet 223 Ilorin, Nigeria, using geo-electric sounding

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Abstract

Electrical resistivity data acquired in one hundred and ten (110) locations using vertical electrical sounding method of Schlumberger array have been used to study the hydrogeological properties and groundwater storage potential of bedrock aquifers in an area covered by Geological Sheet 223 Ilorin, Nigeria. The aim of the study was to identify productive aquifer zones for citing boreholes for community water supply. The data acquired were processed and interpreted using auxiliary curve matching and computer automation method to delineate the different geo-electric layers, their resistivities, thicknesses, and depths. Geo-electrical layers were interpreted to their equivalent geological layers using borehole lithological logs from the study area. Then, the hydraulic conductivity, transmissivity, fracture contrast, reflection coefficient were estimated and plotted in the form of 2D maps to describe the spatial variations of these parameters in the area. The results of the study revealed the presence of three to five geo-electric layers. The geo-electric layers, from top to the bottom, corresponds to the topsoil layer, lateritic layer, weathered rock layer, fractured rock layer, and the fresh basement rock. Lateritic and/or fractured rock layers were not delineated in some places. The weathered and fractured rock layers, where present, correspond to the aquifer units. The thickness of the fracture aquifer ranges from 0.6 to 33.6 m while the thickness of the weathered aquifer ranges from 1.4 to 49.3 m. The transmissivity, T, and hydraulic conductivity, K, range from 3 to 1200 m^2/day and 1 to 48 m/day, respectively. The reflection coefficient and fracture contrast map showed the presence of water-bearing fractures and shared some similarities with T and K maps. A mathematical model for predicting groundwater potential, GW$_P$, of weathered aquifer in the basement complex terrain was proposed in this study. The consistencies between the overall groundwater potential map and aquifers parameters distributions maps suggest the appropriateness of the proposed mathematical model for predicting groundwater potential of weathered rock in the basement complex area of Nigeria. The western, northwestern, and central parts of the study area, having GW$_P$ greater than 0.6 (60%), were recommended for groundwater development through boreholes drilled to a depth ranging between 75 and 100 m.

Keywords Crystalline aquifers · Groundwater potentials · Vertical electrical sounding · Fracture coefficient · Hydraulic conductivity · Transmissivity

Introduction

Climate change is anticipated to affect groundwater availability throughout Africa than it was previously forecast. In addition to shortage in rainfall and excessive loss in surface water due to temperature rise and prolonged evaporation, surface and rain water are severely polluted and unfit for human consumption without prior treatment. Currently, there is heavy dependence on groundwater to meet daily global demand for fresh water. Groundwater accounts for more than 95% of worldwide storage for fresh water (Shiklomanov 1998; Healy et al. 2007). However, groundwater is not evenly distributed in the subsurface. Groundwater distribution is affected by a number of factors including porosity and permeability of the subsurface rocks, amount of rainfall and surface water available for recharge, topography, size of the aquifer, nature of the overburden material among others (Bhattacharya and Patra 1968; Kosinski and Kelly 1981; Kalinski et al. 1993; Olayinka 1996). An aquifer is a body

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of earth material that contains sufficient permeable material to yield significant quantity of water to wells. On a regional annual scale, changes in sedimentary aquifer storage are negligible because water can easily flow from areas of surplus to areas of deficit. On a local scale, in hard rock terrain, changes in aquifer storage, due to groundwater withdrawal can be substantial and significant because the aquifers have limited extent, are not interconnected and poorly recharge (Healy et al. 2007; Raji et al. 2019; Raji and Abdulkadir 2020a, b). This is why groundwater scarcity is common in the basement rock terrain.

Due to global warming, smaller duration high-intensity rainfall showers have now replaced the longer duration low-intensity rainfall events. Consequently, the runoff component of rainfall has increased, thereby reducing aquifer recharge and groundwater availability (Vashisht and Aggarwal 2016). Sedimentary rock aquifers are easily recharged, and they store more water than the crystalline rock aquifers (otherwise known as hard rock aquifers, or bedrock aquifers) due to the abundant interconnected pore spaces in the former and lack of pore spaces in the later. Crystalline rocks are generally impervious to fluid except when it's decomposed by weathering, or fractured, jointed, and faulted by tectonic activities. Unfortunately, these impervious crystalline rocks cover about 50% of the land mass in Africa (MacDonald et al. 2012; UNEP Africa Water Atlas 2020). Groundwater development in hard rock terrain requires carefully designed pre-drill geophysical survey targeted at determining the hydro-geophysical properties and the approximate thicknesses and depths of the weathered and fractured rock layers in the subsurface. The ultimate target of such survey is to locate weathered horizons and/or bedrock with network of interconnected fractures that can store sufficient quantity of water and transmit same to well or boreholes. Weathered and fractured rocks are not evenly distributed in the subsurface. Therefore, the knowledge of the spatial distribution of hydraulic properties of rocks is essential for the prediction of groundwater availability, recharge, and yield in bedrock aquifers (Scanlon and Cook 2002; Ezeh 2011; Raji 2014).

Aside groundwater development for community supply, quantitative overview of hydraulic properties of bedrock aquifers is essential for ensuring all year round water supply for irrigation purposes. However, the evaluation of spatially quantitative dynamic properties of bedrock aquifers requires a deep understanding of the intrinsic rock properties that are not directly measurable by geophysical surveys. Hydraulic properties like yield, recharge, and specific capacity cannot be directly measured through any geophysical method, but can be indirectly inverted from the estimates of closely related parameters such as transmissivity, hydraulic conductivity, fracture coefficient, and fracture contrast (Niwas and Singhal 1981; MacDonald et al. 2001, 2012; Raji and Abdulkadir 2020b). Also, direct measurements

of groundwater volume in bedrock aquifer is a difficult endeavor. But, quantitative estimates of aquifer thickness, porosity, storativity, fracture contrast, and fracture coefficient, among others, may be used to predict the volume of groundwater storable in an aquifer. Therefore, the evaluation of groundwater potentials and availability in aquifers should be based on sub-regional evaluation of aquifer properties rather than the local, on the spot, assessment as commonly done for borehole survey.

Electrical resistivity survey (ERS) is the most commonly use geophysical method for groundwater study in different geological terrains. ERS is a non-invasive depth probing techniques that is most suited for shallow subsurface study in built-up and undeveloped environments. ERS is environmentally friendly, operationally simple, cost effective, time inexpensive, and easy to deploy regardless of the geological terrain. 2D/3D electrical resistivity survey has evolved with technology, and is currently being used for groundwater survey in geologically complex areas. The cost of acquiring the equipment and interpretation packages is restricting the widespread use of 2D/3D methods. So 1D ERS is still reliable for groundwater exploration, and its chance of success can be enhanced by expert's knowledge and the availability of borehole lithologic logs in the study area. ERS method relied on the direct influence of moisture in rocks on the electrical conductivity of such rocks (Zohdy et al. 1974). Among the classical electrode arrays used for resistivity measurement, vertical electrical sounding (VES) of Schlumberger array is the most popular. A study by Raji et al. (2020) compared six classical electrode arrays for resistivity measurement in a field experiment in a basement complex terrain of Nigeria and showed that Schlumberger array is the most dependable method of probing earth resistivity with depth. Parameters inverted from VES measurements have been used for groundwater exploration and development, predicting aquifer seasonal behavior, aquifer vulnerability studies, and groundwater pollution from oil spillage and dump-site leachate in the different parts of the world (e.g., Kalinski et al. 1993; Olorunfemi and Fasuyi 1993; Edet et al. 1994; Sharma and Baranwal 2005; Viase et al. 2005; Casas et al. 2005; 2007; Abubakar and Danbatta 2012; MacDonald et al. 2012; Raji 2014; Abubakar et al. 2014; Raji and Adeoye 2017; Aluko et al. 2017; Raji et al. 2018; Raji and Abdulkadir 2020a). Therefore, VES method using Schlumberger electrodes array will be applied to interrogate subsurface geology for groundwater potential in this study.

The rate of abortive boreholes and the scarcity of portable water in the study area is the motivation for this study. 15–20% borehole failure rate has been reported in the central part of the study area (Geo-Drill 2019, verbal communication). The aim of the study is to interrogate the subsurface geology for groundwater availability and identify the productive aquifer zones for groundwater development in the

study area. The objectives of the study are to: characterize the subsurface geo-electric layers, determine depth to aquifers, and describe the dynamic hydraulic properties of the aquifers (e.g., transmissivity and hydraulic conductivity) in the study area. The expected outcome of this study include spatially quantitative maps of combined aquifer thickness, transmissivity (indicative yield), hydraulic conductivity (indicative recharge), fracture density map, and the overall groundwater potential map of the area. Data acquired for the study and the results obtained from the study, when published, will improve experts' understanding of the hydrogeology of the hard rock terrain.

The study area and its geological setting

The study area lies between latitudes 08° 24.50′ N and 08° 27.99′ N of the equator and longitudes 04° 27.50′ E and 04° 41.00′ E of the Greenwich Meridian (Fig. 1a, b). The area covers about 161 square kilometers in Ilorin South Local Government of Kwara State and falls within Geological Sheet Ilorin 223 of the Nigerian Geological Survey Agency. The study area is part of the Savana region of Nigeria, has two main seasons—rain season and dry season. The mean annual rainfall and temperature range from 75 to 112 mm and 27 and 35 °C. Drainage is provide by River Asa, River Oyun, their tributaries and distributaries. The mean daily sun shine is about 8 hours. Geologically, the study area falls within the Precambrian basement terrain of the southwestern Nigeria considered to be Precambrian to lower Paleozoic in age (Oyawoye 1964; Rahaman 1976; Annor et al. 1987). The rock comprised mostly gneiss, granite, schist, and undifferentiated meta-sediment. In the study area, the rocks outcrop in some places and are covered by weathered rock and topsoil in many places. The rocks are well exposed along river channels.

The oldest rocks in the study area comprise gneiss complex whose principal member are Biotite-Hornblende-Gneiss with intercalated Amphibolites (Annor et al. 1987). The younger suites are granites with medium to coarse
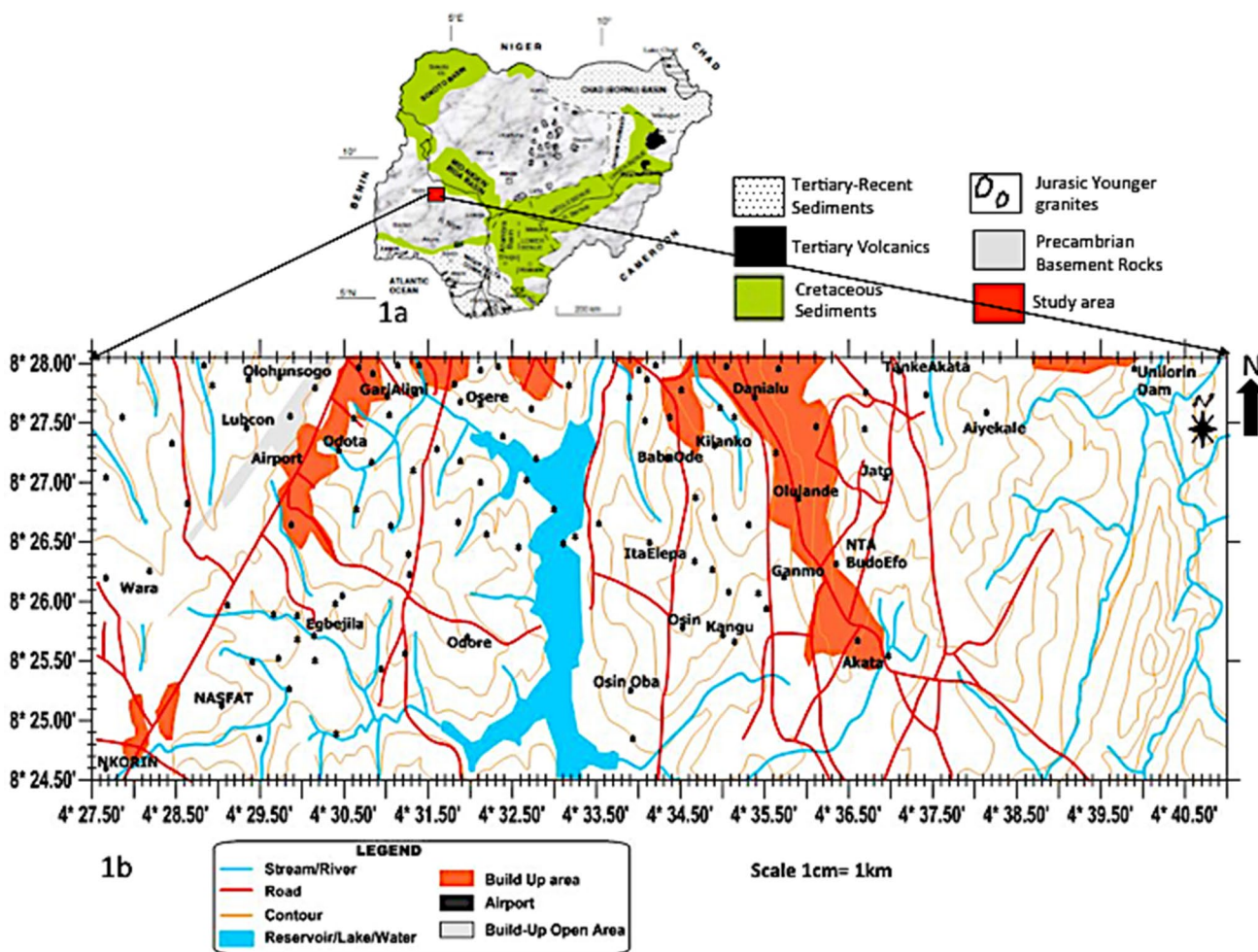

Fig. 1 **a** Geologic map of the Nigeria showing the location of the study area. **b** Map showing the location of VES survey points in the study area

grains light colored rocks with variation in biotite content. In some places, the Biotite minerals are thread-like, arranged in roughly parallel pattern. In other places the Biotite minerals are disoriented in the ground mass. The feldspar mineral occurs as fine to medium grains. Other rock types include schist and quartzite. Minor bodies of pegmatites and quartz intruded the rock at different places during the Pan African orogeny (Oluyide et al. 1998). The quartzite, the metamorphic equivalence of quartz-rich sandstone, filled the preexisting fractures in the area. The rocks have been weathered at shallow depth in some places due to in situ physico-chemical activities. Structural features mapped in the area included fault, fracture, pinch and swell structure, strikes, and dips. The rocks are dipping to the west and east with angles ranging from 28° to 45°.

Groundwater occurrence in the Precambrian basement terrain is hosted within zones of weathering and fracture which are not evenly distributed. The two main aquifer types in the study area are weathered rock and fractured rocks aquifers. The aquifers are overlain by different soil material of variable thickness. The soil materials include laterites, clay, sand, and silt-sized particles deposited by runoff and surface water. Aquifers in the basement complex of southwestern Nigeria are typically found at varied, but shallow depths, have limited extent, low porosity, and permeability. The aquifers depend on secondary porosity derived from weathering and fracturing, faulting, jointing, and cracking of rock units for transmitting fluid from one place to another (Davis and DeWiest 1966; Dan-Hassan 2001; Olasehinde and Raji 2007; MacDonald et al. 2012; Abubakar and Auwal 2012; Abubakar et al. 2014).

Materials and methods

One hundred and ten (110) points were survey in the different parts of the study area using Vertical Electrical Sounding Technique of Electrical Resistivity with Schlumberger electrodes array. Data acquisition equipment comprised ABEM 3000 Earth Resistivity Meter, two current and two potential electrodes, four reels of electrical cables, hammers, measuring tapes, battery, and portable geographic positioning system, GPS. The spacing between one survey point and the other ranges between 100 and 350 m depending on the available space for spreading electrodes and cables for the survey. The obstruction caused by the presence of building, roads, and other engineering infrastructure prevented regular spacing of VES stations. Current electrode spacing, AB, ranges from 1 to 200 m. The GPS coordinates and elevation of every survey point were measured and recorded against the survey number for ease of geo-referencing. Locations of the VES stations are shown in the base map (Fig. 1b).

Resistance measured and resistivity computed were recorded against the respective current and potential electrode separation, and resistivity curve were plotted on the field for quality assurance purposes. In situation where a curve exhibits anomaly peaks in difference to the previous stations, the experiment is repeated to clear any doubt and reduce uncertainties. VES data were subjected to manual and automated processing to invert different geo-electric parameters. The raw data were pre-processed, where necessary to remove spikes and instrumental errors (e.g., contribution from low voltage, poor electrode contact, etc.) using a curve smoothing algorithm (Raji and Adeoye 2017) and the pre-processed/raw data were re-plotted on double logarithm papers. The curves on double logarithm papers were transferred to tracing papers and carefully interpreted using auxillary curve matching techniques (Orellana and Mooney 1966; Koefoed 1979; Telford et al. 1990) to deduce the approximate number of layers, the resistivity, and thickness of each geo-electric layer.

The field data and the number of layers obtained from the manually interpretation were input to WinResist—a computer iterative curve-matching software for final interpretation. The number of geo-electric layers obtained from auxiliary curve matching is used as the starting model in WinResist, rather than guessing the starting model. For an example, if four geo-electric layers were obtained from the manual interpretation, a minimum of three and maximum of five geo-electric layers are set as the model in WinResist. After a preset number of iterations, the software matches the curve from field data to a computer defined curve and output the estimated number of layers, resistivities, thickness and depth of each geo-electric layers, and the inversion uncertainties (RMS error). Some results from the curve-matching procedure are shown in Fig. 2a. The inversion error defines the misfit or mismatch between the field data curve and the computer defined curves. Where the misfit is higher than 10%, the preset values, for examples, the number of layers, or number of iterations is reset, and the interpretation process is repeated until the RMS error falls within a reasonable limit (less than 10%). To describe the hydraulic properties of the aquifers and the groundwater potential of the area, some parameters including hydraulic conductivity, transmissivity, fracture coefficient, and the groundwater potential were estimated at each of the 110 VES points. Hydraulic conductivity (K) and transmissivity (T_r) of the aquifer were estimated following the method of Heigold et al. (1979) and Niwas and Singhal (1981), as shown in Eqs. 1 and 2, respectively. Detailed explanations can be found in some recent literature (e.g., Obiora et al. 2016; Raji and Abdulkadir 2020b).
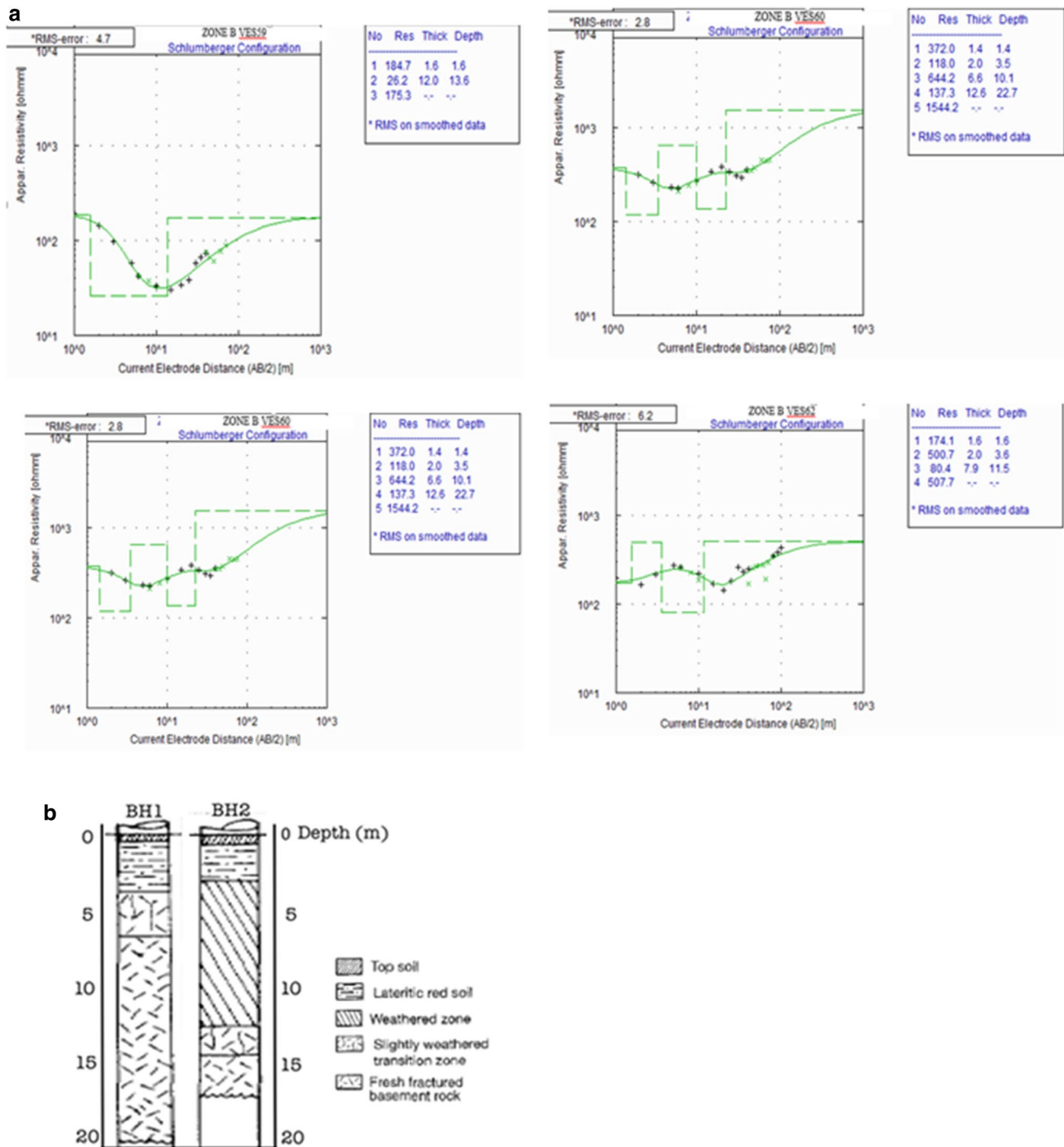
$$K = 386.40 R_{rw}^{-93283} \qquad (1)$$

a

b

Fig. 2 **a** Some VES curves and their interpretations. **b** Lithologic logs from two boreholes in the study area

$$T_r = K\sigma T = \frac{KS}{\sigma} = Kh \qquad (2)$$

where R_{rw} is the resistivity of the aquifer, T, σ, S, and h are transverse resistance, conductivity of the aquifer layer, longitudinal conductance, and the thickness of the layer, respectively. Then, the reflection coefficient and fracture contrast

of the weathered aquifers were computed following Eqs. 3 and 4, respectively.

$$R_C = \frac{\rho_n - \rho_{n-1}}{\rho_n - \rho_{n+1}} \qquad (3)$$

$$F_C = \rho_n / \rho_{n-1} \tag{4}$$

where ρ_n is the apparent resistivity of a geo-electric layer and ρ_{n-1} is the apparent resistivity of the geo-electric layer overlying nth layer. Finally, the groundwater potential of the area was estimated using a combination of different aquifer parameters which include combined aquifer thickness, fracture density, hydraulic conductivity and transmissivity, porosity, and overburden thickness. An empirical equation linking the overall groundwater potential (GW_P) of the weathered rock aquifer to the different aquifer parameters is defined in Eq. 5.

$$GW_P = h_w T^\theta / (R_c / F_c)^\theta \tag{5}$$

where h_w is the thickness of the weathered aquifer; T is transmissivity; θ is the porosity; R_c is the reflection coefficient; and F_c is the fracture contrast. An effective porosity of 7.5% was used for this study. The value was adopted from range of values of 1–10% available in the literature on series of local, national, and regional studies on different types of crystalline aquifers across Africa and other parts of the world (Lott 1998; Petford 2003; Samaila and Singh 2010; MacDonald et al. 2012). The equation is applied at every VES survey point to compute the spatial distribution of groundwater potential for the study area. GW_P at every point was normalized to a scale of 0–1 by dividing the value estimated at each VES point by the maximum values in the survey area. Areas with values greater than 0.6 was considered to have high groundwater potential ($GW_P > 0.6$).

Results and discussion

VES results show that the study area is underlain by three to five distinct geo-electric layers (Fig. 2a). Interpretation of the geo-electric layers to their corresponding geologic unit was guided by lithologic logs obtained from boreholes in the area (Fig. 2b) and previous studies in the area (Olasehinde and Raji 2007). The interpretation showed that the five geo-electric layers correspond to the topsoil layer, lateritic layer, weathered rock layer, fractured rock layer, and fresh basement rock, respectively. The three geo-electric unit that are consistently present in all the survey points are the topsoil layer, weathered rock layer, and the fresh basement rock. Lateritic layer and/or fractured rock layer are present in some places and absent in others. The various VES curves are best described by QQH, QHK, QHA curve types representing over 70% of the survey points. Two aquifer zones were delineated: the first aquifer zone corresponds to weathered rock layer, while the second aquifer zone corresponds to fracture rock layer. The thicknesses, resistivity, and other results were plotted, evaluated and used to compute some

secondary parameters required for assessing the hydraulic properties of the aquifers and the groundwater potential of the study area.

Figure 3a, b shows the thickness and resistivity of the weathered aquifer, respectively. The thickness of weathered aquifer ranges from 1.4 to 49.2 m, while the resistivity ranges from 10.1 to 421 Ωm. The thickest weathered aquifer zones are located in the extreme western part of the study area around VES stations 103, 109, and 108; in the northwestern part around VES stations 90, 97, 105, 101, and 100; and in the center of the study area around VES stations 69, 43, 56, and 57. Variation in the thickness of weathered zone suggests differences in the resistance of the rocks to weathering. It is note worthy that the thickest aquifers in the west, northwest and southwest correspond to very low resistivity values—ranging between 20 and 80 Ωm (Fig. 3b). These values of resistivity suggest the presence of water in the weathered rock and the possibility of water-bearing fractures around the zone (Zohdy et al. 1974; Olayinka 1996; Asry et al. 2012).

Figure 4 shows that the thickness of overburden layer (unsaturated zone) in the study area ranges from 0.4 to 16.2 m. Overburden thickness is estimated as the sum of the thicknesses of the topsoil and the lateritic layer in the respective VES stations. The thicker the unsaturated zone, the higher its capability to retain water from runoff during rainfall and transmit water to the aquifer zone. The unsaturated zone is moderately porous as it contains loose sand particle derived from weathered rocks and other material deposited by wind and runoff water. The zone is particularly useful for agricultural purpose. Figure 5 presents the spatial distribution of total aquifer thickness. The total aquifer thickness was estimated as the summation of the weathered aquifer and fractured rock aquifers thicknesses. The estimated value ranges from 4.5 to 82.8 m. Areas having thick aquifer are potential places for groundwater storage. From the surface, depth to the aquifer bottom was estimated as the sum of the overburden thickness and the total aquifer thickness. Considering an additional 15 m column for groundwater storage or accommodation below the aquifer bottom (in the wells/drill hole), the borehole depth in the area was estimated to range from 75 and 100 m.

The aquifer transmissivity (T) plot presented in Fig. 6 shows that the estimated transmissivity ranges from 3 to 1200 m²/day. Highest values were recorded in the north-central, northwestern and southwestern parts of the study area. Aquifer transmissivity is an indirect indicator of yield (MacDonald et al. 2012), and it describes the lateral movement of groundwater in the aquifer. This why some authors including Acheampong and Hess (1998) and Graham et al. (2009) have found borehole yields to be directly related to transmissivity. Figure 7 shows the spatial distribution of the estimated hydraulic conductivity of the aquifers (K) in the
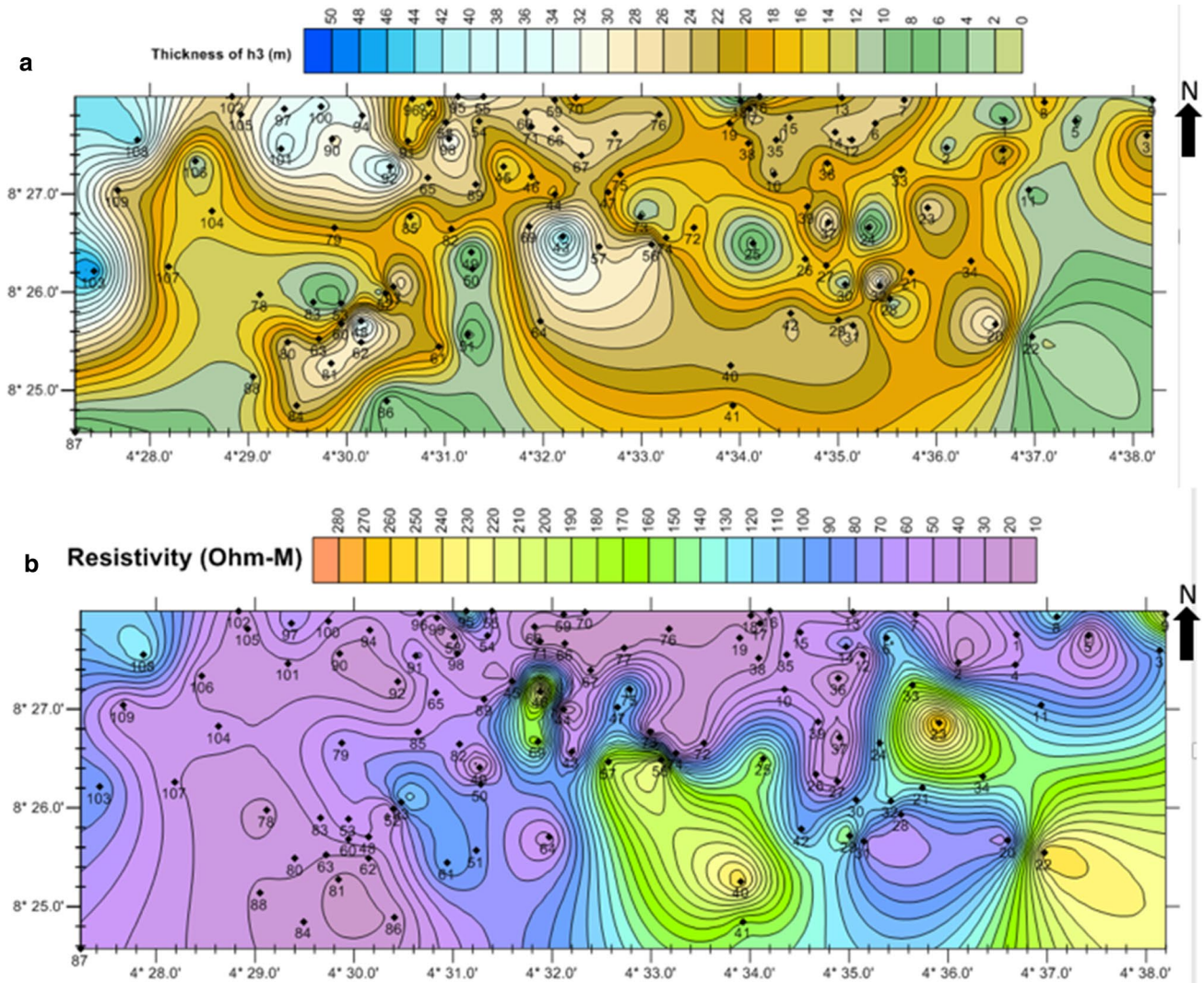
Fig. 3 **a** Estimated thickness of weathered aquifer. **b** Resistivities of the weathered aquifer
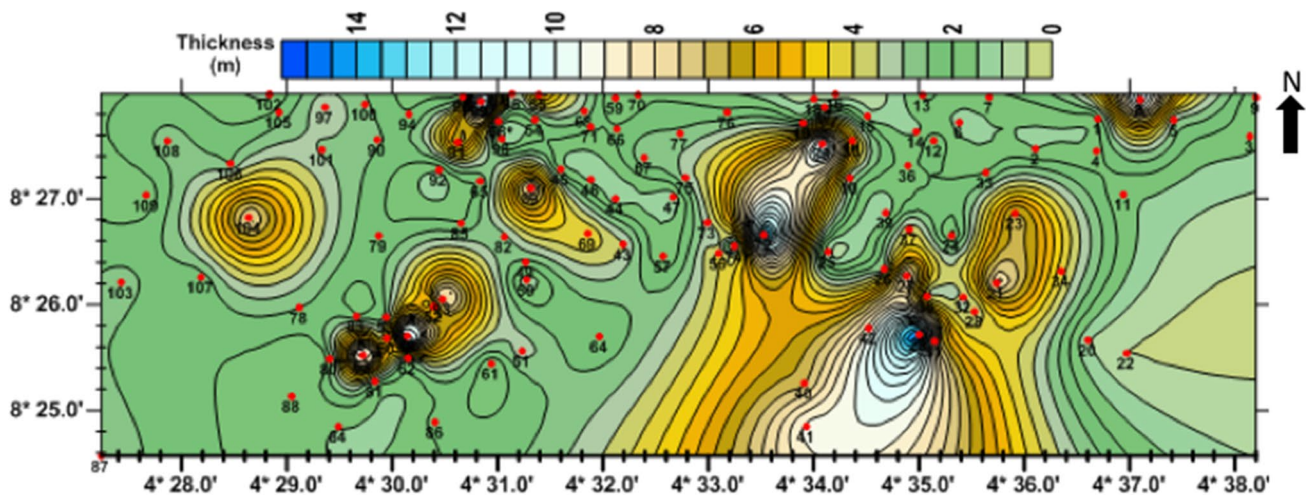

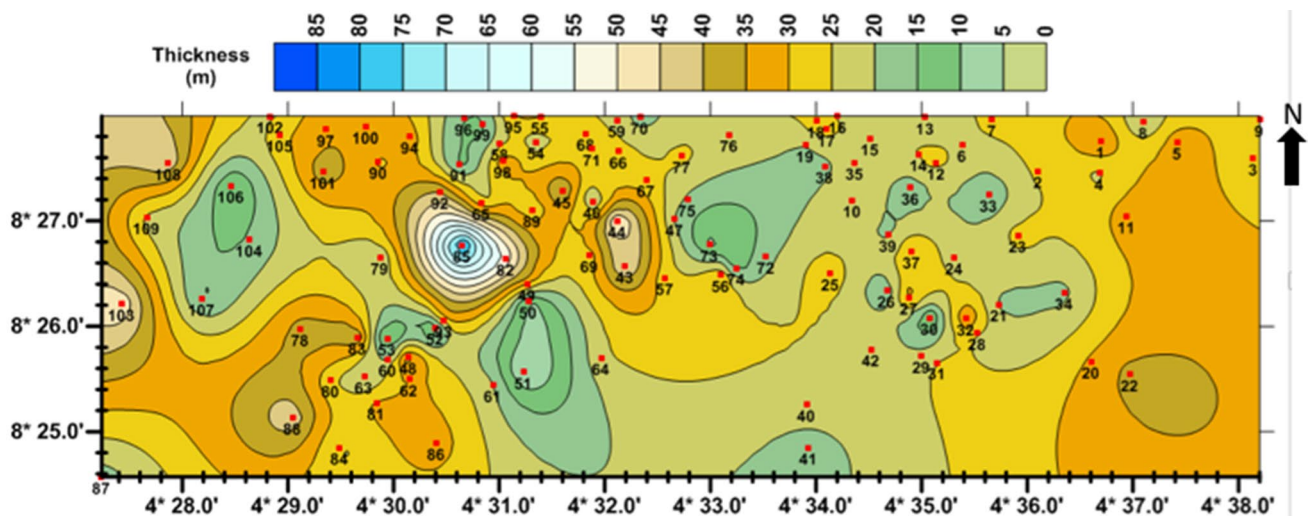**Fig. 4** Spatial distribution of unsaturated zone thickness in the study area
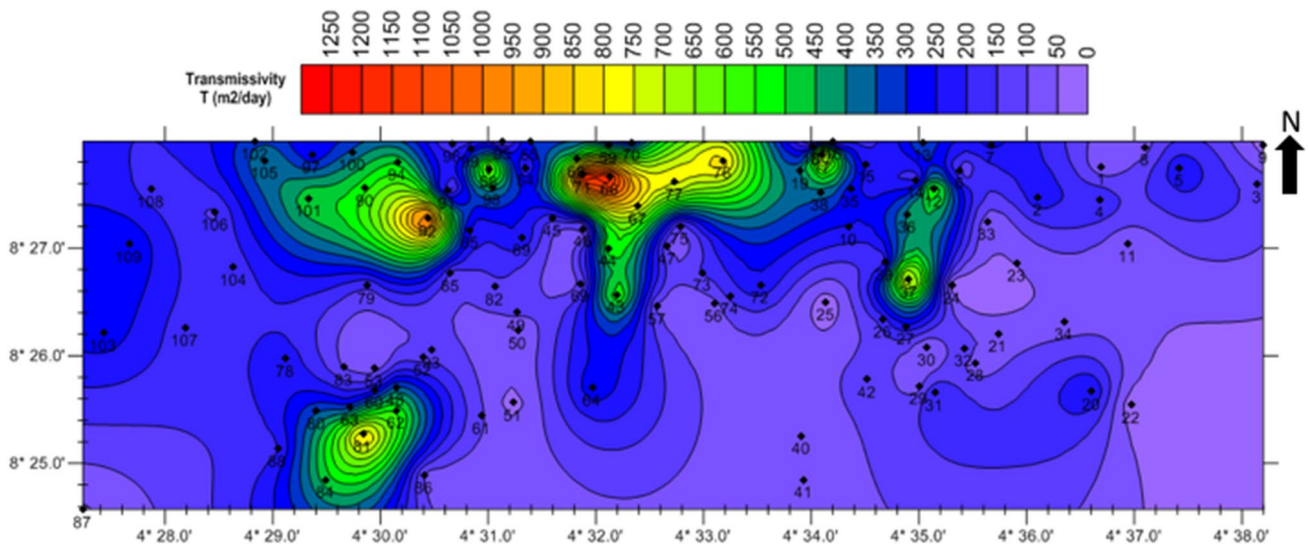
Fig. 5 Estimated total aquifer thickness

Fig. 6 Transmissivity of the aquifer in the study area

area. The values are generally moderate, ranging from 1 to 48 m/day with the highest values concentrated in the north-central and southwestern parts of the study area. Hydraulic conductivity is an indicative parameter for aquifer recharge potential. It describes the vertical movement of water in the aquifer and can be used to express aquifers potential recharge where borehole pump data are unavailable (Heigold et al. 1979; George et al. 2015). Comparing Figs. 6 and 7, the spatial distribution of hydraulic conductivity is similar to that of transmissivity. A joint evaluation of the two parameters suggests that the aquifers in the north-central and southwestern parts of the study area have the highest potentials for groundwater in terms of borehole yield and aquifer recharge potential.

Refection coefficient (R_C) and fracture contrast (F_C) in weathered aquifers in contrast to the fracture aquifer are plotted in Figs. 8 and 9, respectively. Reflection coefficient and fracture contrast are indicators of water-filled fractures (Olayinka et al. 2000; Obiora et al. 2016). Comparing the fractured layer (n) and the weathered layer ($n-1$), low values indicate low contrast between the two aquifers, thereby suggesting good fractured network in the aquifers. Good fracture network implies high groundwater accumulation and fluid flow in the aquifers. As shown in Figs. 8 and 9, R_C ranges from -0.955 to 0.085, while F_C ranges from 0.073 to 1.18. The low values of reflection coefficient and fracture contrast are found in the western part of the study area. This suggest that the aquifers in the western part of the study area
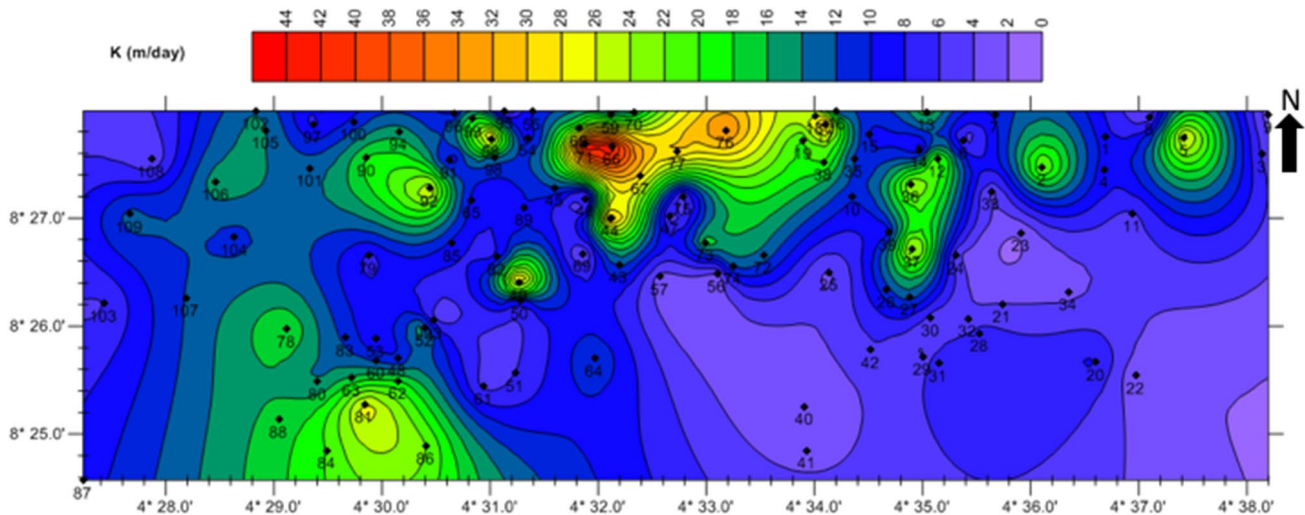
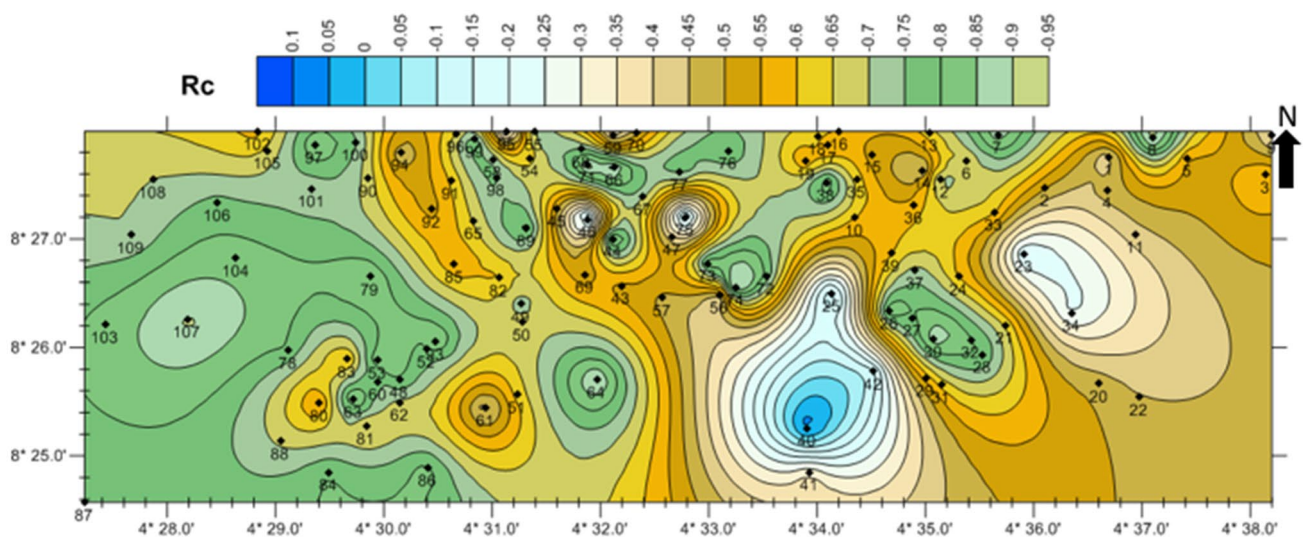**Fig. 7** Hydraulic conductivity of the aquifers in the study area

Fig. 8 Reflection coefficient map of the area

have higher density of water-filled fractures than the aquifer in the eastern part.

Finally, the joint parameters map here known as the indicative groundwater potential map is shown in Fig. 10. The map is a model of the overall groundwater potential comprising the direct and indirect groundwater parameters (aquifer thickness, transmissivity, hydraulic conductivity, and fracture contrast, reflection coefficient, and porosity) as defined in Eq. 3. The values of the indicative ground-water potential ranges from 0 to 1. The areas with ground-water potential of 0.6 (i.e., 60%) and above, on a scale of zero to one (0–1) are recommended for borehole drilling. Figure 10 also shows that the highest value of groundwater potential correspond to the extreme western, northwestern,

and the central parts of the study area. In consideration of the groundwater potential of aquifers in the hard rock terrain (basement rock terrain), the size of the weathered aquifer and the availability of water-bearing fractures are the key indicators of high potential for groundwater. The larger the size of the aquifer adjudged from the thickness of the weather rock and the higher the fracture density, the higher the storage potential. From this study, the distribution of these two parameters (Fig. 5, 8, and 9) are spatially consistent with the overall groundwater potential map (Fig. 10). Therefore, it is reasonable to conclude that the extreme western, northwestern, and the central parts of the study area have the highest groundwater potential in the study area. It is recommended that boreholes should
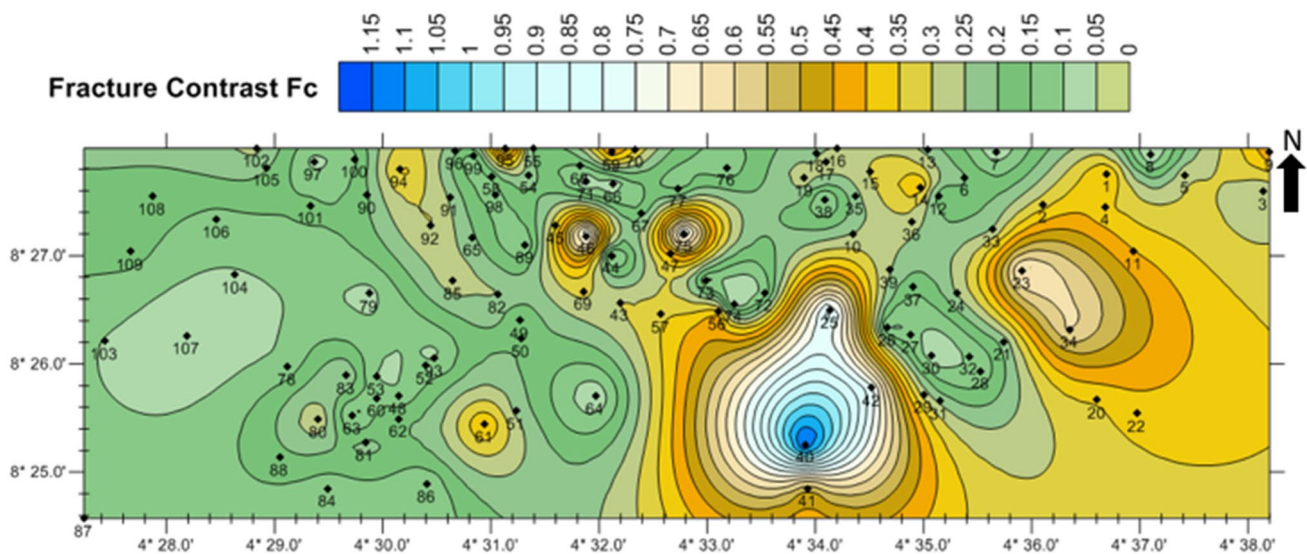
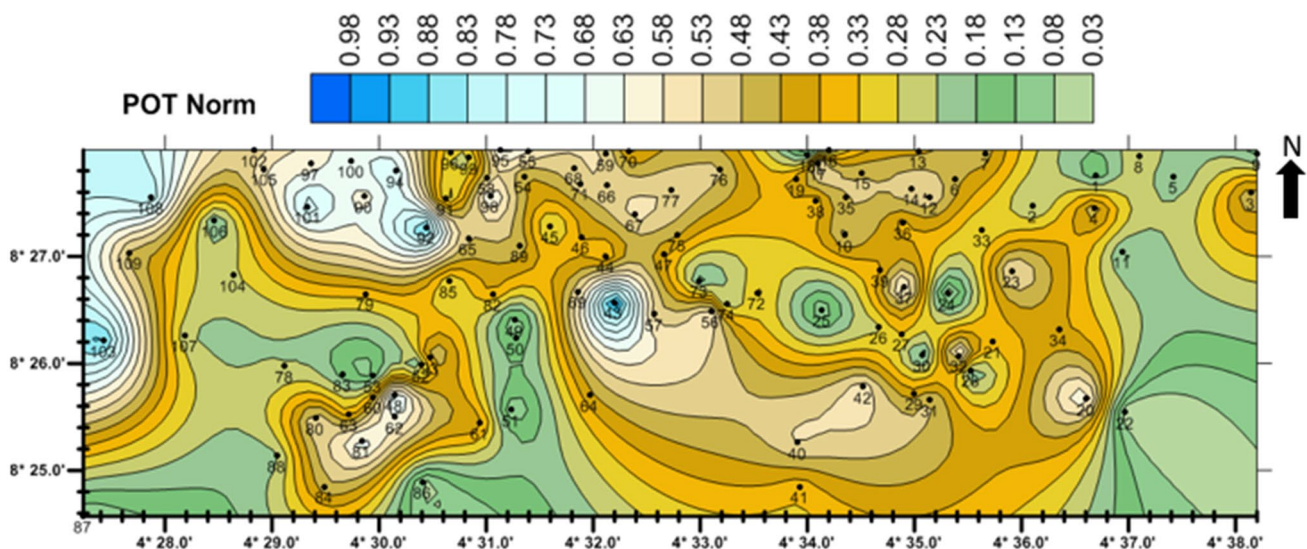**Fig. 9** Fracture contrast map of the area

Fig. 10 Indicative groundwater potential map

be drilled in these areas to depth ranging between 75 and 100 m.

Conclusion

Groundwater aquifer parameters and hydraulic properties of rocks estimated geo-resistivity data acquired in 110 VES stations in an area measuring 161 km^2 within geological sheet 223 Ilorin have been used to evaluate the groundwater potential of the bedrock aquifers in the area. Five geo-electric layer and two aquifer zones were delineated. The estimated thickness of the weathered and fractured aquifer ranges from 1.4 to 49.2 m and 0.6–33.6 m, respectively, while the combined aquifer thickness ranges from 4.5 to 82.8 m. The estimated hydraulic conductivity, transmissivity, and fracture density maps revealed wide variation in aquifer properties across the study area. The north-central and western parts of the study area were recommended for citing boreholes for community water supply. Although the groundwater potential model is subject to improvement for a more robust estimate, the consistencies between the overall groundwater potential map and the hydraulic properties of the aquifer confirmed the appropriateness of the model, developed in this study, for estimating groundwater potential of bedrock aquifers.

Compliance with ethical standards

Conflict of interest To the best of authors' knowledge, there is no known conflict of interest in this study and the information provided.

Code availability Not applicable.

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