ORIGINAL ARTICLE

Groundwater potential and aquifer characterization within Unilorin campus, Ilorin, Southwestern Nigeria, using integrated electrical parameters

O. O. Ige[1] · O. O. Adunbarin[1] · I. M. Olaleye[1]

Abstract

Electrical resistivity investigation was carried out at different sections of University of Ilorin main campus, Ilorin Southwestern Nigeria with the aim of evaluating groundwater potential and properties of the aquifers. Data were acquired at different locations using vertical electrical sounding (VES) method. Hydraulic conductivity, transmissivity, transverse unit resistance, longitudinal conductance, fracture contrast and reflection coefficient were estimated and used for evaluating the groundwater potential and aquifer vulnerability. The results revealed three–five geo-electric layers which correspond to the top soil, lateritic layer, weathered rock layer, fractured rock layer and the fresh basement rock. The top soil has apparent resistivity values ranging from 72.0 to 8117.3 Ωm and thickness range of 0.4–1.6 m while the last geo-electric layer is the infinite fresh basement having apparent resistivity greater than 300 Ωm. The VES curve types obtained are KH, H, A, AKH, HKH and HA with the H curve type covering about 50% of the study area. Aquifers in most part of the study areas are prone to contamination because of low protective capacity of the overburden material. Low groundwater potential covers about 56.79% of the total area and limited to northwestern corner, parts of the north, southwest and northeast. High potential for groundwater was observed at the eastern, northern and southern part of the study area covering about 12.35%. All areas that have thick overburden, high transmissivity, low fracture contrast and reflection coefficient are characterized by intense fracture. These areas are recommended for exploration for water at optimum yield.

Keywords Groundwater potential · Hydraulic conductivity · Nigeria · Overburden · Transmissivity

Introduction

The importance of groundwater for human use cannot be overemphasize but there has been a problem of inadequate supply most importantly in the basement complex terrain because most boreholes developed there are either abortive or cannot produce substantial amount to wells (Akinrinade & Adesina, 2016; Anomohanran et al., 2017; Badejo et al., 2015; Emenike et al., 2017). Water is usually buried within the pores of overburden, weathered and secondary porosity within the fresh hard rock in the basement area. The intensity of weathering and fracturing differ considerably even over close range, therefore, it is pragmatic to understand the occurrence and distribution of groundwater. Ten percent of the world's population is already being affected by non-availability of water and this is expected to increase to 33% by 2025 (WHO, 1996). Hence, the need for development of groundwater resource to catch up with the demand of the expanding population has called up for comprehensive geophysical investigations to delineate and classify terrains according to their potential for groundwater. These zones are often identified by relatively low resistivity values against the background high resistivity values of fresh basement rocks. It has been observed however, that aquifers in crystalline basement terrains are extremely localized and are principally controlled by weathered regoliths and secondary porosity developed from fractures and joints (Abdullahi, 2014; Olasehinde & Raji, 2007). The capacity of the fractured crystalline rocks to store, transmit and yield substantial quantity of water bank upon the thickness of regolith and continual existence of the fractures (Bayode, 2000). The most commonly used geophysical method for exploration

✉ I. M. Olaleye
olaleye.im@unilorin.edu.ng

[1] Department of Geology and Mineral Sciences, University of Ilorin, P.M.B. 1515, Ilorin, Nigeria

of groundwater in the crystalline basement rock terrains is the electrical resistivity because it establishes a useful tool for characterizing the significant contrast in the geoelectric parameters of the superficial deposits, in-situ weathered material, fractured and fresh crystalline rocks and has been greatly used to study hidden subsurface structures such as fractures and joints (Olasehinde, 1989; Olayinka, 1996).

Several studies have been carried out on the determination of groundwater potential using electrical resistivity method. Ige and Ajiboye (2016) used electrical resistivity method to delineate the groundwater potential in Tanke area of Ilorin, Southwestern Nigeria. Twenty-four (24) vertical electrical sounding was used to carry out the investigation. Results gotten were partially matched and interpreted with WinResist application. Three–five geoelectric layers with H and HA curve types were delineated. The area was characterized into low, medium and high potential for groundwater exploration using the hydroresistivity map developed, with the southwestern region having the highest potential. Olatunji et al. (2020) carried out aquifer characterization of Ilorin crystalline basement complex. Vertical electrical sounding (VES) technique was used and a total of ninety-eight (98) VES points were probed and analyzed to achieve the layer resistivity values and corresponding thickness. Three–six geo-electric layers with H, K, Q, HK and A curve types were delineated. H-type is the dominant curve type which is considered to have three successive layers with resistivities $\rho1$, $\rho2$, $\rho3$ and a central low value ($\rho1 > \rho2 < \rho3$). Raji and Abdulkadir (2020) evaluated groundwater potential of aquifers in Ilorin using geo-electric sounding, a total of 110 VES were carried out and results revealed three–five geo-electric layers. Fractured aquifer thickness ranges from 0.6 to 33.6 m while the weathered aquifer ranges from 1.4 to 49.3 m, the fracture contrast map and reflection coefficient show the presence of water bearing fractures. It was concluded that the extreme western, northwestern and central parts of the study area have the highest groundwater potential. Thomas et al. (2018) conducted a comprehensive research on the hydraulic and geoelectric relationships of aquifers in parts of Obudu, Southern Nigeria. Vertical electrical sounding (VES) method was used. Formation factor, porosity, transmissivity and hydraulic conductivity were assessed, result shows that there is a strong correlation between hydraulic conductivity (K) with porosity and formation factor, respectively as 0.81 and 1.00, while a weak correlation occur between transmissivity with porosity and formation factor, respectively as 0.11 and 0.15. Most of the estimated aquifers have low designation, poor protective capacity rating, and smaller withdrawal for local water supply. The work of Oyeyemi et al. (2018) shed more light on geoelectrical resistivity surveys using Schlumberger configuration in parts of Southwestern Nigeria, results showed that the study area has majorly low value of overburden materials which serves as the protective

capacity to the aquifers that are commonly high in porosities and transmissivities. This low protective capacity connotes the high vulnerability of the aquifer system to the influx of surface-based contaminants. High storativity property is possessed by the aquifer systems within the study area due to their high porosity and transmissivity. The vertical electrical sounding (VES) of the Institute of Technology, Kwara State Polytechnic Campus, Ilorin was conducted by Olatunji et al. (2016). Fifteen (15) VES were carried out using Schlumberger electrode array configuration. Results revealed three–four geoelectric layers with varying thicknesses and resistivity. The lateritic clay layer ranges from 53.1 to 302 Ωm, the weathered horizon resistivity ranges from 22.7 to 474.2 Ωm while the competent rock has resistivity values greater than 220.3 Ωm. The lateritic clay layer resistivity and thickness varied between 53.1–302 Ωm and 1.9–8.0 m, respectively, the weathered horizon resistivity varied between 22.7–474.2 Ωm and 4.4–11.7 m, respectively, whereas the competent rock has resistivity values greater than 220.3 Ωm and 6.1 to ∞m, respectively.

The studies of Akinola (2020) and Bayewu et al. (2018) have all shown the importance of using geophysical method for holistic groundwater appraisal. Thus, this present study is aimed at integrating various electrical resistivity parameters to characterize groundwater potential. The advantage of this method over other geophysical method is that it is non-destructive to the subsurface, cost effective, rapid survey time and less ambiguity in result interpretations (Todd, 1980).

The study area and geological setting

The study location is the University of Ilorin main campus which lies between Latitude 8° 27′40″ N–8° 29′0″ N and Longitude 4° 39′20″ E–4° 40′42″ E (Fig. 1). The University campus occupies about 15,000 ha of land and situated at about 15 km east of Ilorin Township western part of central Nigeria. The research was carried out between October 2019 and January 2020.

Accessibility to the University is by a major road leading through Tanke area from Ilorin Township and minor roads within the institution. The area has a typical guinea savannah type of climate with shrubs and undergrowth. The climate of the area is made up of two major and distinct seasons: a wet season, which usually lasts from March to October, and a dry season which lasts from November to early March. Occasionally there are rainfalls in the months of January and February. The total annual rainfall ranges from 800 to 1200 mm with a mean annual temperature of 30–35 °C (Oyegun et al., 2007). The mean annual evapo-transpiration falls between 1500 and 1750 mm Isolines (Olasehinde, 1999). The area is well drained with the most prominent drainage system formed by the Oyun River which traverses Unilorin from the

Fig. 1 VES positions on the contour map of Unilorin
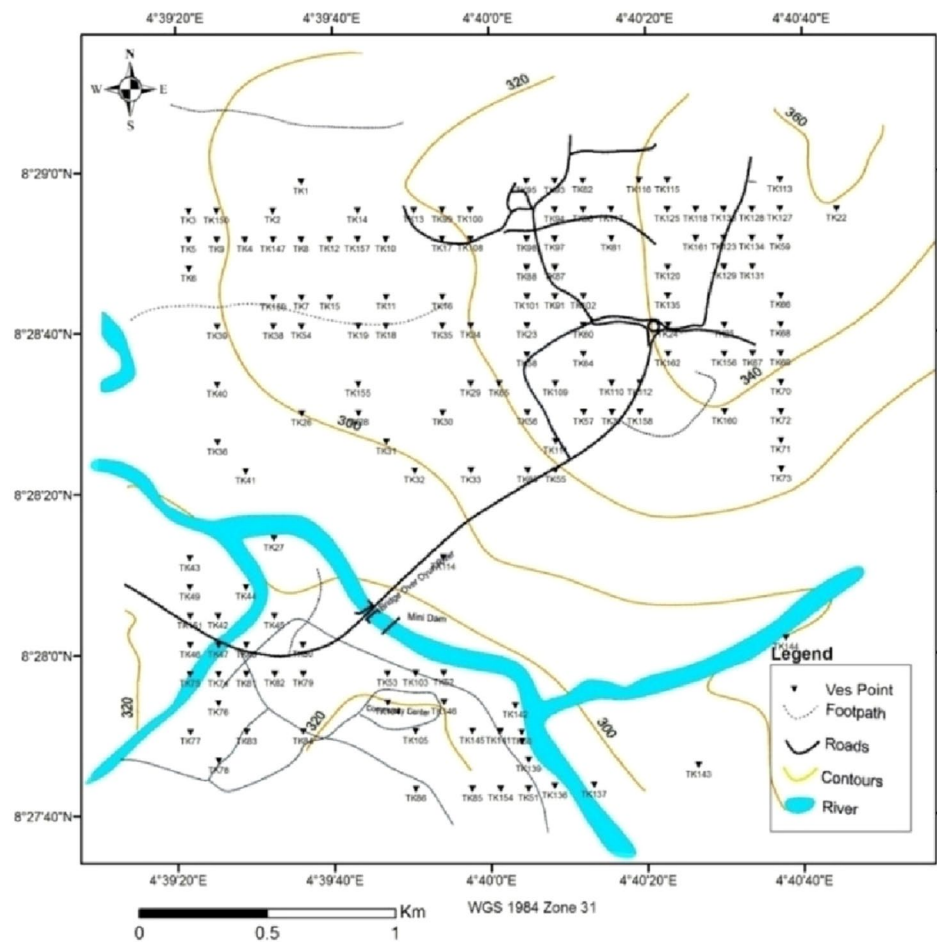
southeast to the northwest direction. There are small streams adjoining river Oyun to form a trellis to sub-dendritic drainage pattern. The size of the drainage changes with season, reaching its peak in the raining season. Rocks in the drained area are highly fractured both at the surface and at depth thus making the drainage to be fracture-controlled.

Geologically, the area is situated on an undifferentiated Precambrian basement complex of granitic and metamorphic origin and forms part of the regional Northwestern highlands of Nigeria running Northwest–Southeast parallel to the River Niger (Annor & Freeth, 1985). The rocks in this terrain include the Migmatites, Granites, and Gneisses (Oluyide et al., 1998) and are well exposed along river channels. The western part of the university is made up of gneiss rocks with strike foliation in NW–SE direction and dipping 10°–45° westernly. In the eastern part, granite rock suites emplaced in the NE–SW direction dip 70°–90° easternly (Fig. 2). The area appears to have been isoclinically folded into a south plunging antiform with a steep eastern limb. Several joints trending 120°–160° dominated the rocks in the area (Olasunkanmi et al., 2018). In the Precambrian basement complex, groundwater occurrence is hosted within zones of weathering and fractures which are not evenly distributed. The main aquifers in the study area are the weathered rock and fractured rock aquifers.

Materials and methods

Determination of electrical properties

In this study, the vertical electrical sounding method using Schlumberger configuration was employed for the geophysical data collection. This array is the most widely used because of its high probing capabilities in groundwater investigation (Ako, 1996; Zohdy et al., 1974) and its ability to measure vertical and lateral distribution of electrical current within the subsurface.

In this method, an electrical current is passed through two current electrodes into the ground and two potential electrodes allow us to record the resultant potential difference between them, giving us a way to measure the electrical impedance of the subsurface material. The apparent resistivity is then a function of the measured impedance (ratio of
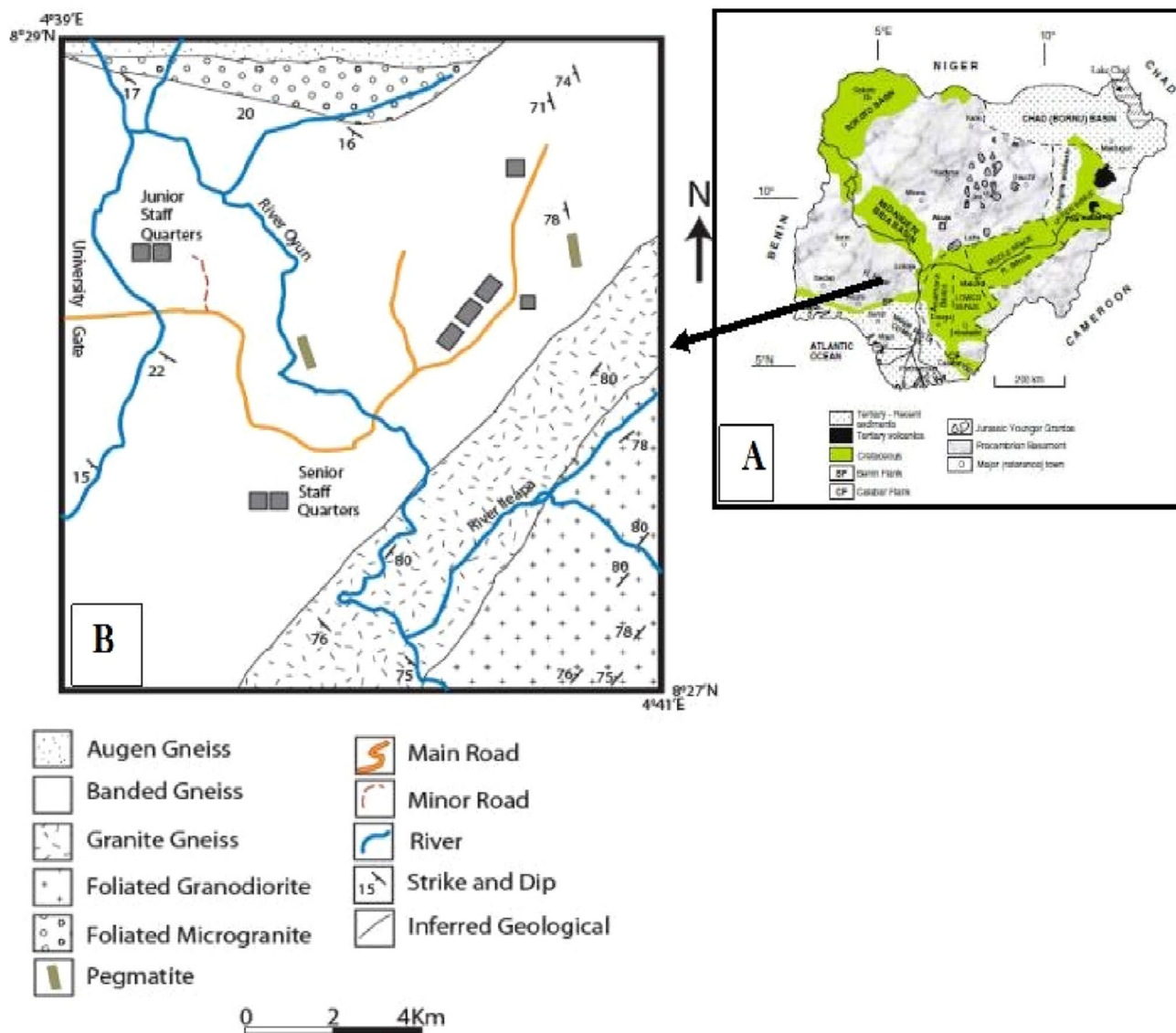
Fig. 2 **a** Geological map of Nigeria showing Ilorin (Obaje, 2009), **b** geological map of Unilorin main campus (Olasehinde & Raji, 2007)

potential to current) and the geometry of the electrode array. Depending upon the survey geometry, the apparent resistivity data are plotted as 1-D soundings, 1-D profiles, or in 2-D cross-sections to look for anomalous regions. Resistivity measurements are associated with varying depths depending on the separation of the current and potential electrodes in the survey and can be interpreted in terms of a lithologic and/or geohydrologic model of the subsurface. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. The data were collected at one hundred and sixty two (162) locations using the Petrozenith resistivity meter.

The apparent resistivity values obtained were plotted against half current electrode spacing on log–log graph

paper. The initial interpretation of the VES data was accomplished using conventional partial curves matching technique utilizing master curves and the corresponding auxiliary curves from which resistivity values and thicknesses of the layers were obtained. The software WinResist version 1.0 was used for refining the partial curves matching interpretative results (Vander-Velpen, 2004) which successfully reduced the interpretation errors to acceptable levels (Barker, 1989).

Estimation of aquifer properties

The estimation of aquifer properties (hydraulic conductivity and transmissivity) was estimated using Niwas and Celik

(2012) empirical equation as expressed in the equation below:

Hydraulic conductivity K (in m/s) $= 10^{-5} \times 97.5^{-1} \times \rho^{1.195}$, (1)

$$K \text{ (in m/day)} = 60 \times 60 \times 24 \times (K \text{ in (m/s)}),\qquad(2)$$

where K = hydraulic conductivity, ρ = aquifer resistivity.

Transmissivity T (m²/day) is given as;

$$T = Kh,\qquad(3)$$

where T = transmissivity, K = hydraulic conductivity (m/day) and h = aquifer thickness.

The secondary parameters such as transverse unit resistance (T_i) and longitudinal conductance (S) were determined from the layer resistivities and thicknesses using the mathematical relations shown below (Zohdy et al., 1974):

$$T_i = \sum_{i=1} h_i \rho_i,\qquad(4)$$

$$S_i = \sum_{i=1} \frac{h_i}{\rho_i}.\qquad(5)$$

The reflection coefficient (R_c) and fracture contrast (F_c) of the study area were also calculated using the method of Oladunjoye and Jekayinfa (2015)

$$R_c = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}},\qquad(6)$$

$$F_c = \frac{\rho_n}{\rho_{n-1}},\qquad(7)$$

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.

Results and discussion

Geo-electric layers and curve types

Summary of curve types (Fig. 3), frequency and distribution is presented in Table 1. One hundred and sixty-two VES carried out at various locations within Unilorin reveals that the area is dominated by three–five geo-electric layers. The first geo-electric layer is the top sandy soil with apparent resistivity values ranging from 72.0 to 8117.3 Ωm and thickness ranging from 0.4 to 1.6 m. The resistivity of the top soil depends on clay volume, moisture content and degree of compaction. The underlying geo-electric layer is the lateritic soil with apparent resistivity values from 25.6 to 4132.2 Ωm and thickness of 0.4–5.3 m. The third geo-electric layer is

the weathered basement with resistivity values from 17.9 to 4441.7 Ωm and thickness ranging from 1.6 to 39.7 m. The fourth geo-electric layer is the slightly weathered /fractured basement which has a resistivity range of 37.8–17359.1 Ωm and thickness from 4.9 to 41.3 m. The last geo-electric layer is the fresh basement having apparent resistivity ranging from 245.4 to 100,000 Ωm and thickness of this layer is infinite. Tables 2 and 3 show the summary of the range and average values of the evaluated electrical parameters respectively at different sections of the study area.

Iso-resistivity map of the weathered basement

The iso-resistivity map reflects the lateral variation of apparent resistivity over a horizontal plane. Figure 4 shows the iso-resistivity map of the weathered aquifer. The resistivity of the weathered aquifer varies between 17.9 and 6118.1 Ωm. The sports complex, Faculty of Education and business school areas have the highest values of resistivity while the other parts of the study area shows resistivity values between 17.9 and 500 Ωm. Very low resistivity values observed in bank area, parts of the teak plantation, dam and post graduate school area suggested the presence of water in this layer. Highly saturated areas have low resistivity values signifying loose geologic material. From the aquifer potential rating as a function of weathered basement resistivity (Alabi & Makinde, 2016; Wright, 1992), 43.8% of the studied area falls within the optimum weathering and groundwater potential rating with a weighting of 10.5. Areas that fall within the medium aquifer conditions and potential covers 16.0% (101–150 Ωm) and areas which fall within the limited weathering and poor aquifer potential occupies 21.6% (150–300 Ωm) in places such as the business school area, sports complex and part of faculty of education. The area that falls within the negligible rating covers about 18.51% (> 300 Ωm) this area offers no appeal for groundwater development unless it is overlain by thick overburden.

Iso-resistivity map of the fresh basement

Rock resistivity depends on a number of factors such as the amount of water present in fractures, weathering, porosity, degree of fracturing and saturation. The fresh basement rocks in the study area are characterized by apparent resistivity values ranged between 245.4 and 10,000 Ωm. The Iso-resistivity map of fresh basement rock is presented in Fig. 5. The northeast and southeastern part of the study area is characterized by low to high resistivity values ranged between 200 and 6200 Ωm. However, high resistivity values greater than 8200 Ωm are observed on the teak plantation and behind faculty of education extending towards the dam area suggests that the occurrence of groundwater in the fresh
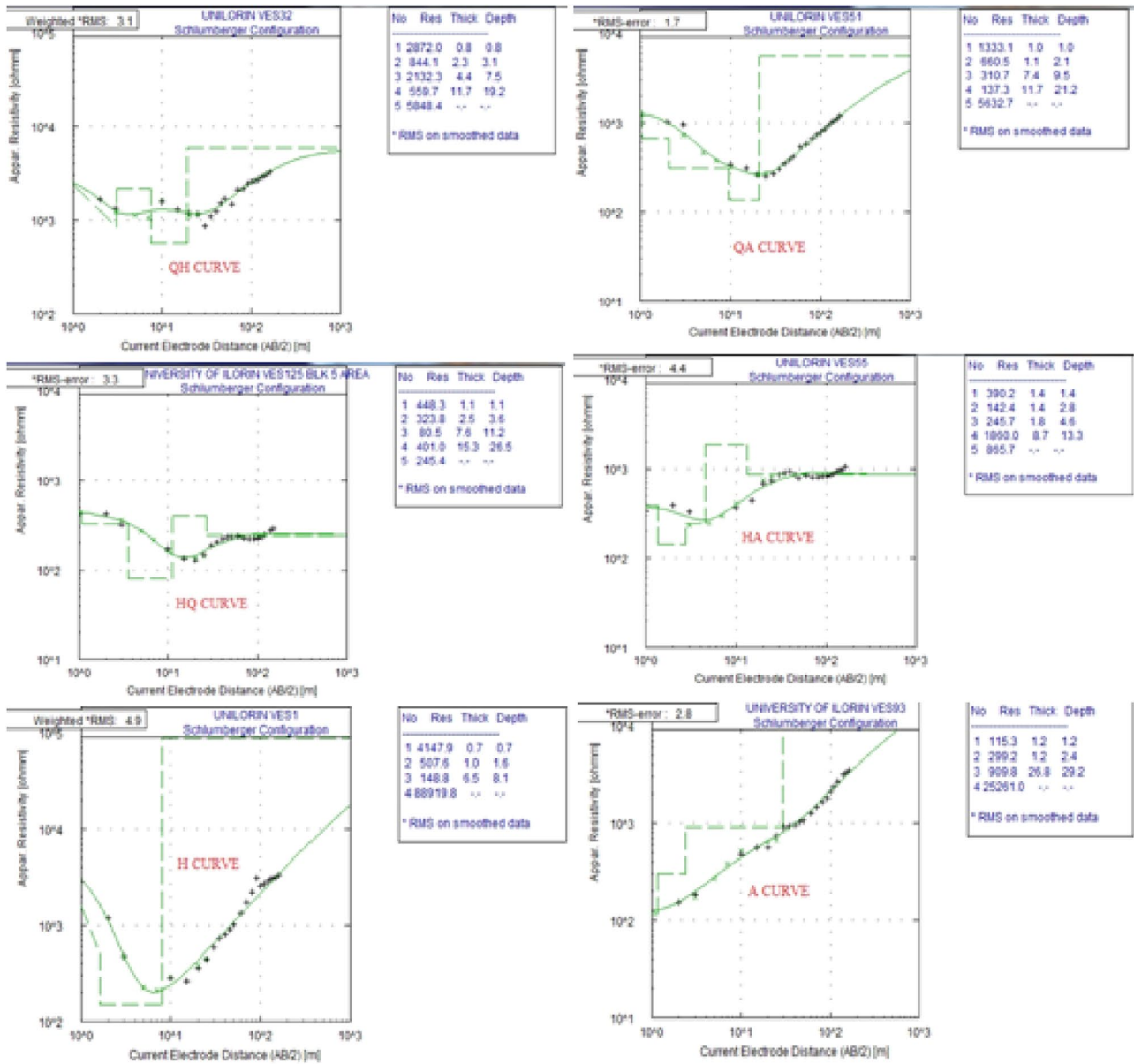
Fig. 3 Typical curves over the study area

Table 1 Summary of curve types identified in the study area

S/N	Curve type	Curve description	Frequency	Distribution (%)
1	H-type curve	$\rho1 > \rho2 < \rho3$	81	50
2	A-type curve	$\rho1 < \rho2 < \rho3$	14	9.26
3	HA-type curve	$\rho1 > \rho2 < \rho3 < \rho4$	37	25.3
4	HQ-type curve	$\rho1 > \rho2 < \rho3 < \rho4$	3	3.70
5	QH-type curve	$\rho1 > \rho2 > \rho3 < \rho4$	14	8.64
6	QA-type curve	$\rho1 > \rho2 > \rho3 < \rho4$	5	3.08
7	HK-type curve	$\rho1 > \rho2 < \rho3 > \rho4$	3	1.85
8	KA-type curve	$\rho1 < \rho2 > \rho3 < \rho4$	2	1.23

ρ resistivity

Fig. 4 Iso-resistivity map of the weathered basement
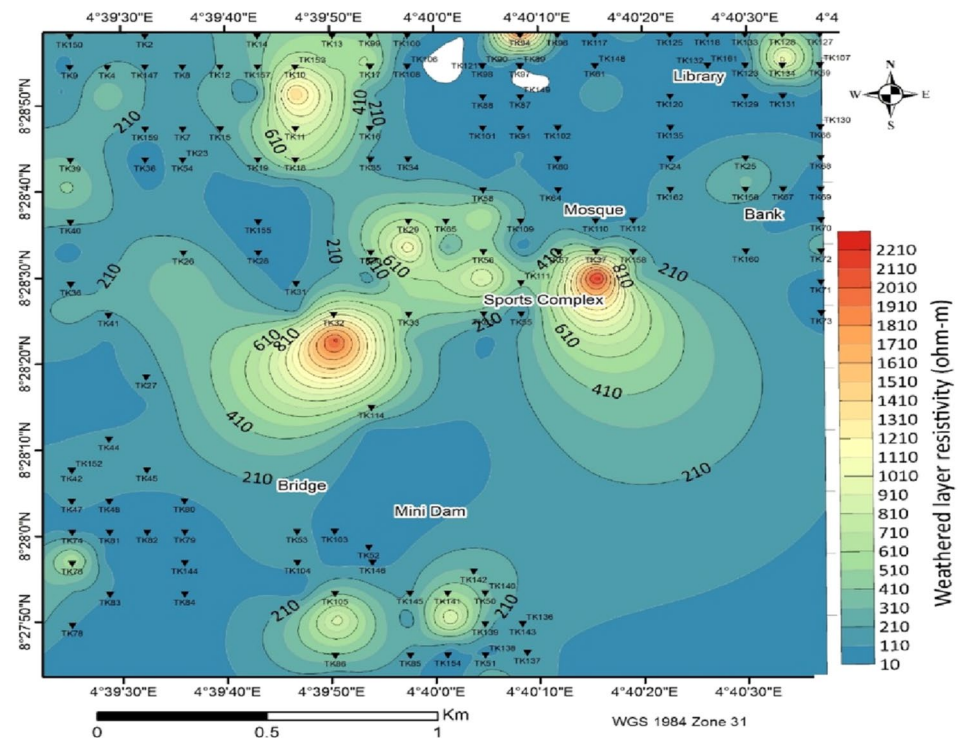
Table 2 Range of values obtained from electrical parameters

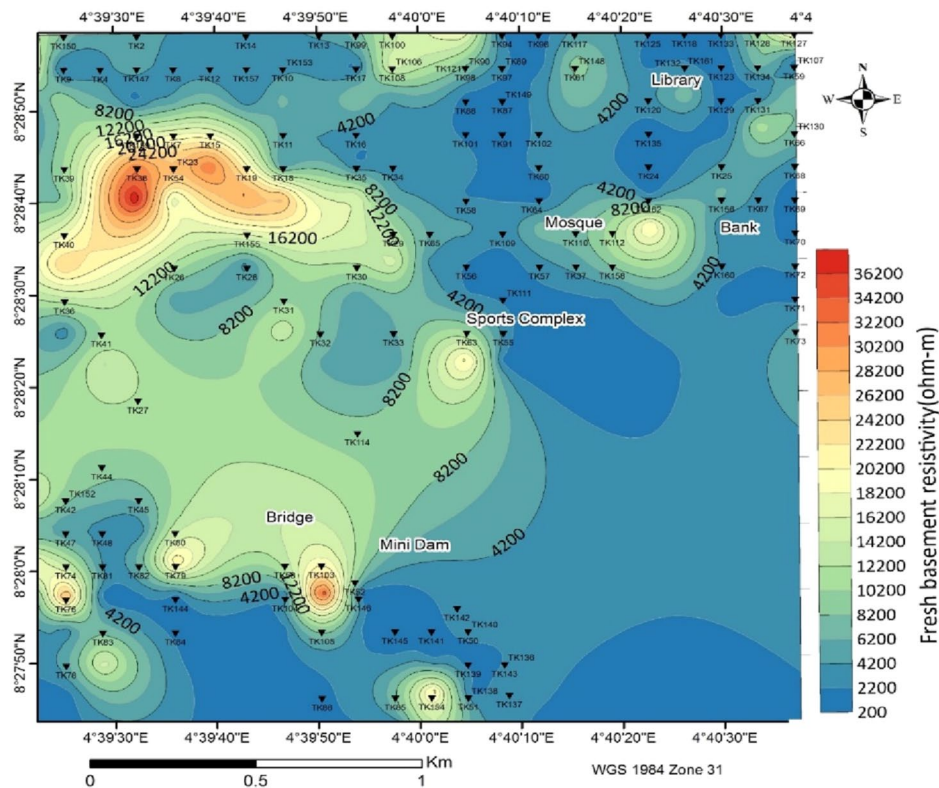| Location	Electrical parameters (range of values obtained)							
	Dominant curve types	Depth to aquifer (m)	K (m/day)	T (m²/day)	TUR (Ωm²)	TLUC (/Ω)	F_c	R_c
Teak plantation/ power station	H, HA	3.3–44.4	0.41–53.9	2.096–480.15	877.15–31453.6	0.015–0.288	0.019–6.332	0.112–0.998
Dam area	H, HA	2.2–31.4	0.77–108.6	0.496–684.18	74.58–41647.4	0.019–0.319	0.0608–6.063	0.526–0.994
Education/sports complex	H	4.6–19.5	11.1–84.2	6.72–373.92	1340.2–70659.2	0.026–0.149	0.037–4.854	−0.364–0.998
Mosque area	H, HA	1.44–25.2	0.59–23.2	27.94–253.36	1081.4–25835.4	0.0068–0.58	0.129–1.749	0.635–0.979
Reception ground/bridge	HA	4.1–9.2	0.82–8.43	2.377–60.717	680.42–8735.76	0.069–0.073	0.104–1.729	0.863–0.998
Senate chamber	A, HA	9.9–27.8	32.9–296.8	49.46–3324.1	2707.7–70659	0.0085–0.163	0.409–6.562	−0.583–0.986
Admin building/ zamfara area	HQ, H	4.0–36.6	0.39–52.8	3.105–491.1	211.31–8049.7	0.029–0.478	0.078–2.451	−0.240–0.986
Clinic/Abuja area	H, A	5.5–29.2	0.74–30.4	6.125–815.8	598.99–24880.0	0.044–0.258	0.257–3.051	0.802–0.995

K hydraulic conductivity, T transmissivity, *TUR* total transverse unit resistance, *TLUC* total longitudinal unit conductance, F_c fracture contrast, R_c reflection coefficient, *GP* groundwater potential

basement will depend on secondary porosity developed from fractures and joints (Abdullahi, 2014; Olasehinde & Raji, 2007). Generally, the fresh basement around the studied area exhibits higher resistivity values.

Depth to basement (overburden)

The depth to basement (overburden) within the study area ranges from 3.0 to 39.7 m (Fig. 6). The reception ground, dam site and post graduate school areas have overburden thickness between 12.0 and 22.0 m while at the teak plantation, the overburden ranges between 2.0 and 14.0 m. The

Fig. 5 Iso-resistivity map of the fresh basement

Table 3 Summary of evaluated parameters at different section of the study area

| Location	Average electrical parameters								
	Dominant curve types	Depth to aquifer (m)	K (m/day)	T (m²/day)	TUR (Ωm²)	TLUC (/Ω)	F_c	R_c	ΣGP
Teak plantation/power station	H, HA	13.5	5.79	67.9	5674.3	0.097	1.02	0.88	Medium to low
Dam area	H, HA	19.3	12.72	132.4	9335.2	0.112	1.15	0.83	High to medium
Education/sports complex	H	15.1	13.65	97.78	8084.3	0.068	0.73	0.78	Medium
Mosque area	H, HA	17.3	8.22	77.19	6667.2	0.151	0.49	0.89	Medium to low
Reception ground/bridge	HA	6.64	4.63	31.55	4708.1	0.071	0.92	0.93	Low to poor
Senate chamber	A, HA	18.0	63.85	75.38	17781.8	0.064	3.09	0.60	Medium to low
Admin building/Zamfara area	HQ, H	12.9	5.51	53.84	2610.4	0.152	0.41	0.78	Medium to low
Clinic/Abuja area	H, A	13.3	5.61	126.3	4861.9	0.135	1.05	0.95	Medium to low

K hydraulic conductivity, T transmissivity, *TUR* total transverse unit resistance, *TLUC* total longitudinal unit conductance, F_c fracture contrast, R_c reflection coefficient, *ΣGP* cumulative groundwater potential

central part of the study area shows shallow overburden with values between 2.0 and 8.0 m while at the oil palm plantation (southwestern corner) overburden thickness varies between 16 and 40 m. Overburden thickness plays an important role in groundwater recharge and groundwater accumulation, hence areas with thick overburden are expected to yield sufficient amount of groundwater. According to Olorunfemi and Fasuyi (1993), highest

groundwater yield in the basement terrain is found in areas where thick overburden overlies fractured zones. These zones are often characterized by relatively low resistivity. According to Alabi and Makinde (2016), rating of aquifer potential as a function of overburden thickness, 32.1% of VES locations have overburden thickness less than 10 m which signifies areas of poor groundwater potential while about 44.44% of the location fall under the moderate groundwater potential. Areas with good and very high

Fig. 6 Depth to basement (overburden)
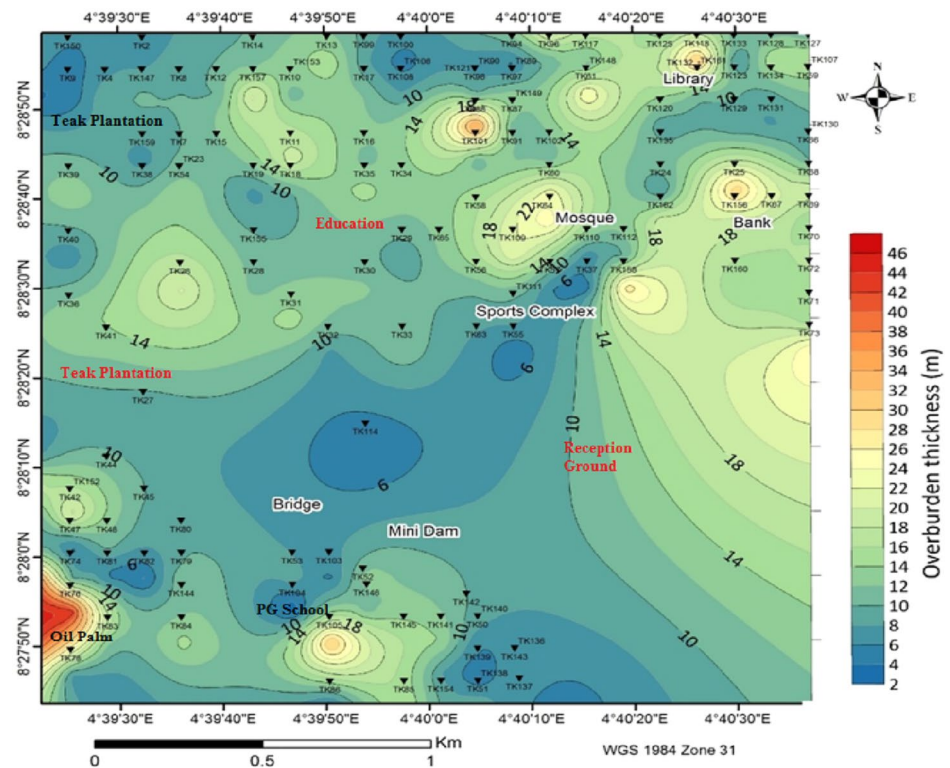
potential for groundwater occupies 14.20% and 9.26%, respectively.

Hydraulic conductivity (*K*)

Hydraulic conductivity is a measure of the ease with which a fluid will pass through a medium and an indicative parameter for aquifer recharge potential. Figure 7 shows the contour map of hydraulic conductivity (*K*) distribution in the study area (*K* ranges from 0.278 to 296.8 m/day). The high range of hydraulic conductivity of the aquifer may be due to the heterogeneity nature of the aquifer, a condition responsible for wide range in hydraulic conductivity (George et al., 2015). High *K* values between the range 140–300 m/day were identified around the sports complex, education, dam and post graduate school area and this corresponds to area with relatively thick overburden which is expected to influence the aquifer recharge potential. The library area, business school, central mosque and parts of teak plantation have low *K* values ranged between of 0.278 and 120 m/day. This low *K* values fall within areas characterized by shallow overburden and rock exposures therefore aquifer recharge potential in this area is expected to be low. Hence, high groundwater potential in this area will depend on secondary porosity in the fresh basement.

Aquifer transmissivity (*T*)

Transmissivity is an indirect indicator of yield (MacDonald et al., 2012) and it also describes the lateral movement of groundwater in aquifers. Thus, borehole yields are directly related to transmissivity (*T*) (Graham et al., 2009). The contour map showing the trends of the transmissivity within the study area is presented in Fig. 8.

The transmissivity values estimated ranges from 0.496 to 877.0 m²/day with mean transmissivity value of 99.045 m²/day which suggests that the area falls within the intermediate transmissivity and groundwater potential rating with withdrawal of local water supply (Kransy, 1993). Areas with high transmissivity values can be identified as area of high water bearing potential and aquifer materials are known to be relatively permeable to fluid movement. It was observed from the study that areas which have shallow aquifer depth are characterized by lowest transmissivity ranged between 0.496 and 33.7 m²/day and aquifer depth of 2.2–12.9 m such as at the teak plantation and power station. The areas with semi-deep aquifer of 13.0–24.5 m which are randomly sited within the study area have transmissivity values ranged from 34.0 to 97.84 m²/day. The areas that have deep aquifer depth of between 24.5 and 45.3 m have the highest transmissivity (*T*) which ranged from 101.01 to 877.0 m²/day such as oil palm area, behind business school and parts of faculty of education. The study can therefore be classified into areas of high,

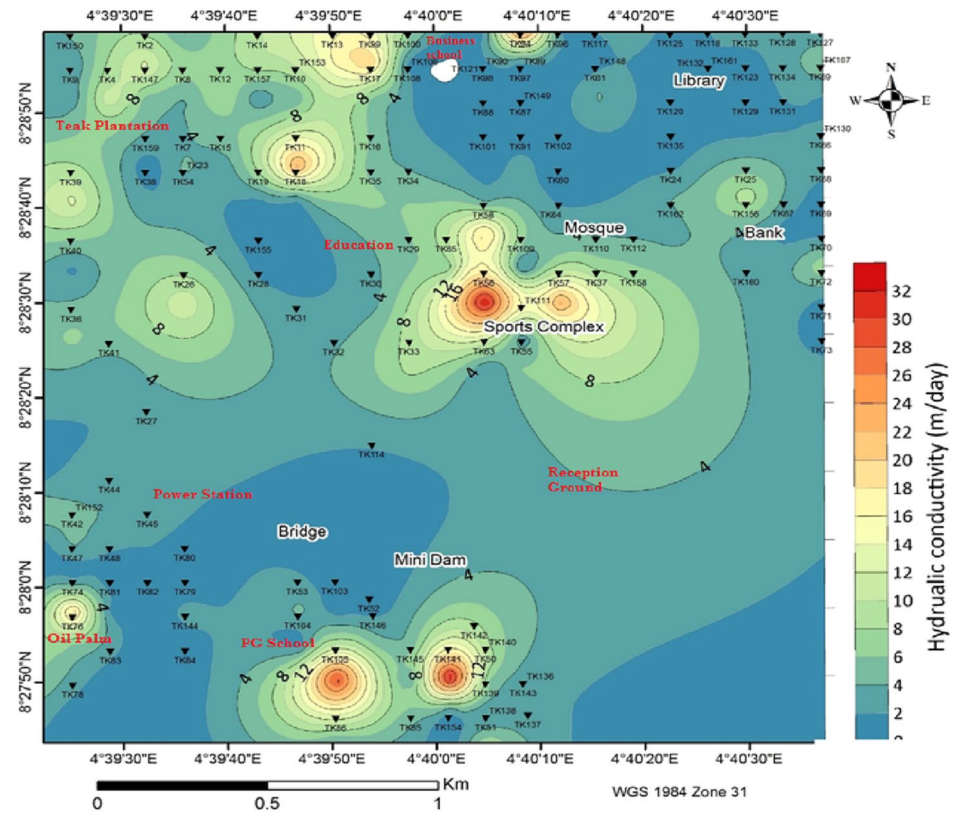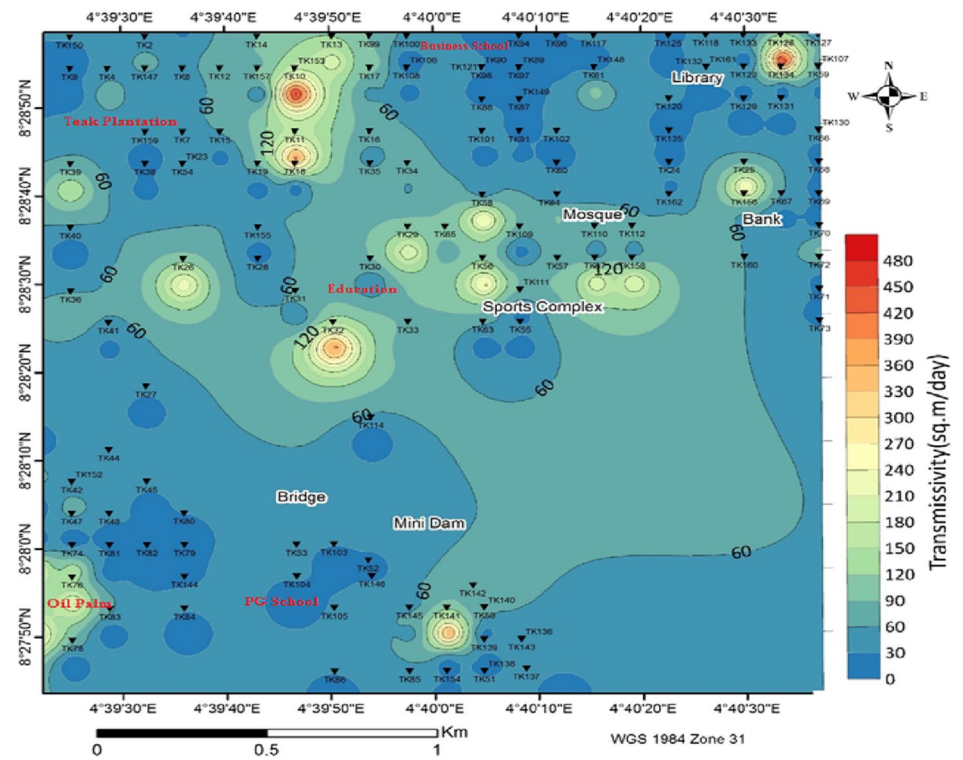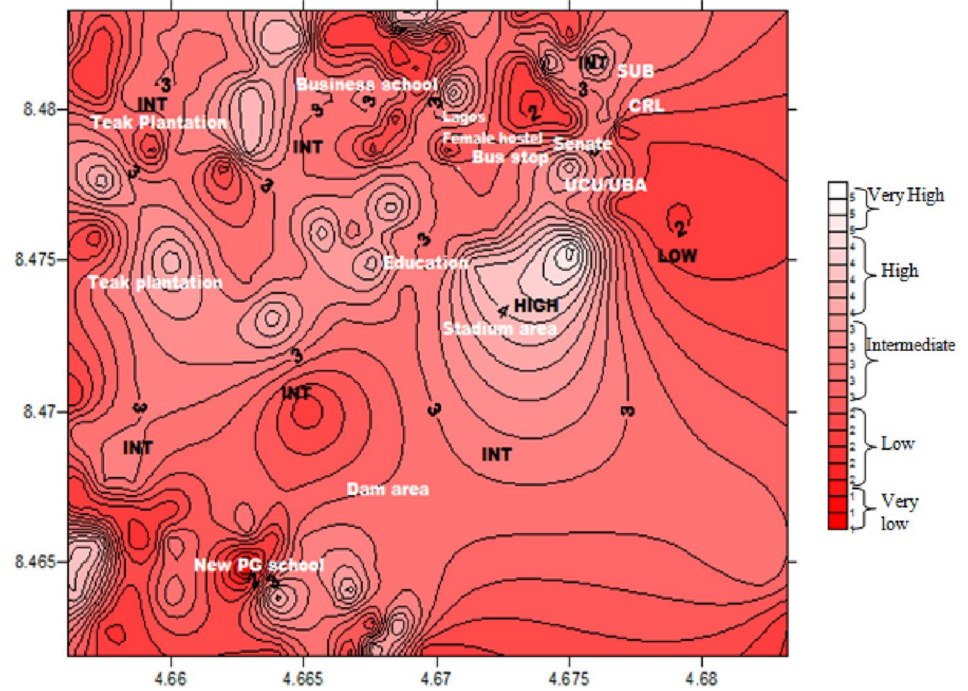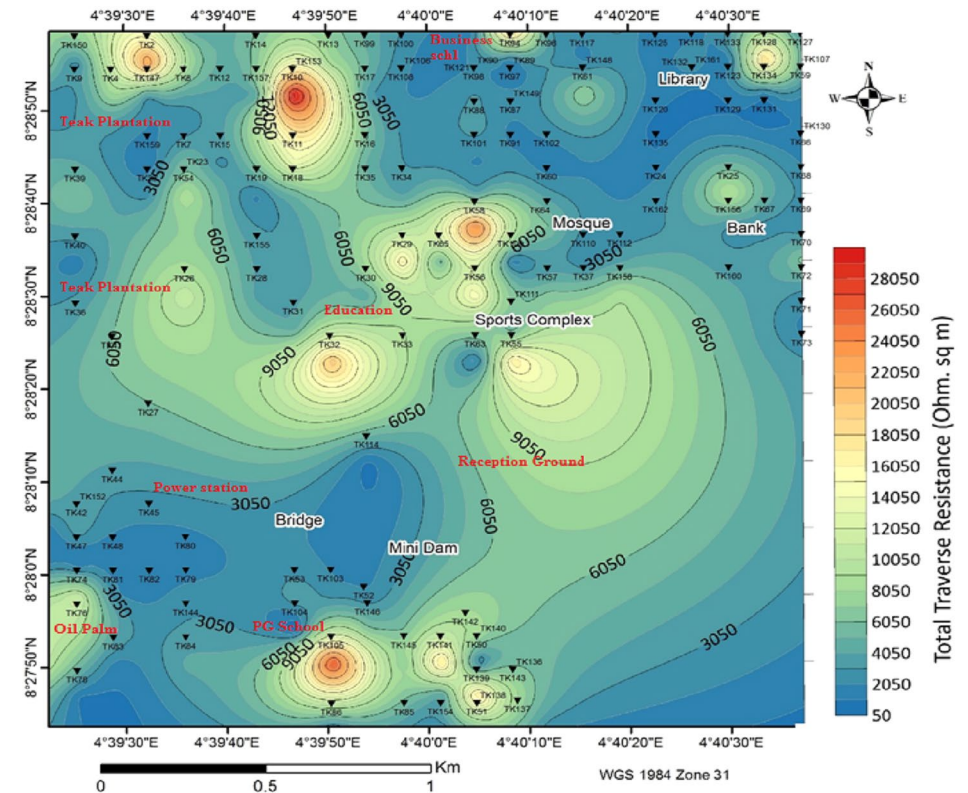**Fig. 7** Contour map of hydraulic conductivity

Fig. 8 Contour map of aquifer transmissivity

Fig. 9 Groundwater potential map developed from scoring of transmissivity values

Fig. 10 Contour map of total transverse unit resistance

intermediate and low groundwater potential (Fig. 9) based on the level of transmissivity (Kransy, 1993).

Total transverse unit resistance (*T*)

The total transverse unit resistance (*T*) was employed to delineate areas of prolific groundwater potential (Fig. 10).

Transverse resistance (*T*) has been extensively used in identifying the ground water potential zones combined with the values of longitudinal conductance (*S*) (Ayolabi, 2005). The transmissivity of an aquifer is also directly proportional to transverse resistance therefore high values of transverse resistance (*T*) indicates higher transmissivity/ high resistivity formations and a relatively deeper basement occurrence while low *T* values are characteristic of low resistivity formation and a relatively shallow basement formation, (Abdullahi, 2014; Henriet, 1976). The transverse unit resistance (*T*) of the study area range between 74.56 and 221,594 Ωm^2. The calculated mean transverse unit resistance of the study area is 7236.055 Ωm^2. The highest values of the total transverse unit resistance were observed around the sports complex, faculty of education, behind business school and postgraduate school. Lower values of *T* are obtainable in the teak plantation, power station, admin area and business school area indicating a shallow basement unit. The transverse resistance within the study area has been classified into areas of low, medium and high groundwater potential. Locations with *T* values > 34,000 Ωm^2 are classified to be high, those between 3700 and 33,999 Ωm^2 to be medium while those ranging between 74.56 and 3699 Ωm^2 are classified to be low (Olatunji et al., 2020). Places such as mosque, dam area, reception ground, some parts of stadium and teak plantation have low *T* values. Medium values were identified at places such as faculty of education, stadium, bank

area, palm plantation and around the water works. High values of *T* greater than 34,000 Ωm^2 were only identified at two locations which are, at the front of and behind senate chamber.

Total longitudinal unit conductance (*S*)

One of the versatile geo-electric parameters being used to determine target areas of groundwater potentials is the total longitudinal conductance (*S*) and it has been utilized mostly in the evaluation of overburden protective capacities over hydrogeologic structures (Zohdy et al., 1974). For this research, resistivity and layer thickness was used to compute the longitudinal conductance of the layers. High longitudinal conductance indicates a relatively high protective capacity. The contour map of longitudinal conductance of the study area is presented in Fig. 11. Variation in longitudinal conductance (*S*) from a VES point to the other suggests changes in the total thickness of low-resistivity materials (Glain, 1979; Worthington, 1977). Longitudinal unit conductance values within the research area varied between 0.625 and 0.00685/Ω. The mean longitudinal conductance was estimated to be 0.12496/Ω which suggests a weak aquifer protective capacity according to protective capacity rating for longitudinal conductance (Oladapo et al., 2004), while low *T* values are linked with low-resistivity formation (such as clayed soil) and a relatively shallow basement formation, higher *T* values are attributes of high-resistivity formations

Fig. 11 Contour map of total longitudinal unit conductance
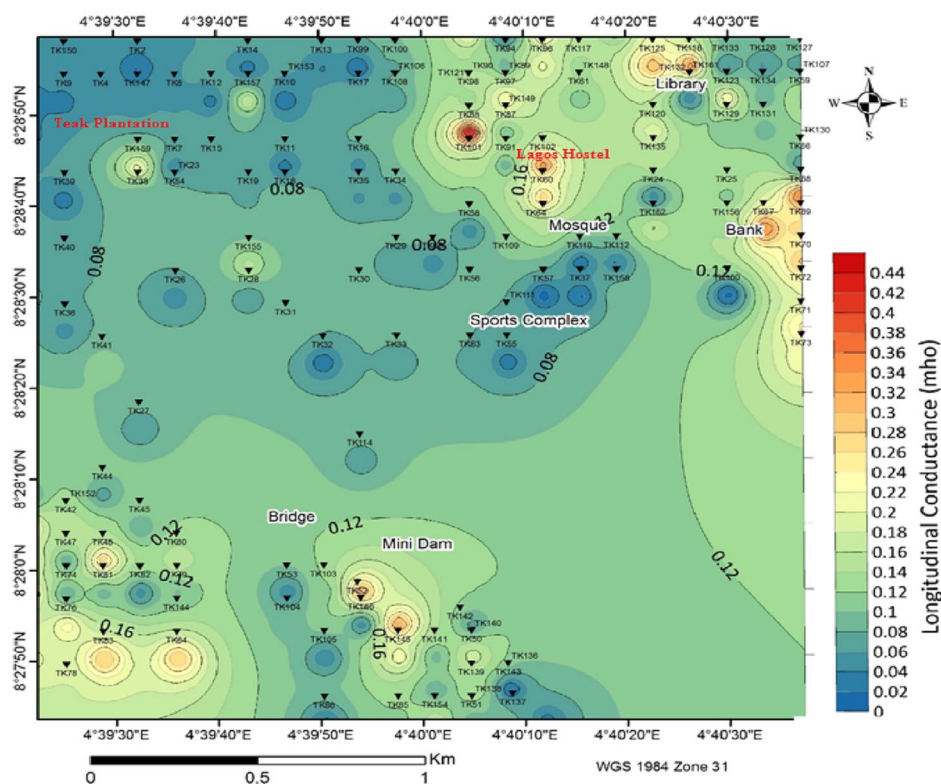
and relatively deeper occurrence of the basement. Very high transverse resistance values correlates to very highly resistive formations in the subsurface.

It was observed that places such as the oil palm plantation, Lagos female hostel, senate chamber and dam area shows moderate conductance which fall within the range 0.2–0.69/Ω this implies a moderate aquifer protective capacity. However, at the southern part of the study area are low values of longitudinal unit conductance ranged from 0.1 to 0.19/Ω suggesting weak aquifer protective capacity at places such as UBA and stadium area. The teak plantation extending towards the faculty of education at the northwestern corner the study area has low values of longitudinal unit conductance ranged less than 0.1/Ω suggesting poor aquifer protective capacity.

Aquifer protective capacity

The aquifer protective capacity for the study area was determined using the aquifer protective capacity rating after Oladapo et al., 2004, the parameters longitudinal conductance (S) and transverse resistance (T) to generate the aquifer protective capacity map for the study area as shown in Fig. 12. The study area has been classified into area of moderate, weak and poor aquifer protective capacity. The study area

is characterized by low values of longitudinal conductance with values between 0.0068 and 0.6250/Ω, this corresponds to aquifer protective rating between poor and moderate capacity. This shows that the part of Unilorin studied has poor to moderate aquifer protective capacity.

The mean longitudinal conductance (S) value of 0.1249/Ω estimated from the study area fall within the weak protective capacity zone. The transverse resistance (T) of the study area also shows values between 74.56 and 221,594 Ωm². Most of the studied area shows high T values indicating the occurrence of high-resistivity formations. The aquifer in most part of the study area may be prone to contamination as the thickness of the overlying layers is not deep enough to protect the aquifers from percolating fluids. Groundwater usually is given protection by geological barriers/layers having sufficient thickness (protective layers) and low hydraulic conductivity. Silts and clays are suitable protective layers and when they are found as thick layers above aquifer, they constitute a protective cover (Olusegun et al., 2016).
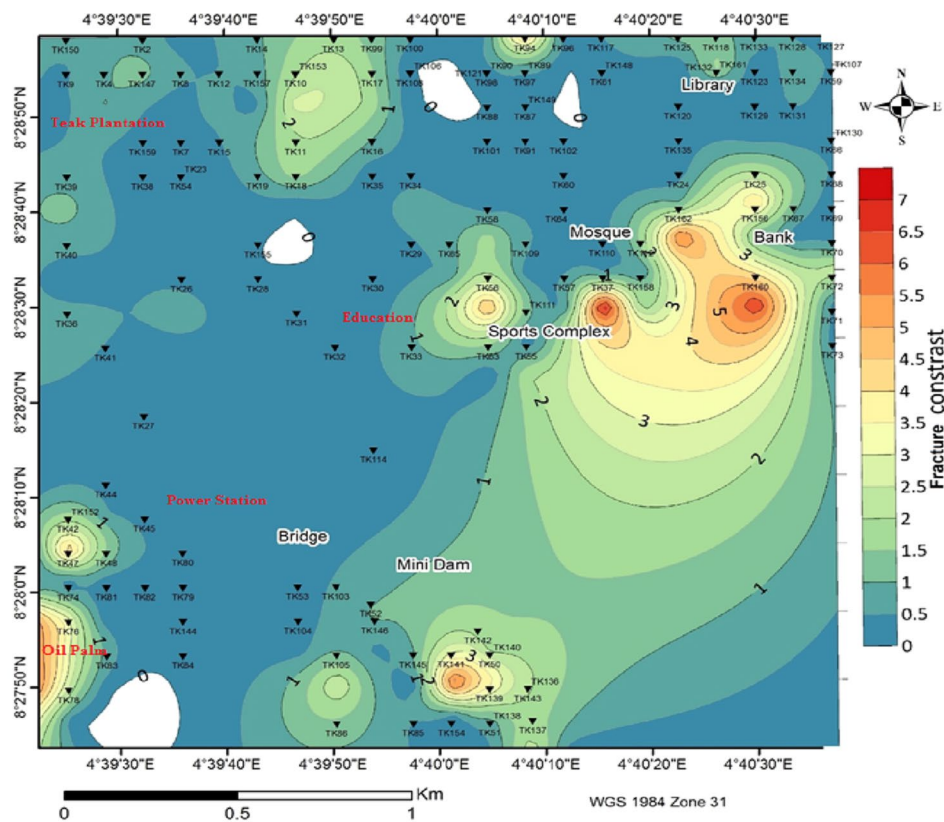
Fracture contrast (F_c)

According to Olayinka et al. (2000), fracture contrast is a good indicator of water filled fractures. Low values of fracture contrast indicate low contrast between two aquifers thereby implying good fracture network in the aquifers with

Fig. 12 Aquifer protective capacity map of the study area (Unilorin)
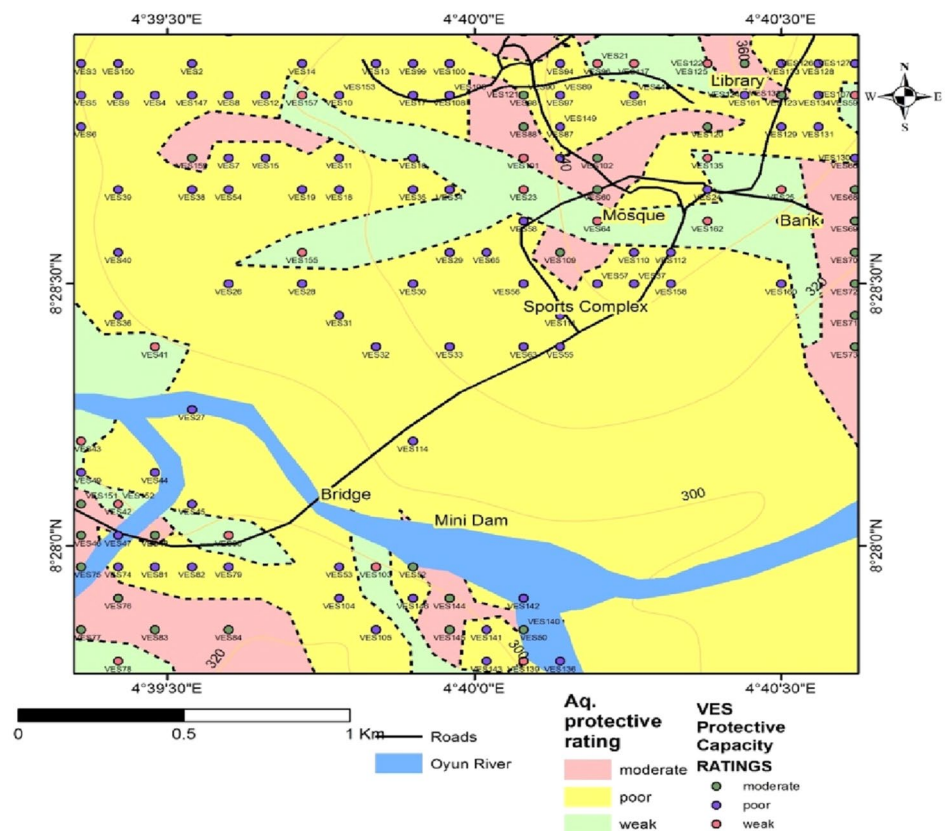
Fig. 13 Contour map of fracture contrast for the study area (Unilorin)

high groundwater accumulation and fluid flow in the aquifers. As shown in Fig. 13 the fracture contrast estimated ranges between 0.01575 and 7.3109. The low values of fracture contrast between 0.01 and 1.25 found in the northwestern, southwestern, north and northeastern corner in places such as the teak plantation, library, education, power station clinic and Lagos hostel suggest that the aquifers in those area have relatively higher density of water filled fractures than the aquifers in the eastern part such as the bank and stadium area.
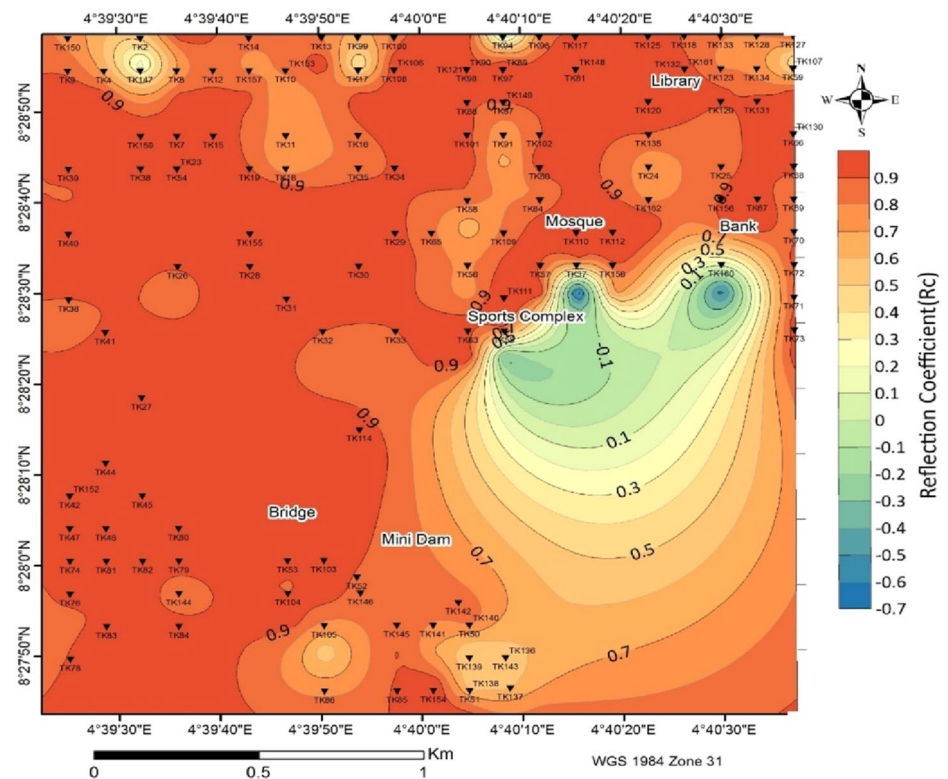
Reflection coefficient (R_c)

Groundwater assessment within the crystalline basement focuses on complementary, interconnectivity of overburden and the fractured basement rock. However, resistivity values are not sufficient in adequately describing fractured basement rock and corresponding areas of promising groundwater yield. Hence, geo-electric parameter such as reflection coefficient was employed to compliment efforts at groundwater potential delineation (Fig. 14). Reflection coefficients are able to better reflect the degree of fracturing in the underlying basement. According to Bayewu et al. (2018), areas of low reflection coefficient (< 0.8) and or thick overburden in a basement complex depicts a good aquiferous/high water potential zone. Good fracture

network implies high groundwater accumulation and fluid flow in the aquifers. Olayinka (1996) also observed that areas of lower reflection coefficient value exhibits fracture of the basement rock and hence, has higher water potential. The reflection coefficient of the study area falls within the range of 0.112397–0.9990 for all locations except for VES locations 37, 55, 92, 125 and 160 which have negative values of reflection coefficient of −0.776, −0.364, −0.127, −0.240 and −0.583, respectively. The study area has a mean value of reflection coefficient of 0.84552.

Groundwater potential (GWp)

In hydro-geologic maps, transmissivity has been the best hydraulic property to clearly express ground water potential. However, in this study, an overlay of various maps such as transmissivity, overburden thickness and reflection co-efficient were used to produce the groundwater potential map. According to Olayinka (1996), the resistivity of the basement cannot be completely relied upon in identifying areas of promising aquifer potential hence, the consideration of its reflection coefficient in groundwater potential evaluation. The reflection coefficient shows the degree of fracturing of the underlying basement rocks better than depending solely on the resistivity values. Good

Fig. 14 Contour map of reflection coefficient for the study area (Unilorin)

aquiferous zones are usually found either where the overburden is relatively thick and/or where reflection coefficient is low (< 0.8) in the basement terrain. Three basic criteria were considered in evaluating promising locations for groundwater potential as follows:

1. Areas with overburden thickness greater than 13 m and with reflection coefficient less than 0.8 are classified as having high groundwater yield.
2. Areas with overburden thickness greater than 13 m and with reflection coefficient greater than or equal to 0.8 are classified as having medium groundwater yield.
3. Areas with overburden thickness less than 13 m and with reflection coefficient greater than or equal to 0.8 are classified as having low potential for groundwater yield.

The above mentioned criteria were the used to develop groundwater potential map and to characterize the area studied into low, medium and high potential for groundwater as shown in Fig. 15. Low groundwater potential covers about 56.79% of the total area studied in areas such as northwestern corner, parts of the north, southwest and northeast. The central, parts of the northwest, southwest and the north area fall under the medium groundwater potential covering about 30.86%. High potential for groundwater is observed at the eastern, northern and

southern part of the study area covering about 12.35% of the total area.

Ratings of 1–5 from classification rating of transmissivity magnitude (Kransy, 1993) to classify transmissivity values for all VES locations into very low, low, intermediate, high and very high potential for groundwater to generate a groundwater potential map as shown in Fig. 9.

Conclusion

Integration of various electrical resistivity parameters to elucidate aquifer properties has proven to be efficient in the characterization of groundwater potentials in a basement terrain.

Three–five geo-electric layers namely top soil, lateritic/clayey layer, weathered basement, fractured/slightly weathered basement and the fresh basement rocks were delineated. The dominant curve type within the study area is H-type which occupies about 50% of the area studied is considered to have a three successive lay with resistivities $\rho 1$, $\rho 2$, $\rho 3$ and a central low value ($\rho 1 > \rho 2 < \rho 3$). The study revealed two aquifer zones which are the weathered and fractured/slightly weathered basement with the estimated thickness of the combined aquifer range from 2.2 to 45.3 m. It was inferred based on weathered basement resistivity that 43.8% of the studied area (the Northeast, part of northwest and

Fig. 15 Thematic map from overlay of maps generated from all electrical parameters (groundwater potential of Unilorin)
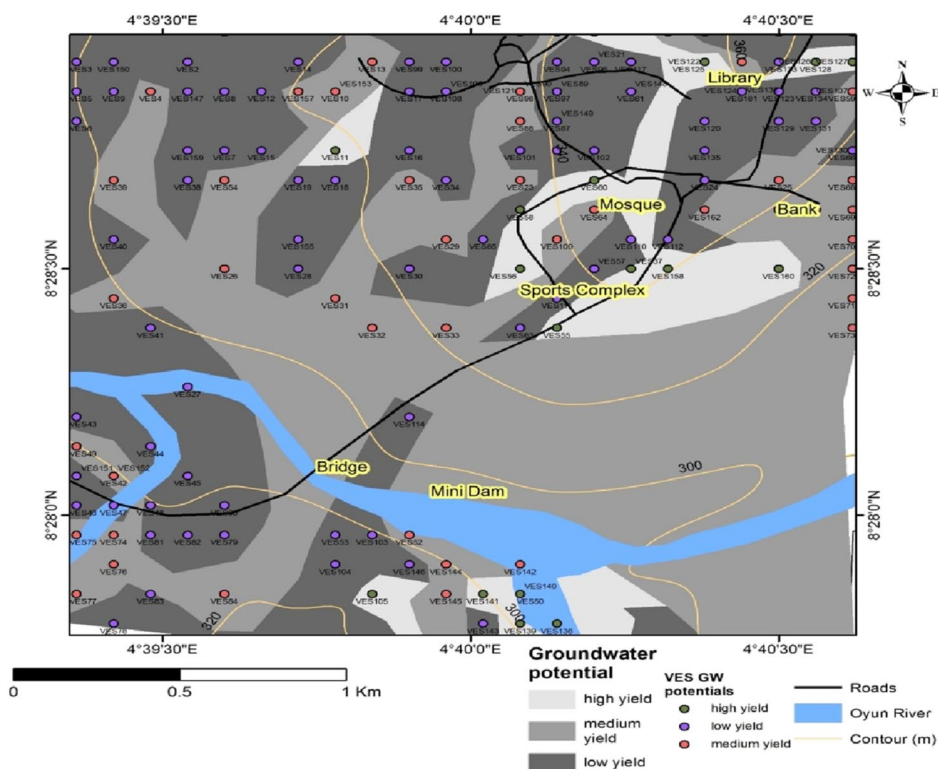
southwestern) falls within the optimum weathering and groundwater potential with a weighting of 10.5. About 16.0% fall within the medium aquifer conditions and potential. 21.6% falls within the limited weathering and poor aquifer potential in places such as the extreme north and central part of the study area. The area that falls within the negligible rating covers about 18.51% of the area studied. This region offers no appeal for groundwater development unless it is overlain by thick overburden.

Based on aquifer potential as a function of overburden thickness, 32.1% of the study area has overburden thickness less than 10 m which signifies areas of poor groundwater potential while about 44.44% of the location fall under the moderate groundwater potential. Areas with good and very high potential for groundwater occupies 14.20% and 9.26%, respectively. Hence, most of the locations studied are classified to be of moderate groundwater potential.

The estimated hydraulic conductivity, transmissivity, longitudinal conductance, transverse resistance, fracture contrast and reflection coefficient maps all revealed wide variation in aquifer properties across the study area and were used in the development of the groundwater potential maps of the study area. About 56.79% of the area fall within the low groundwater potential rating while the other area falls within the medium to high yield groundwater potential rating covering about 30.86% and 12.35%, respectively.

The transmissivity of the study area which falls between 0.496 and 877.0 m^2/day has been used to classify areas of high, intermediate and low groundwater potential. 16.67% of the area studied fall within the high groundwater potential rating at 27 VES locations. About 27.16% falls within the low groundwater potential at 44 VES locations. 56.2% of the study area falls within the intermediate groundwater potential at 91 VES locations across the study area. Hence, the study area can be generally rated to be of intermediate groundwater potential.

The values of transverse resistance (T) range between 74.56 and 221,594 mΩ^2. The highest values of the total transverse unit resistance were observed around the central part of the study area at just two locations. Lower values of T are obtainable in the northwestern, south western and eastern parts of the study area indicating a shallow basement unit. The transverse resistance within the study area has been classified into areas of low, medium and high groundwater potential. Locations with T values $> 34,000$ Ωm^2 are classified to be high, those between 3700 and 33,999 Ωm^2 to be medium while those ranging between 74.56 and 3699 Ωm^2 are classified to be low. Places such as mosque, dam area, reception ground, some parts of stadium and teak plantation have low T values. Medium values were identified at places such as faculty of education, stadium, bank area, palm plantation and around the water works. High values of T greater than 34,000 Ωm^2 were only identified at two locations which are, at the front of and behind senate chamber.

Longitudinal unit conductance values within the study area range between 0.625 and 0.00685/Ω. It is observed that 59.88% of the study area has a very low longitudinal unit conductance which implies a poor aquifer protective capacity making such areas prone to contamination. However, 19.14% of the area shows weak aquifer protective capacity and 20.98% of the area have moderate aquifer protective capacity.

Good aquifer zones are usually found either where the overburden is relatively thick and/or where reflection coefficient is low (< 0.8). Low reflection coefficient was identified in places such as the central, eastern, southern, northwestern corner, parts of the north thereby reflecting thick overburden and fractured basement. This also implies that fracturing in the basement is relatively high and with high groundwater potential this areas are recommended for citing boreholes for community water supply.

Based on the above results, integration of different electrical parameters obtained from VES has revealed seamless delineation of aquifer geometry and estimation of hydraulic parameters such as hydraulic conductivity and transmissivity. Hence, VES can be used not only for qualitative estimation, but also for quantitative estimates of aquifer parameters, which further reduces the additional expenditures of carrying out pumping tests and offers an alternate approach for estimating the hydraulic properties.

Declarations

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