



Hydrogeological characterisation and prospect of basement Aquifers of Ibarapa region, southwestern Nigeria

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Abstract

The present study involved the use of 82 geo-electric soundings, and the measurement of well inventory and conduct of yield tests in 19 wells across the various bedrock terrains of Ibarapa region of southwestern Nigeria. The aim is to proffer solution to the unsustainable yield of the available boreholes in order to effectively exploit the existing groundwater resource in the area. From the geological reports, the area is underlain by four principal crystalline rocks that include porphyritic granite, gneisses, amphibolite and migmatite. The geo-electric studies revealed that the degree and extent of development of the weathered–fractured component varied, leading to diversity in groundwater yield and in aquifer vulnerability to contamination. The thickness of the weathered layer is greater than 18 m in areas underlain by amphibolite and gneisses and less than 13 m within migmatite and porphyritic granite terrains. High groundwater yield greater than 70 m³/day was recorded in wells within the zones of rock contacts and in areas with large concentration of bedrock fractures and elevated locations across the various bedrock terrains. Aquifer vulnerability is low in amphibolite, high in granitic terrains, low to moderate in gneisses and high to moderate in migmatite. Also, wells' depths and terrain elevation have a moderate to strong indirect relationship with groundwater yield in most bedrock terrains, except in high topographic areas underlain by porphyritic granite. Therefore, there is need for modification of well depth in accordance with the terrain elevation and hydrogeological complexity of the weathered–fractured components of the various bedrock terrains, so as to ensure a sustainable groundwater yield.

Keywords Geo-electric studies · Borehole topography and depth · Groundwater yield · Basement aquifers

Introduction

Large parts of southwestern (SW) Nigeria are completely underlain by intrusive crystalline rocks that can neither store nor transmit water, except when fractured, or where there is significant regolith thickness over the basement. The study area, which lies within Ibarapa region of SW Nigeria, has no functioning town water supply scheme, and human settlements are not connected with piped water facilities (Fashae et al. 2014; Akanbi 2016). Therefore, for domestic water needs and even for agricultural purposes, residents

of Ibarapa areas rely on groundwater supply tapped from hundreds of hand-pump boreholes that penetrated various intrusive crystalline bedrocks of Precambrian age. Yet, even with these provisions, availability of potable water is still inadequate, largely due to the unsustainable yield of many of the functioning boreholes (Akanbi 2017). This scenario is further complicated due to rise in human population in the area as typical of many developing nations including Nigeria. This has led to increase in demand for fresh water supply in Ibarapa area. However, groundwater development is hampered in this region as a result of lack of pre-drilling and drilling data and little is known about the hydrogeology of the present study area. This has not helped in providing information needed for further groundwater development in the area. Also, considering the fact that the hydrogeology of weathered–fractured aquifers is highly heterogeneous due to complexity in geological, structural and geomorphological features (Akanbi 2017), expansion of the existing groundwater supply in Ibarapa is quite challenging. These high demand for groundwater resource and the variability of its

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occurrence in basement terrains have made it mandatory to investigate the hydrogeological setting and to validate the groundwater yield of the basement aquifers across the various bedrock terrains of the study area within Ibarapa region of SW Nigeria.

For hydrogeological characterisation of the basement aquifers in Nigeria, the applications of electrical resistivity methods have been used for decades (Olorunfemi and Olorunniwo 1985, 1990; Ako et al. 1990; Malomo et al. 1991; Olayinka and Mbachi 1992; Olorunfemi and Okhue 1992; Olayinka and Olayiwola 2001; Oseji et al. 2005; Alile et al. 2008). Most of these investigations used the primary geo-electric parameters, which are the layer resistivity and the corresponding thickness for interpretations of the hydrogeological settings of the crystalline basement aquifers. These studies described the lithology and deduced the aquifer characteristics and water saturation of the residual overburden and the underlying fractured bedrocks. However, more recent research works (Oladapo and Akintorinwa 2007; Abiola et al. 2009; Aweto 2011; Jayeoba and Oladunjoye, 2013; Akanbi 2016) employed Dar-Zarrouk variables in conjunction with the primary geo-electric parameters to demarcate areas into various groundwater potential zones and for estimation of the groundwater vulnerability assessment and protective capacity of the overburden unit. The Dar-Zarrouk variables are the secondary geo-electric parameters that included the longitudinal conductance, the traverse resistance and the coefficient of anisotropy first introduced by Mailliet (1947). These variables were derived from the integration of primary geo-electric parameters (i.e. the layer thicknesses and their corresponding true resistivities) and comparison of the passage of electric current across and parallel to the geo-electric boundaries to water passage through subsurface layers was made.

However, for further understanding of groundwater sustainability at Ibarapa region of SW Nigeria basement terrains, measurements of groundwater yield and evaluations of the well inventory of the basement aquifers also have to be incorporated. This is due to erratic and localised nature of groundwater occurrence in subsurface rock discontinuities and within the weathered unit (Offodile 2002). Therefore, the present study used vertical electrical sounding (VES) geophysical method, well inventory and yield to characterise the hydrogeological settings and to attest the groundwater prospect of the basement aquifers of Ibarapa region.

The study area

Location, climate and vegetation

The study area lies between longitude 3°07'E to 3°21'E and latitudes 7°21'N to 7°37'N (Fig. 1) of Ibarapa region of Oyo

state in the SW Nigeria and covers a total landmass of about 750 km². The area encompasses most township areas that include Igboora, Idere, Ayete and Tapa and their adjoining human communities within Ibarapa region (Fig. 1). SW Nigeria is bounded at the west by the Republic of Benin and by Atlantic Ocean at the south.

Ibarapa region lies within the tropical climatic zone, marked by two distinct seasons of wet and dry periods. The dry season extends from November to March with an average monthly precipitation of less than 25 mm. The wet season peaks around June and September with monthly rainfall exceeding 100 mm. The total annual rainfall in the area ranges from 813 to 1853 mm, while the annual temperature ranges from 24 to 29 °C. When compared to an average rainfall of 1541 mm/year for the entire SW Nigeria, the study area has lower average precipitation and higher average temperature (Munaserei 1979; Daly et al. 1981; David 1988; Tijani 2016). Hence, it is expected that the vegetal cover will not be as thick, compared to other parts of SW Nigeria. The vegetal cover is more of derived savannah forested land marked by scattered-scanty small trees and shrubs, sandwiched by tall grasses. It lies between the transition zone of lowland rain forest of southern areas of Nigeria and the savannah zone of the further northern areas of Oyo state.

Geology, geomorphology and drainage

The study area is underlain by igneous and metamorphic rocks of Precambrian age (David 1988; NGSA 2009; Weerawarnakula 1986) and the four principal crystalline rocks, namely porphyritic and homogeneous medium-grained granite; banded and augen gneisses; amphibolite; and migmatite (Akanbi 2017). The distribution of the major rock units in the study area is presented in Fig. 2. The outcropping exposures of porphyritic biotite granite are the dominant bedrock at the middle section and occupy about one-third of the entire study area. The landforms formed by granitic outcrops are ridges and inselbergs with intermediate low-lying areas, and porphyritic granite is the major rock that underlain Idere, Ayete and Tapa township areas. Porphyritic granite is composed mainly of quartz, biotite and larger-grained potassic feldspar. The porphyritic biotite granite is a felsic rock as a result of the presence of larger amount of leucocratic minerals that include the quartz and the feldspars. The medium-grained granite occurs as major mappable intrusions in other principal rock units and is confined to a small section at the eastern part of the study area. The mineral grains are massive, medium-grained and homogeneous and massive.

The amphibolite outcrops are found as disjointed low-lying boulder-sized units, and it is the major rock unit that underlies Igboora Township. In respect of textural attribute, the amphibolite is fine to medium-grained

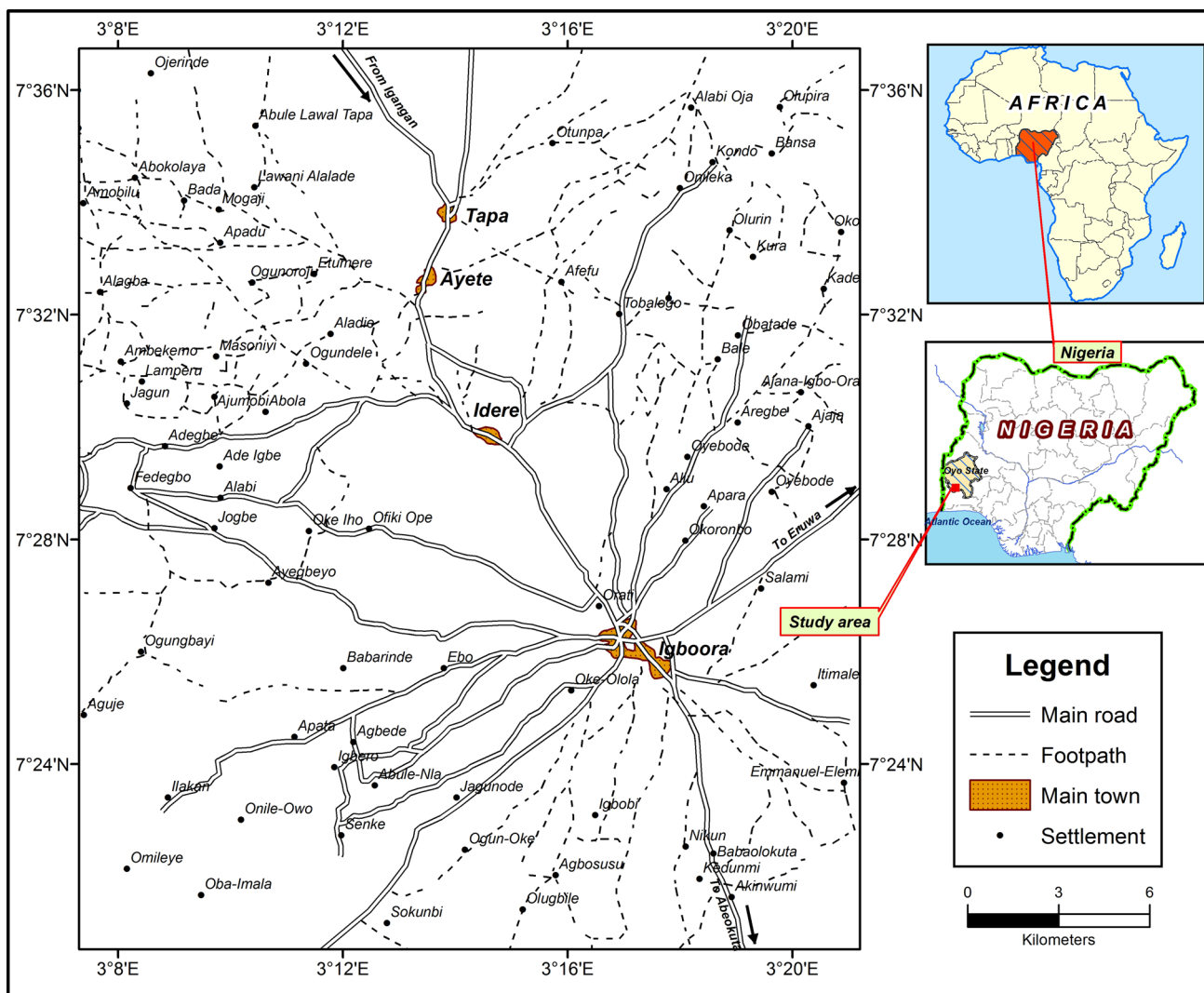


Fig. 1 Location and accessibility map of the study area

dark-coloured rock. Two varieties of amphibolite are found at Igboora due to textural difference. These are the massive and the schistose varieties. Lineation trend on the schistose variety ranges from 093° to 124°, and the foliation plane dips between 38° and 44°W. Gneisses are mainly restricted to the western part, though small area is underlain by augen gneiss at the south-east section of the study area. The gneissic rock in the area is of the banded and the augen varieties. Mineral foliation strikes between 339° and 360° and dips between 36°E and 40°E. However, at the north-west region around Alagba area, the dip of the foliation is vertical (Fig. 2). Lastly, the migmatite terrains are mostly restricted to the adjoining villages such as Kondo, Obatade, Tobalogbo and Alabi Oja at the northeastern part, and it is intruded upon at Idere by porphyritic granite. The outcrops of migmatite preserved a lot of structural

post-crystallisation structural events like folds and fractures in the areas.

The geomorphology of the area widely varies and can be categorised into two main hydro-geomorphic units, namely the high-lying and low-lying areas. The highlands are characterised by granitic hills, ridges and inselbergs that traversed the upper central section and extending from the north of Tapa to Idere, and small parts at the north-east and north-west regions of the study area. The elevations of some of the hills are above 200 m above the mean sea level. The ridges and inselbergs are granitic, and the texture is often porphyritic. However, major sections of the terrains underlain by migmatite are also highlands. The southern areas are largely lowlands and gently high rising landforms underlain by gneisses and amphibolite. The major floodplain in the

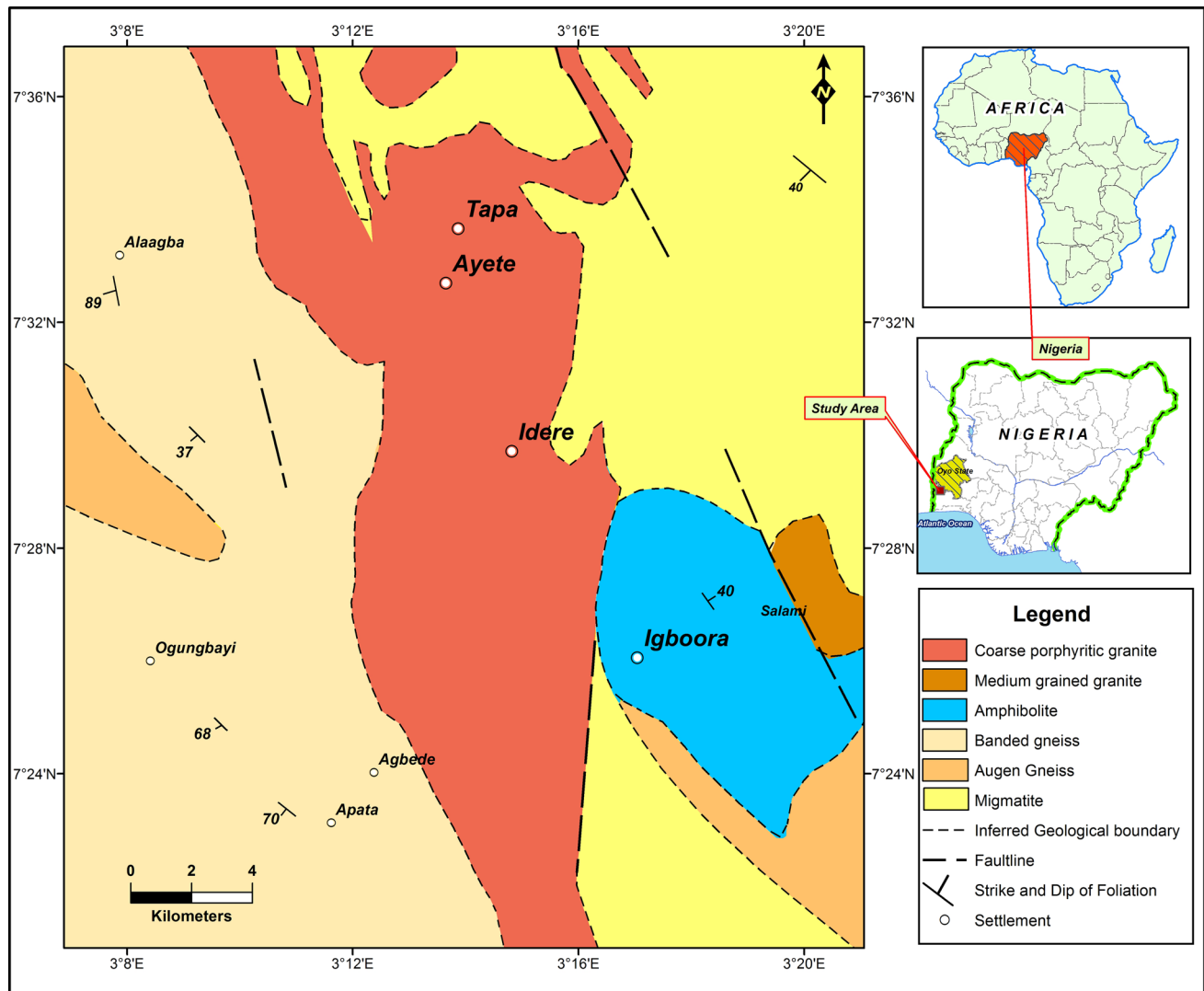


Fig. 2 Geological map of the study area (updated after Weerawarnakula 1986)

area is found at the south-west part underlain by banded gneiss.

The drainage pattern is dendritic as common in basement areas characterised by high contrast in relief. In a dendritic drainage pattern, tributary streams generally join at an acute angle forming Y-shaped junctions. The river network consists of primary rivers, namely Iworo, Ayin, Afo-Ape, Opeki and Aboluku sourced from the highlands terrain underlain by crystalline rocks. River Ofiki is the major river that drains the gneissic and granitic terrains, and it runs into River Ayin (secondary river) at the SW region. It is remarkable to note that the primary rivers in the area run along the rock boundaries and coincide with the major structural NNW–SSE and NNE–SSW trends development in the area. Other streams are intermittently

connected to the primary rivers forming in orthogonal and oblique manners. This drainage pattern is more or less a design that separates the entire study area into interfluvial regions.

Materials and methods

Existing topographical and geological maps of the study area were processed using ArcGIS 10.0. Conventional geological mappings were also conducted to update the existing map for accurate fixing of rock boundary and demarcating the area into various bedrock settings. A total of 82 geo-electric soundings, groundwater yield tests and taking

of well inventory data were conducted in 19 boreholes in a systematic approach across the various bedrock settings.

Geo-electrical surveys and groundwater prospect

The spread of the 82 electrical soundings across the study area included a total of 25 soundings within terrains underlain by amphibolite, 19 on gneisses, 18 on migmatite and 20 on porphyritic granite using Schlumberger electrode configuration. The apparent resistivity field data were acquired with Campus Omega resistivity meter, and the range of current electrode (AB) separation was between 200 and 266 m. This range of AB separation was considered appropriate for groundwater investigation in typical crystalline basement of Nigeria, where groundwater occurs at shallow depths (Offodile 2002). The systematic approach to VES surveys involved selective appropriation of suitable locations for sounding in order to cover the various bedrock settings and to avoid sounding close to outcropping rock exposures. For interpretation of VES data for hydrogeological characterisation, quantitative and qualitative methods of interpretation of the field apparent resistivity data were employed (Murali and Patangay 2006).

Quantitative methods

The VES quantitative interpretation method involved originating primary geo-electric parameters that included the layers' resistivities and thicknesses from partial curve matching and computer iteration techniques. This was done by plotting the apparent resistivities obtained from the field against half electrode spacing ($AB/2$) on a log–log chart. The plotted field curves were then matched with standard auxiliary curves of Orellana and Mooney (1966) to derive the initial layer resistivity and corresponding thickness for each geo-electric layer. These initial geo-electric parameters were used in modelling in Vander (1988) modelling package to generate the true resistivity and thickness that are the primary geo-electric parameters.

Qualitative methods

True layer's resistivities and corresponding thicknesses were employed for qualitative interpretation. This involved characterising the extent and the degree of rock decomposition from layers' thicknesses and lithologic description of the geo-electric layers, particularly the saprolite and the bedrock using the corresponding layers' resistivities. The saprolite is the weathered layer and one of the water-bearing zones in basement areas, characterised by high porosity, and when the bedrocks are not fractured the saprolite is the only alternative water-bearing zones in basement area. In this regard, successful groundwater prospect of the saprolite depends on its resistivity and its thickness and availability of regular source of recharge (Singhal and Gupta 1999). The range of resistivity for lithological characterisation and groundwater prospect of the saprolite is presented in Table 1. Groundwater prospect of saprolite is poor if the resistivity is between 1 and 60 Ωm for predominantly clayey lithology and when it is more resistive and greater than 400 Ωm for 'hardpan' or compacted lateritic clays. This is because clayey saprolite are characterised by low to negligible water transmission attributes. The prospect is adjudged moderate when the resistivity lies within the range 61–150 Ωm for less clayey and sandy soils and good when the saprolite is more sandy to gravelly and resistivity lies between 151 and 400 Ωm . However, sustainability of groundwater supply is guaranteed when the bedrock is fractured and there are good connections between the fractures and the weathered layer (Akanbi 2016). Hence, for bedrock, groundwater prospect is good when fractured and the resistivity is below 600 Ωm . The prospect is moderate when the bedrocks are partially or slightly weathered and the resistivity is between 601 and 1800 Ωm . Fresh bedrocks are marked with high resistivity in excess of 1800 Ωm and have little or no groundwater potential (Table 1).

Also, the variation in weathering with depth was established by contouring the apparent resistivities for depths corresponding to half of the current electrode distances ($AB/2$) of 10, 24, 42 and 75 m. Additionally, the true resistivities of the saprolite and the bedrock were equally contoured to interpret the groundwater prospect of the subsurface

Table 1 Range of resistivity for lithological characterisation and groundwater prospect of saprolite and bedrock Modified after Olorunfemi and Olorunniwo (1985), David (1988), and Akanbi (2017)

S/n	Resistivity range (Ωm)	Lithological description of the saprolite	Groundwater prospect of saprolite	Bedrock resistivity (Ωm)	Description of the bedrock	Groundwater prospect of bedrock
1	0–50 > 400	Predominantly clayey Compacted clay/hardpan	Poor	>1800	Fresh	Negligible
2	51–150	Sand and clay mixture	Moderate	601–1800	Weak/slightly weathered	Moderate
3	151–400	Predominantly sandy to gravelly	Good	< 600	Fractured	Good

environments. From the bedrock iso-resistivity map, local fracture zones that ensure continuity of groundwater prospecting in the underlying rocks were demarcated. Furthermore, aside the lithology of the saprolite units, the thickness of the saprolite is another crucial factor that is considered in groundwater prospecting of the weathered layer in basement terrain. Hence, qualitative method also involved generating the thickness map of the saprolite and the resistivity maps of both the bedrock and that of the former to classify groundwater prospect of the various bedrock terrains across the study area.

Likewise, qualitative interpretation included the estimation of the longitudinal conductance, which is one of the Dar-Zarrouk variables. The Dar-Zarrouk variables are secondary geo-electric parameters derived from true layer's resistivity and corresponding thickness. The background

concept for longitudinal conductance assumes that the earth is parallel with n layer and the flow of current through and across such sequence is controlled by individual layer's resistivity and its respective thicknesses. The longitudinal conductance of a geo-electric layer is the ratio of individual thickness and the corresponding resistivity. The unit of measurement is in mhos. However, for a geo-electric sequence with more than one layer, the total longitudinal conductance (S) is the summation of the ratios of individual layer's thickness and corresponding resistivity; that is for a geo-electric sequence with n th layers above the bedrock, $S = \sum hi/\rho_i$, where $i = 1$ st, 2nd, 3rd, ..., n th layer above the bedrock. S is crucial in relating the ratios of individual layer thickness to its lithology and is applicable for measuring aquifer vulnerability to surface environment contamination. Therefore, locations with thicker and more clayey

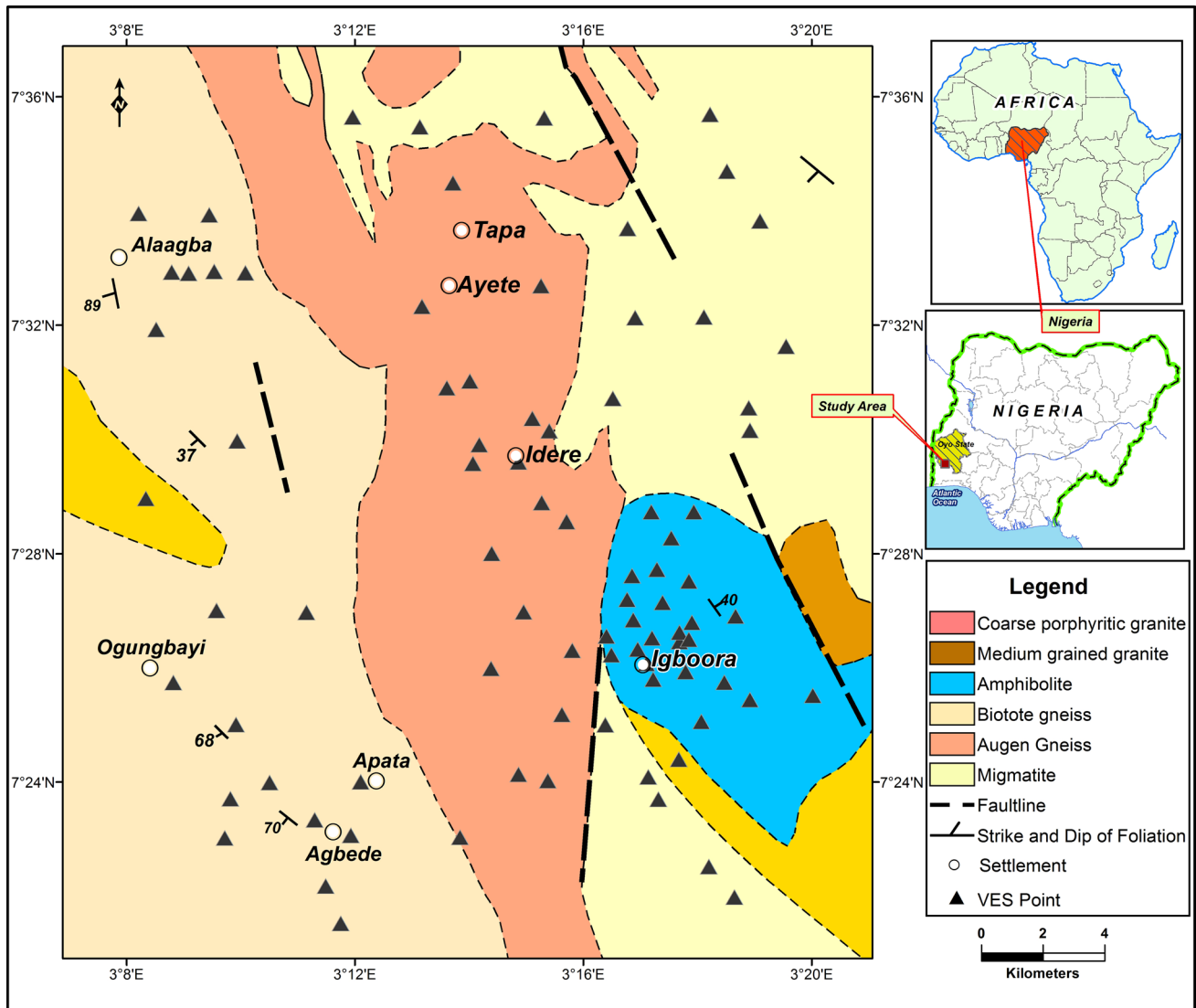


Fig. 3 Locations of VES points on geological map

weathered-regolith will be characterised by higher *S*, and consequently, higher protective capacity than areas with thinner and more sandy regolith. The spread of the VES points across the area is presented in Fig. 3.

Measurement of groundwater yield and well inventory

Taking of well inventory including well topography (WT), well depth (WD), groundwater table (GWT) and measurement of groundwater discharge (*Q*) was conducted on nineteen drilled wells that spread through the principal bed-rock terrains. The numerical distribution of the boreholes included five each in locations underlain by amphibolite, migmatite and gneissic bedrocks, and the last four on granitic terrain (Fig. 4).

Groundwater table and depth of each borehole were measured in metre in the field using automatic water level indicator. Groundwater discharge was carried out with half horse power submersible pump, and the yield was measured in m³/day using ISO 4064 DN20 water flow meter with accuracy of 0.1 l. The pipe was extended to nearby concrete surface water drains to expel the discharge water beyond the vicinity of the pumped well so as to avoid artificial recharge of the pumped well.

A portable etrex Garmin Global positioning System (GPS) was used to record the coordinates of all soundings and wells locations across the area. Elevations were measured relative to the mean sea level. These coordinates are geo-referenced and used for contouring of geo-electric parameters and siting of survey points in maps using Surfer 10 software. The generated maps were applicable

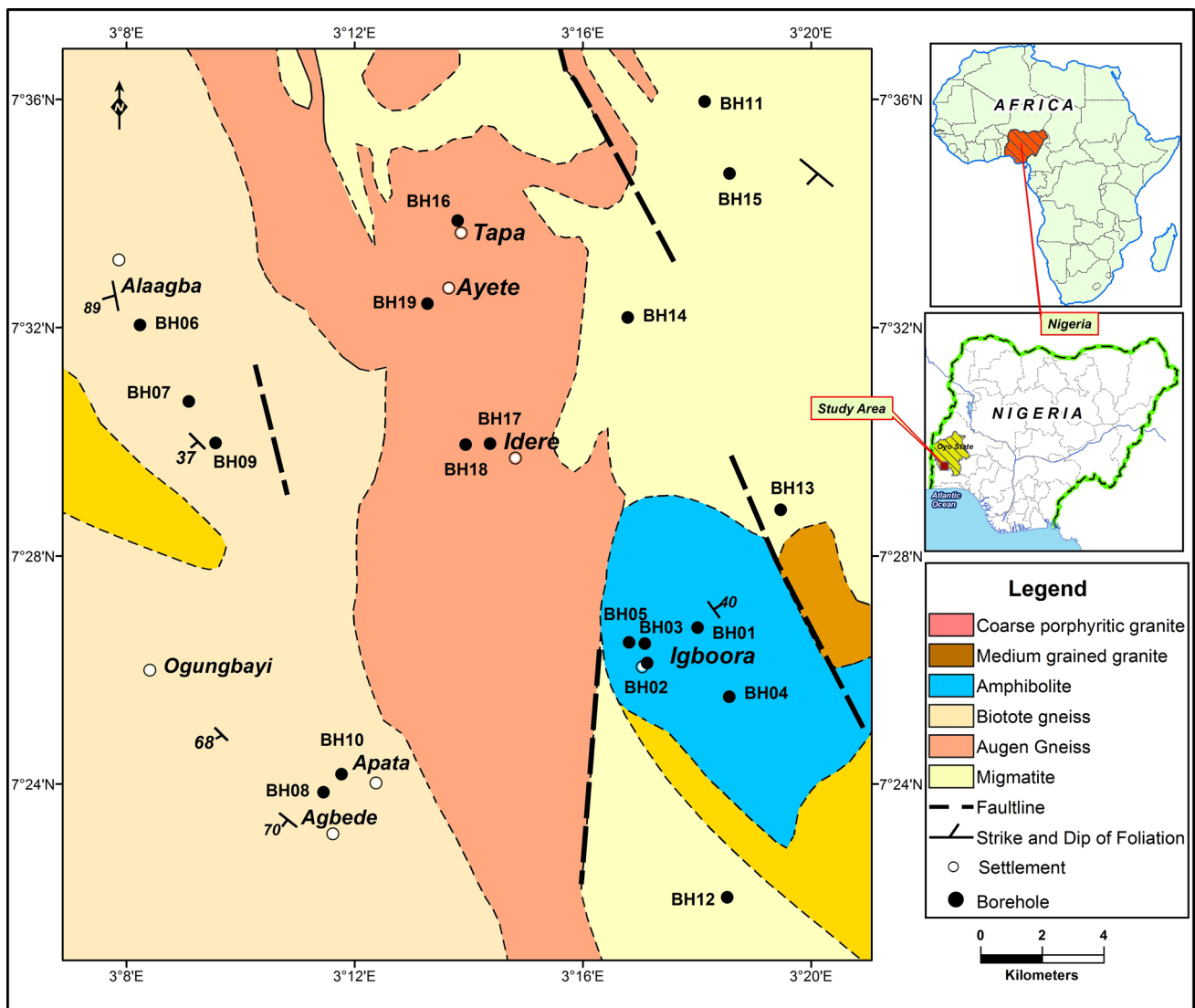


Fig. 4 Borehole locations on geological map

for visual descriptions of vertical and spatial variations of geo-parameters across the study area. Window 10 Excel software was used for statistical evaluation of data such as for estimation of mean and correlation analyses of variables.

Results and discussion

The geo-electric curves

The generated VES curves are dominantly 3-layer H type, characterised by relatively more conductive middle layer that terminates on more resistive infinite layer. Only seven curves that represented just 8.5% exceeded 3-layer geo-electric sequence, and this included four-layer KH-type curve that are four in number, one each of HK and HA sequence, and two 5-layer HKH VES curves.

Weathering characterisation

Iso-apparent resistivity map

The apparent iso-resistivity maps (Fig. 5a–d) revealed the weathering attributes at various depths corresponding to half AB separations of 10, 24, 42 and 75 m. These diagrams reflected weathering heterogeneities typified by increase in resistivity with depth. At corresponding depth of $AB/2$ separation of 10 m (Fig. 5a), highly to moderately weathered zones with resistivities below 300 Ωm are predominant and soil development is at the peak. Localised zones with $< 100 \Omega\text{m}$ are more dominant within amphibolite and terrains underlain by gneisses. At half AB separation of 24 m, there is reduction in area coverage of the highly weathered zones at the corresponding depth. This resulted in the thinning out of highly weathered lithology on areas underlain by gneisses and amphibolite, while the spatial coverage of moderately weathered lithology with resistivity 100–600 Ωm (Fig. 5b) expanded. At higher half AB separations of 42 m, poorly weathered and bedrock subsurface horizons with resistivity $> 600 \Omega\text{m}$ are conspicuously represented (Fig. 5c). Lastly, at $AB/2$ separations of 75 m, highly weathered zones have virtually disappeared and the weathering is poor, and bedrock horizon are now becoming dominant (Fig. 5d). However, even at $AB/2 = 75$ m, large part of the study area is still categorised as being moderately weathered. This is an indication of a fairly deep weathering development with resistivities 100–600 Ωm across the study area.

General profile of weathering and bedrock fracturing

Apart from fractures, the regolith thickness and its lithological attributes are crucial to groundwater occurrence. The summary of the primary geo-electric parameters is presented in Table 2. The general weathering profile in the study area irrespective of bedrock type is mainly three (3)-layered sequence, namely the topsoil, the saprolite and the bedrock. The resistivity of the topsoil varies, ranging from as low as 38.4 Ωm in amphibolite to as high as 4478.2 Ωm at Alaraba underlain by gneissic bedrock. The mean value of 658.5 Ωm obtained over amphibolite is typically lower as compared to the range of 1152–1344 Ωm as average values for other bedrocks. Topsoil is commonly made up of alluvium particles, characterised by wide resistivity variations as a result of land use pattern. The thickness of the top soil is however an important factor when considering contamination through direct groundwater recharge. The thickness of the top soil exceeded 2.0 m only in 20 locations, and this is more frequent in areas underlain by amphibolite and porphyritic granite. Nonetheless, on the average, the thickness of the top soil is generally less than two metres for all the bedrocks (Fig. 6).

The iso-resistivity and isopach (thickness) map of the saprolite layer are presented in Fig. 7a, b, respectively. The general spread of the resistivity of the saprolite across the study area was between 9.1 and 1903 Ωm (Table 2). The minimum resistivity obtained for the bedrocks is lowest in amphibolite with 9.1 Ωm and highest in migmatite with 28.1 Ωm . The range of the maximum resistivity is 225.2–810.6 Ωm . The mean value of the resistivity of the saprolite is also lowest in areas underlain by amphibolite with 53.1 Ωm , while average resistivities for areas underlain by other bedrocks are higher with 93, 118 and 204 Ωm in porphyritic granite, gneisses and migmatite, respectively. Based on the most widespread resistivity range of 61–150 Ωm (Fig. 7a and Table 2), the saprolite is dominated by composite of sand and clay across the area. Occasionally, there is occurrence of compacted lateritic clay layer, otherwise known as ‘hardpan’ associated with very high resistivity that ranged between 433.7 and 4412.9.

The thickness of the saprolite ranges from 3.80 to 38.70 m at an average (av.) of 16.56 m, 4.40–57.70 m (av. 15.83 m), 3.40–22.40 m (av. 11.31 m) and 1.80–19.40 m (av. 9.52 m) correspondingly on amphibolite, gneisses, migmatite and porphyritic granite bedrocks. On the average, areas underlain by gneisses and amphibolite are characterised by deeper weathered layer. The total regolith thicknesses were correspondingly 18.49 and 18.23, compared to 12.77 and 11.29 for migmatite and granitic terrains, respectively (Table 2). The most widespread thickness from the isopach map (Fig. 7b) is within the range of 7–17 m. However,

Fig. 5 Indication of weathering development at corresponding depths to half AB separations of **a** 10 m, **b** 24 m, **c** 42 m, and **d** 75 m

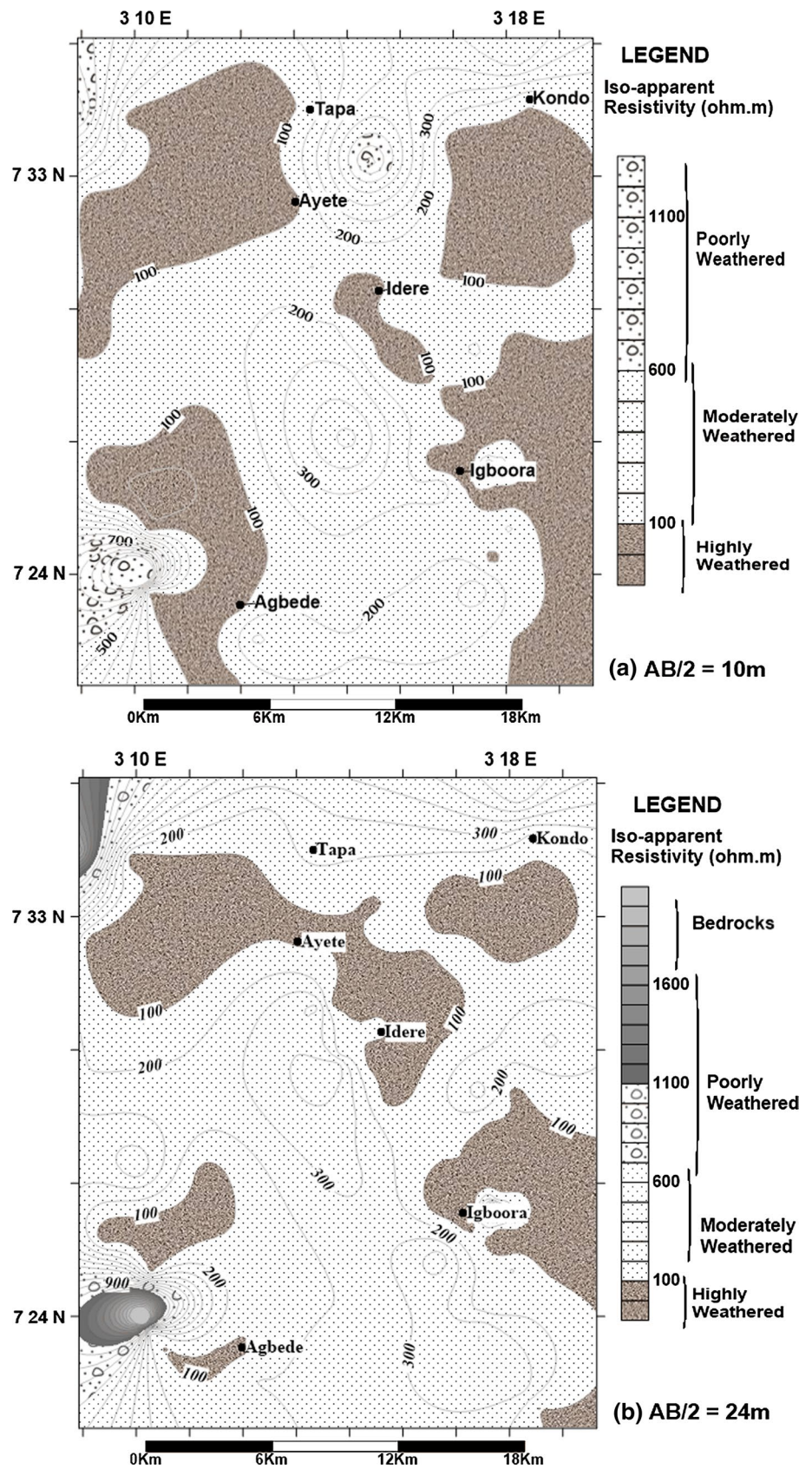


Fig. 5 (continued)

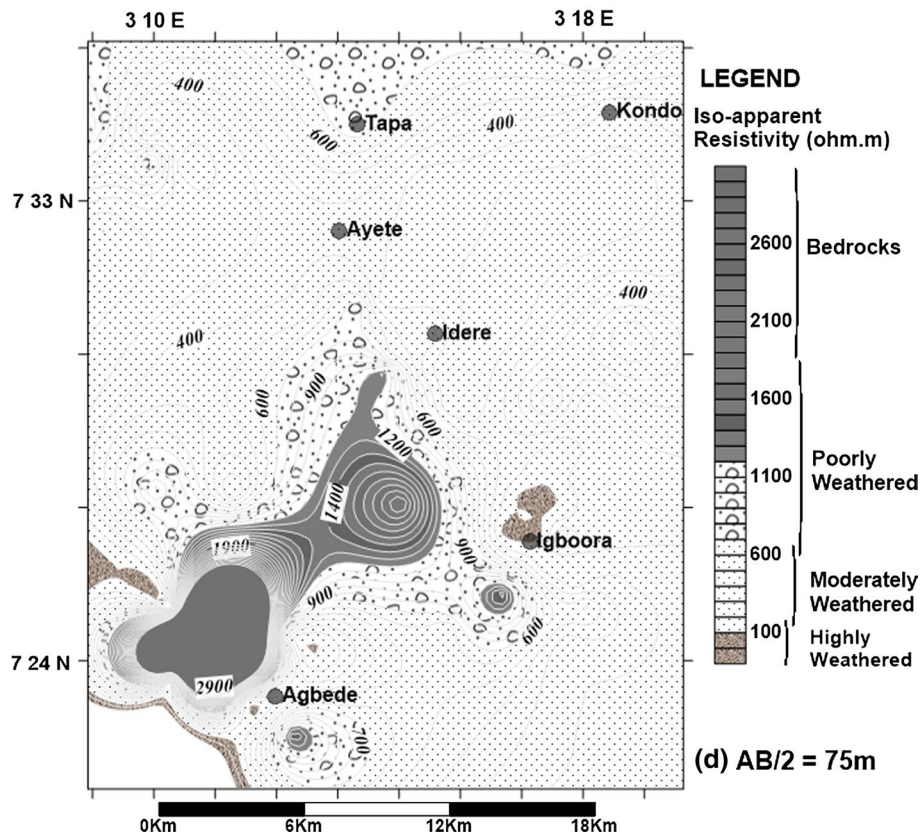
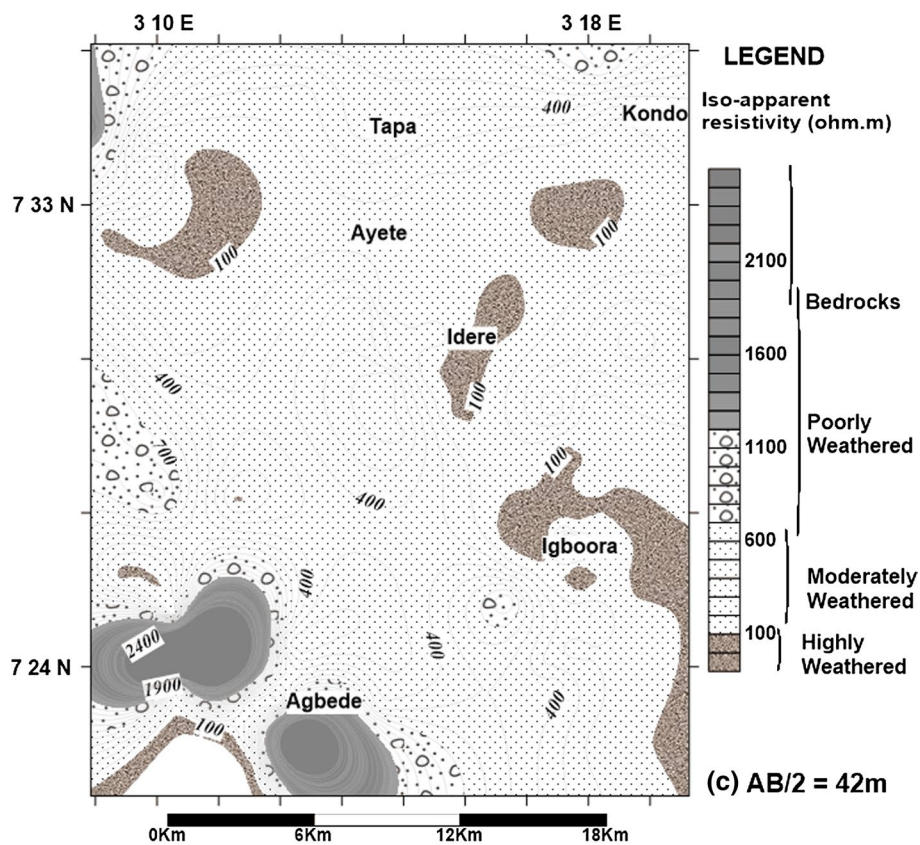


Table 2 Statistics of the geo-electric parameters by bedrocks

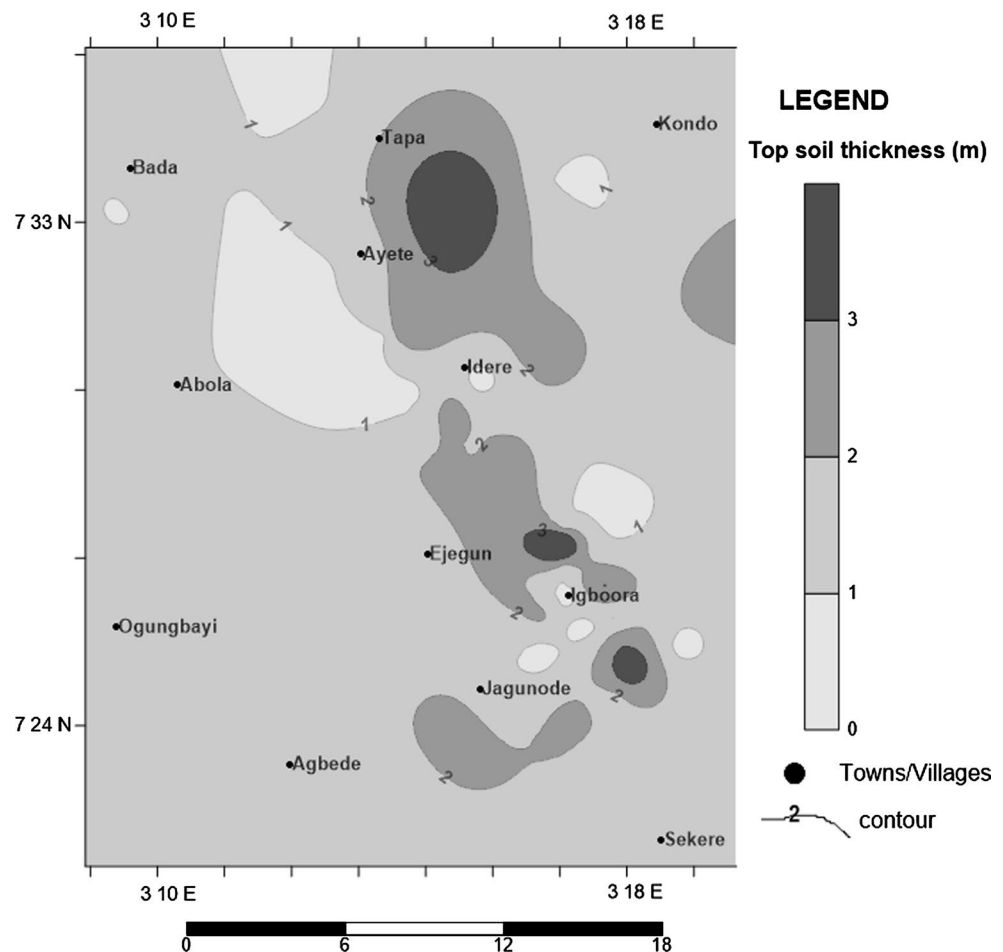
Geo-electric parameters	Explanation	Min	Max	Mean	Median
Amphibolite ($n = 25$)					
ρ_1 (Ωm)	Resistivity of the topsoil	38.40	3478.00	658.47	407.60
ρ_2 (Ωm)	Resistivity of saprolite layer	9.10	225.20	53.10	36.35
ρ_3 (Ωm)	Resistivity of bedrock	105.70	5472.70	1515.59	927.00
h_1 (m)	Thickness of top soil	0.40	5.80	1.68	1.45
h_2 (m)	Thickness of saprolite layer	3.80	38.70	16.56	16.00
H (m)	Total regolith thickness	4.40	39.40	18.06	17.20
S (mhos)	Total longitudinal conductance	0.02	1.42	0.45	0.40
Gneisses ($n = 19$)					
ρ_1 (Ωm)	Resistivity of the topsoil	176.90	4478.20	1343.59	984.30
ρ_2 (Ωm)	Resistivity of saprolite layer	18.80	810.60	117.95	69.00
ρ_3 (Ωm)	Resistivity of bedrock	196.60	9601.40	1814.92	934.50
h_1 (m)	Thickness of top soil	0.80	2.30	1.51	1.40
h_2 (m)	Thickness of saprolite layer	4.40	57.70	15.83	12.50
H (m)	Total regolith thickness	6.30	59.00	18.49	16.60
S (mhos)	Total longitudinal conductance	0.01	1.06	0.28	0.20
Migmatite ($n = 18$)					
ρ_1 (Ωm)	Resistivity of the topsoil	237.20	2331.10	1194.21	965.70
ρ_2 (Ωm)	Resistivity of saprolite layer	28.10	565.50	204.39	61.00
ρ_3 (Ωm)	Resistivity of bedrock	191.30	6863.30	1488.25	989.15
h_1 (m)	Thickness of top soil	0.50	2.80	1.56	1.40
h_2 (m)	Thickness of saprolite layer	3.40	22.40	11.31	11.85
H (m)	Total regolith thickness	4.60	23.60	12.77	12.95
S (mhos)	Total longitudinal conductance	0.02	0.60	0.23	0.18
Porphyritic granite ($n = 20$)					
ρ_1 (Ωm)	Resistivity of the topsoil	110.50	3271.90	1151.57	995.40
ρ_2 (Ωm)	Resistivity of saprolite layer	26.50	294.00	93.03	65.55
ρ_3 (Ωm)	Resistivity of bedrock	547.20	29,903.80	4601.23	2605.35
h_1 (m)	Thickness of top soil	0.60	4.50	1.76	1.25
h_2 (m)	Thickness of saprolite layer	1.80	19.40	9.52	8.30
H (m)	Total regolith thickness	2.40	20.80	11.29	10.65
S (mhos)	Total longitudinal conductance	0.05	0.38	0.15	0.12

localised deeper weathered zones with thickness exceeding 17 m are found on gneisses and to a lesser extent on amphibolite (Fig. 7b).

The bedrock iso-resistivity contour map is presented in Fig. 8 with resistivity range of 105–29,903 Ωm . Bedrock resistivity of < 600 Ωm are indicative of basement fractures and this occurred at 24 locations, out of which eleven were within amphibolite, five in gneissic, seven in migmatite terrains and only one location at Idere on porphyritic granite. The most promising fracture zones with < 600 Ωm bedrock resistivity are localised in areas underlain by banded gneiss at the NW and SW regions, and SE zone underlain by migmatite and amphibolite (Fig. 8). Porphyritic granitic terrains are characterised by higher resistivity at an average of 4601 Ωm . Bedrock fracturing is least within granitic terrains.

Exactly two-thirds of the bedrock fractures are restricted to the south-east part in areas close to rock contact zones around Sekere and Igboora. These fractures are also aligned along the same direction of NW–SE trend at which the rock contacts are aligned (Fig. 9). The depth to fractured zones varies and are found at 7.9–29.9 m (av. 18.3 m) below the earth surface on amphibolite terrains and at depth range of 16.6–27.3 m (av. 22.3 m) on gneisses. Fracture bedrocks were found at relatively shallower depths of 6.7–19.5 m (av. 13.6 m) on migmatite and 5.8 m on porphyritic granite at Idere.

Fig. 6 Topsoil thickness map across the study area



Total longitudinal conductance (S) and aquifer vulnerability

From Table 2, the total longitudinal conductance (in mhos) of the regolith ranged from 0.01 to 1.42 across the study area. The conductance is however relatively higher in terrains underlain by amphibolite and gneisses with corresponding values of 0.02–1.42 at an average of 0.45 (av. 0.45) and 0.01–1.06 (av. 0.28), compared to 0.02–0.60 (av. 0.23) in migmatite and 0.05–0.38 mhos (av. 0.15) for porphyritic granite. Aquifer is more vulnerable in areas with lower conductance, most especially within porphyritic granitic terrains and other adjoining areas with < 0.20 mhos (Fig. 10). The conductance in areas underlain by gneisses varies extensively, but large area lies within the low to moderate catchment. Locations with low vulnerability occur in three pockets/localised zones at the mid-north-west and south-west. However, the latter zone occupies more extensive area than the two localised portions at the north-west area. Nonetheless, the vulnerability is high for the regolith overlying Alagba area at the north-west zone. For areas underlain by migmatite, the vulnerability lies between moderate to high. For most terrains underlain by migmatite, S exceeds

0.20 mhos but the vulnerability is even higher at Jagunode and Sekere in the SE region (Fig. 10). Within amphibolite terrains, S largely exceeds 0.30 mhos and aquifers are less vulnerable to surface contamination.

Well inventory data and groundwater yield

The results of groundwater yield and well inventory data of the nineteen boreholes across the four principal bedrock terrains are presented in Table 3. Boreholes BH01 to BH05 were those on amphibolite terrains, while BH06 to BH10 on gneisses, BH11 to BH15 on migmatite and BH16 to BH19 penetrated porphyritic granite (Fig. 4). From the general statistics, borehole elevation was between 139 m and 215 m above mean sea level, while borehole depths were between 15.9 and 43 m. The depth to water table ranges from 1.5 to 14.5 m and groundwater yield was between 32.8 and 99.8 m³/day (Table 3), which was approximately 32,800–99,800 l/day.

However, to show the influence of bedrock on groundwater yield and on well inventory data, statistical summary of the parameters by bedrocks are presented in Table 4. The well depths range about 20–38 m on amphibolite, 31–43 m

Fig. 7 **a** Resistivity map of the study area. **b** Saprolite thickness map of the area

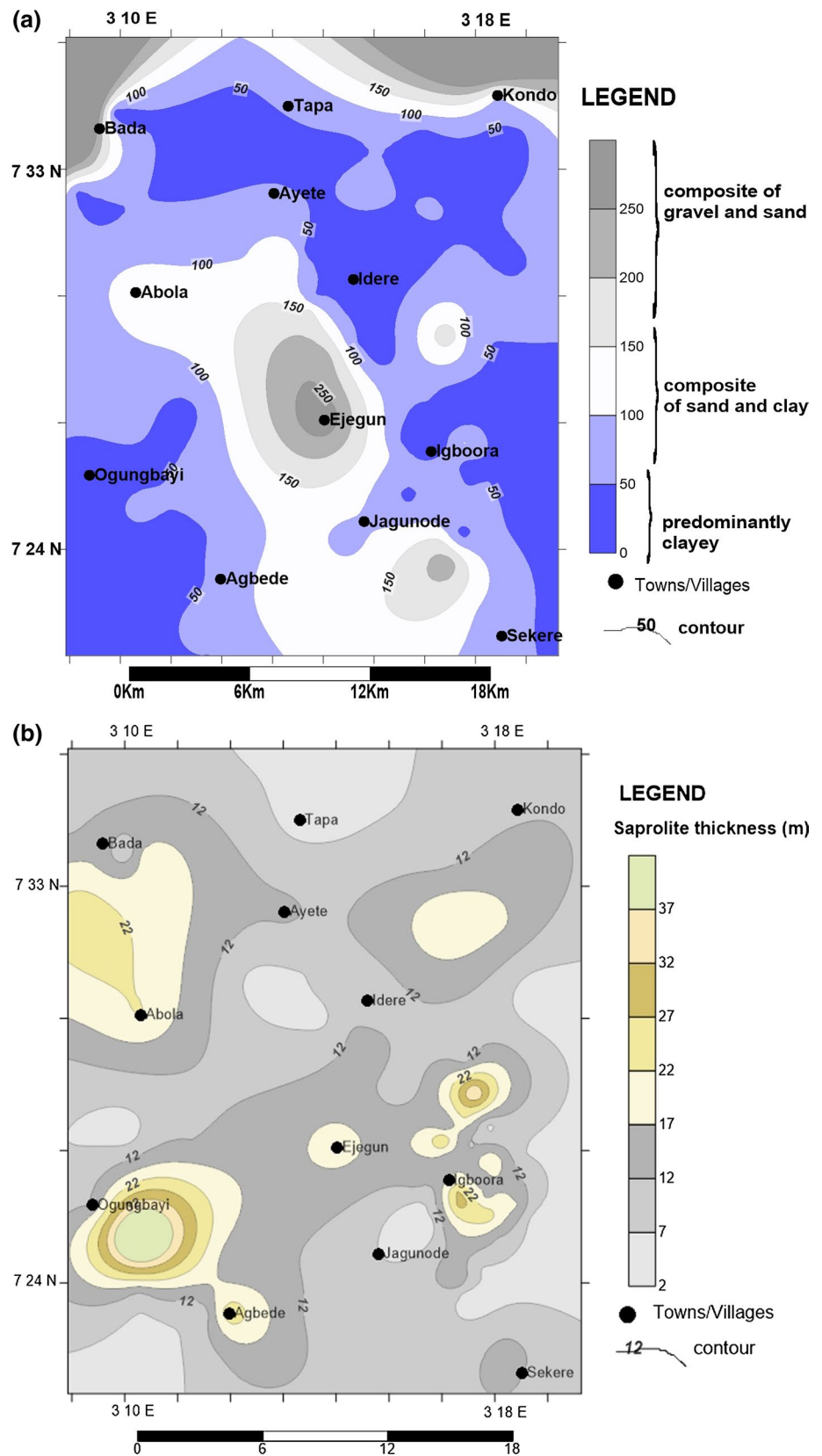
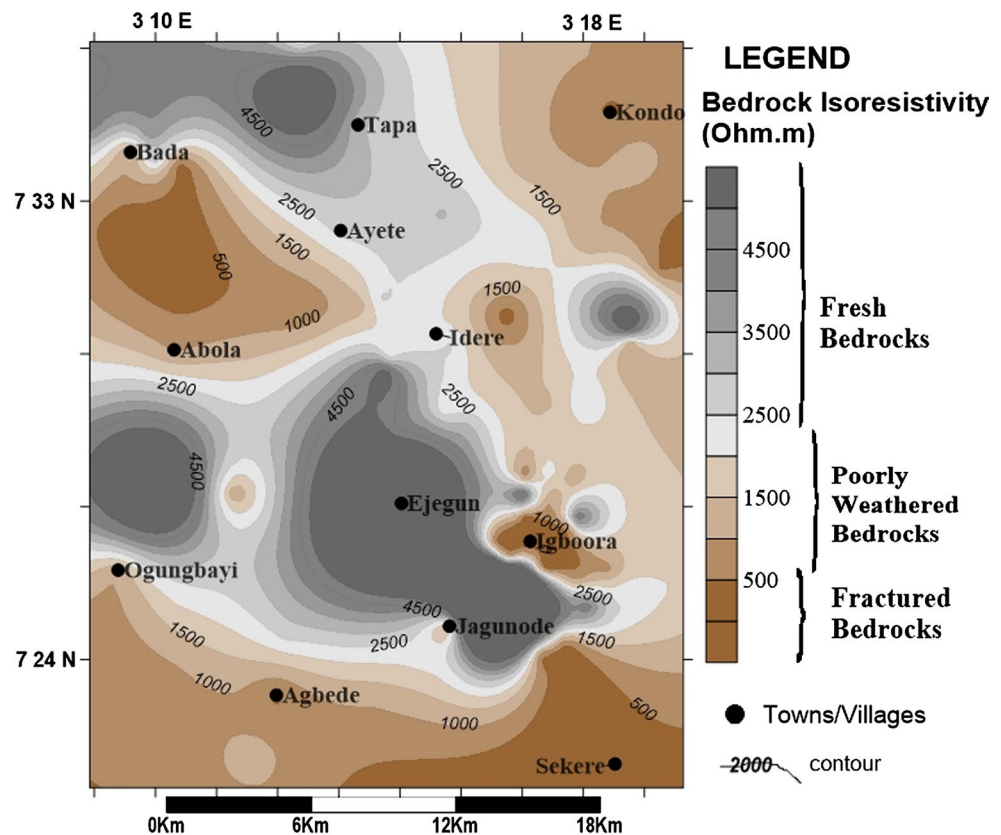


Fig. 8 Bedrock iso-resistivity map of the study area



on gneisses, and 18–36 m on migmatite and 16–37 m on porphyritic granite. Also, GWT occurred in the range 1.5–10.7, 4.2–14.5, 3.3–11.8 and 2.0–6.5 m, while Q in m^3/day was 56–93.6, 32.8–78.9, 41.9–99.8 and 56.8–91.1, respectively. Based on the average values, terrains underlain by gneisses were characterised by deeper wells with 36.1 m compared to those measured in other terrains with corresponding mean values of 29.3, 27.7 and 25.2 m for wells within amphibolite, migmatite and granite. Equally, GWTs are found at shallower average depths of 4.0–6.0 m within these bedrocks in comparison with those within gneisses with a mean of 8.2 m. On the other hand, groundwater yield, Q , was lowest in gneissic bedrock with $53.2 \text{ m}^3/\text{day}$, compared to the highest yield of $72.5 \text{ m}^3/\text{day}$ obtained within amphibolite terrains, and $69.0 \text{ m}^3/\text{day}$ and $68.3 \text{ m}^3/\text{day}$ correspondingly in wells that penetrated granitic and migmatite bedrocks.

Results of statistical correlation of well data and groundwater yield by bedrock affiliations are shown in Fig. 11. The coefficients of correlation, R , is strong and negative (i.e. $R < -0.5$) between groundwater yield (Q), well depth (WD) and groundwater table (GWT) in the bedrocks, except within migmatite, where $R = -0.04$ for Q/WD and -0.21 for Q/GWT and the relationships are insignificant and weak, respectively (Fig. 11a, b). This implies that deep wells do not guarantee high groundwater yield, particularly in aquifers within gneisses, amphibolite and granitic terrains. This is

collaborated by Q/GWT (Fig. 11b) relationships, whereby shallow groundwater table will guarantee high groundwater yield in amphibolite and gneisses terrains (where $R = -0.83$ and -0.50 , respectively) and to a lower extent within migmatite terrains where the relationship is weak ($R = -0.21$). However, within granitic terrains, the relationship between Q and GWT is positive and strong ($R = 0.52$). This showed that shallow groundwater table does not guarantee high groundwater yield within granitic terrains. On the other hand, the relationships between depth to water table and well depth are diverse across the bedrock terrains (Fig. 11c). It is strong and negative within granitic terrains ($R = -0.92$), moderate and negative in gneissic terrains ($R = -0.38$), strong and positive within migmatite ($R = 0.78$) and weak and amphibolite with $R = 0.29$. This indicated that deep wells are characterised by shallower water table in granitic and to a lesser extent within gneissic terrains. However, this relationship is direct in both migmatite and amphibolite aquifers, though the significance is lower within terrains underlain by the former bedrock.

For the relationships occurring between groundwater discharge, Q , and well topography, the associations are negative across the bedrocks, with the exception of granitic terrains. In respect to significance of relationships, it is fairly strong in amphibolite ($R = -0.50$), moderate in migmatite ($R = -0.39$) and weak in gneisses with $R = -0.21$ (Fig. 11d). However, the relationship is very strong and positive in granitic terrain

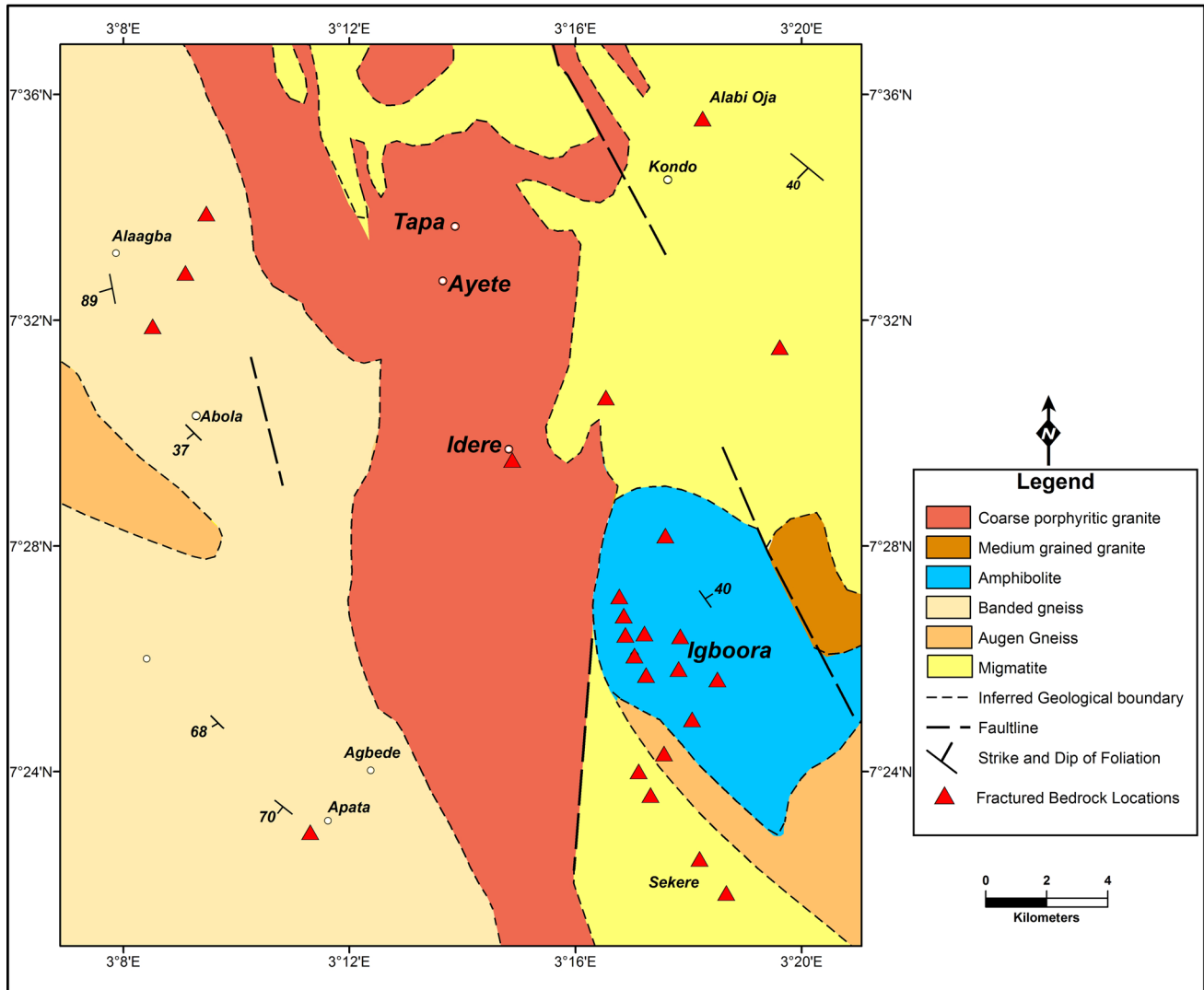


Fig. 9 Fractured bedrock locations on geological map of the study area

with $R=0.88$ (Fig. 11d). This implied that locations with high topography are characterised by high groundwater yield in granitic terrains, whereas the yield is low in elevated areas underlain by other bedrocks.

The study has shown that there is no viable significant relationship existing between well topography and well depths within terrains underlain by both gneisses and migmatite, whereas these associations are strong in amphibolite and granitic terrains. Nevertheless, it is indirect in granite with $R=-0.82$ and positive in amphibolite with $R=0.56$ (Fig. 11e). This means that the topography of the area is not a factor that

influences well depth within locations underlain by gneisses and migmatite. However, the relief of the area has a direct association with the depth of the wells in amphibolite and an indirect relationship in granitic terrains. Equally, there is no significant relationship between groundwater table and well topography also within gneisses and migmatite terrains, while the associations are perfect and negative in granitic terrains ($R=-0.95$) and positive and moderate within amphibolite with $R=0.43$ (Fig. 11f). The perfect negative relationship between these parameters in granitic terrains indicated that

Fig. 10 Aquifer vulnerability map of the area

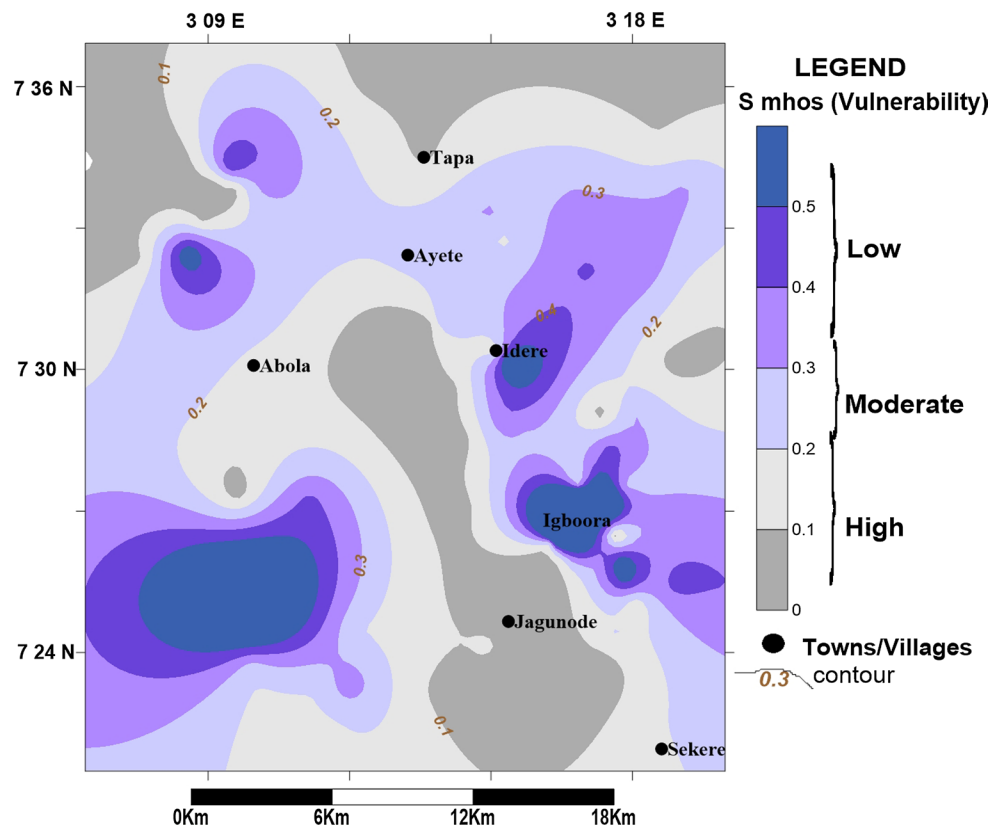


Table 3 Results of groundwater discharge and well inventory data

S/n	Borehole no.	WT (m)	WD (m)	GWT (m)	Q (m ³ /day)
1	BH01	172	27.7	10.7	56.0
2	BH02	187	31.6	6.4	73.2
3	BH03	170	38.0	5.0	71.7
4	BH04	175	30.4	3.2	67.9
5	BH05	159	18.9	1.5	93.6
6	BH06	174	43.0	4.2	40.4
7	BH07	169	30.9	6.7	75.9
8	BH08	143	34.6	6.4	78.9
9	BH09	171	34.1	14.5	32.8
10	BH10	139	38.0	9.4	37.9
11	BH11	188	26.4	3.3	41.9
12	BH12	142	29.1	7.1	77.0
13	BH13	182	29.7	4.2	99.8
14	BH14	188	17.8	3.5	69.5
15	BH15	199	35.6	11.8	53.2
16	BH16	155	36.5	2.1	57.7
17	BH17	215	20.3	5.3	91.1
18	BH18	209	15.9	6.5	70.4
19	BH19	141	28.0	2.0	56.8

terrain elevation has a very strong indirect influence on the groundwater table of aquifer zone.

Hydrogeological characterisation and groundwater prospects of the weathered–fractured aquifers by bedrock terrains

Amphibolite terrains

The total thickness of the regolith units of areas that were mainly underlain by amphibolite were between 4.40 and 39.40 m (av. 18.23 m). The middle layer (or the saprolite unit) alone has thickness range of 3.80–38.70 m at an average of 16.56 m. The saprolite units have an average resistivity value of 53.10 Ωm, and localised zones of high longitudinal conductance (*S*) occurred within amphibolite terrains (Fig. 10). The high *S* values obtained within amphibolite terrains also suggest that the degree and extent of rock weathering is high (Fig. 7). The development of fine-grained regolith is attributable to the high susceptibility of the amphibolite bedrock to weathering due to large composition of dark-coloured ferromagnesian minerals such as hornblende and biotite in the mineral assemblage (Akanbi, 2016). These minerals (i.e. ferromagnesian) are largely unstable at surface environment, since they crystallise at higher melting points. Additionally, the schistose textural attributes of Igboora amphibolite facilitates easy breakdown of rock by physical processes and rock mass decomposition by chemical processes. Hence, aside the fact that the weathering development is well pronounced in areas underlain by amphibolite,

Table 4 Statistical summary of geo-electric parameters and well inventory data by bedrocks

Bedrocks	Statistics	WT (m)	WD (m)	GWT (m)	Q (m ³ /day)
Amphibolite, <i>n</i> = 5	Minimum	159.0	18.9	1.5	56.0
	Maximum	187.0	38.0	10.7	93.6
	Mean	172.6	29.3	5.4	72.5
Gneisses, <i>n</i> = 5	Minimum	139.0	30.9	4.2	32.8
	Maximum	174.0	43.0	14.5	78.9
	Mean	159.2	36.1	8.2	53.2
Migmatite, <i>n</i> = 5	Minimum	142.0	17.8	3.3	41.9
	Maximum	199.0	35.6	11.8	99.8
	Mean	179.8	27.7	6.0	68.3
Por. granite, <i>n</i> = 4	Minimum	141.0	15.9	2.0	56.8
	Maximum	215.0	36.5	6.5	91.1
	Mean	180.0	25.2	4.0	69.0

this terrain also has the highest number of bedrock fractures compared to other terrains. Eleven (11) locations out of a total of 24 locations with $< 600 \Omega\text{m}$ bedrock resistivities are found within amphibolite terrains. This represented 46% of all fractured bedrock locations. Also, the relative percentage of fractured bedrocks occurrences to those that are unaltered is larger (Table 5, Figs. 9, 12). Furthermore, aside the fractured bedrocks, another 12% amphibolite bedrocks are partially weathered. The partially altered bedrocks are those that are slightly weathered and are also liable to having moderate groundwater prospect with resistivity range of 600–1800 Ωm . Generally, from the 25 soundings conducted within amphibolite terrains, the bedrocks of about 44% locations are fractured, 12% are regarded as weak or partially weathered while 44% bedrocks are unaltered (Fig. 12). Depths to fractured bedrocks are within 7.9–29.9 at an average of 18.3 m (Table 5). Also, fresh bedrock resistivity was less than 2500 Ωm , except at the southwestern section of Igboora where bedrock resistivities range between 4500 and 5500 Ωm .

The hydrogeological setting of terrains underlain by amphibolite, as described above, hereby supports generation of artesian aquifer. This is supported by very strong indirect relationship occurring between yield and groundwater table (Fig. 11b). This means that the water table occurs at shallow depth in more prolific wells at Igboora, which emphasised that the groundwater is under pressure and rises above the fractured bedrock aquifers. This is as a result of widespread occurrence of thick and largely fine-grained regolith overlying the main groundwater-bearing zones of fractured and weak amphibolitic bedrocks. Additionally, groundwater quality is expected to be fairly good as a result of the overlying fine-grained regolith that prevents direct groundwater recharge of the bedrock aquifers (Fig. 10). Furthermore, the occurrences of fractured bedrocks at relatively deeper zones at an average of 18.3 m will further enhance the protection of the enclosed groundwater resource in the area. Hence,

groundwater prospect within areas underlain by amphibolite is high and largely from the fractured zones. This is also supported by the higher yields that is $> 67 \text{ m}^3/\text{day}$ for most wells (Table 3) within amphibolite. However, from hydrological relationships, well elevation has a moderate and an indirect effect on groundwater yield, and higher groundwater yields are more associated with lowland areas (Fig. 11b, d).

Gneisses terrains

Just like terrains underlain by amphibolite, areas underlain by gneisses are also characterised by occurrence of thick regolith units of 6.30–59.00 m with an average thickness of 18.49 m. The thickness of the saprolite was between 4.40 and 57.70 m and average of 15.83 m (Table 2). Localised zones of deeper weathering also exist at the NW area and at the SW floodplain regions where saprolite thickness exceeds 22.0 m (Fig. 7b). Possible factors that may favour the development of thick regolith in areas underlain by gneisses are mineralogical content and foliation features of the gneisses.

The resistivity of the saprolite ranged extensively from 18.80 to 810.60 Ωm . Based on the average regolith resistivity of 117.95 Ωm , the regolith units are coarser compared to amphibolite terrains. The total longitudinal conductance ranges from 0.01 to 1.06 with an average of 0.28 mhos (Table 2). This is markedly lower than those obtained in amphibolite (0.45 mhos), which means that the aquifer vulnerability in gneisses is relatively higher compared to those in amphibolite terrain. Accordingly, the potential for water infiltration through the regolith, inferred from the total longitudinal conductance, is better in gneiss terrains than in amphibolite. Notwithstanding, bedrock resistivities of only five out of nineteen (19) locations were fractured (Table 5, Fig. 12). However, the percentage of occurrences of partially weathered basement was 48% and quite enormous (Fig. 12), and with this, the degree of rock decomposition can also be said to be equally high. Bedrock fractures occurred at

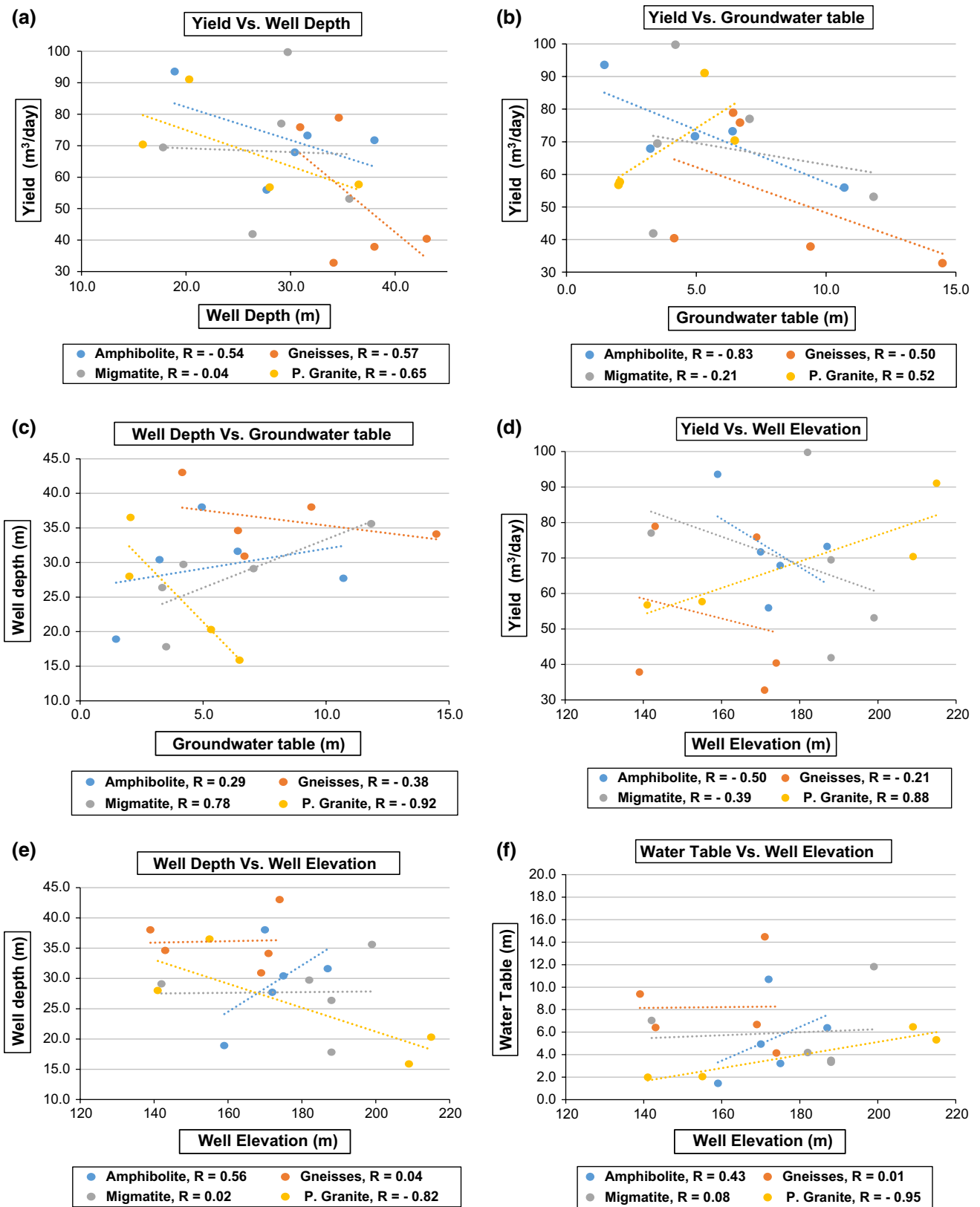


Fig. 11 a Plot of groundwater yield against well depth. b Plot of groundwater yield against water table. c Plot of well depth against groundwater table. d Plot of groundwater yield against well elevation.

e Plot of well depth against well depth. f Plot of groundwater table against well elevation

Table 5 Frequency and depths of occurrence of fractured bedrocks

S/n	Rock units	Total no of VES points	Frequency and relative percentage of occurrences of fractured bedrock in each bedrock <i>n</i> (%)	Depth of occurrence (m)		
				Min	Max	Mean
1	Amphibolite	25	11 (44%)	7.9	29.9	18.3
2	Gneisses	19	5 (26%)	16.6	27.3	22.5
3	Migmatite	18	7 (39%)	6.7	19.5	13.7
4	Porphyritic granite	20	1 (5%)	–	–	–

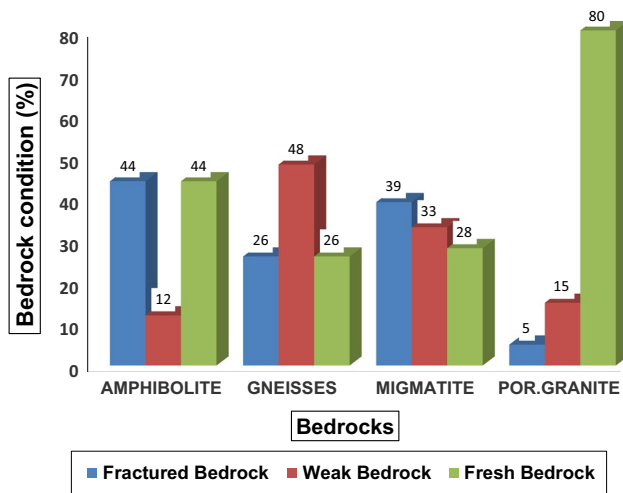


Fig. 12 Comparative percentage frequencies of bedrock conditions

the depth of 16.6–27.3 m (av. 22.5 m). This is comparatively deeper than other bedrocks (Table 5). Nonetheless, areas underlain by gneisses are expected to have better water transmission ability owing to the thick and the fairly coarser regolith. Additionally, the foliation structures in gneisses will also serve as subsurface water conduits apart from aiding rock weathering.

The hydrogeological setting in gneissic terrains will generate a semi-confined aquifer system due to occurrence of coarser regolith that is overlying the largely partially altered bedrocks. The thick weathered units will serve as both water-bearing zone and a semi-confining unit to the largely partially weathered bedrocks that are expected to have good water-bearing capacity. Water quality may be poor in these terrains when tapped from the regolith, whereas water from wells that tap into the relatively deeper fractured bedrocks at an average depth of 22.5 m will be safer. Well topography in gneisses has little effect on the groundwater yield, whereas well depth has moderate indirect significance on yield, and deep wells do not support high groundwater yield (Fig. 11a).

Migmatite terrains

The thickness of regolith development in areas underlain by migmatite is shallower when compared with terrains underlain by amphibolite and gneisses. The thickness of the regolith was 4.60–23.6 m and average 12.77 m, while that of the saprolite was 3.40–22.40 at an average of 11.31 m. The resistivity of the regolith was 28.10–565.50 Ωm with mean value of 204.39 Ωm. Based on the mean resistivity of 204.39 Ωm, the regolith units are sandy and coarser. Hence, migmatite terrains are characterised by lower longitudinal conductance of 0.02–0.60 (av. 0.23 mhos), compared to those within amphibolite and gneisses. Additionally, seven bedrocks out of eighteen were fractured (Table 5, Fig. 12). However, most of the fractured bedrock were found localised within the SE region and aligned in NW direction, while other fractured zones are widely spaced from one another. Notwithstanding, 33% of bedrock were classified as weak, which is higher than those found in porphyritic granite and even in amphibolite terrains (Fig. 12). However, the risk of groundwater contamination is higher in migmatite terrains than in gneisses and much higher in comparison with amphibolite terrains. From these results, groundwater occurrences in terrains underlain by migmatite exist in unconfined state, and the water table is exposed to atmospheric conditions. Additionally, as a result of occurrences of bedrock fractures at shallower depths of 6.7–19.5 m (av. 13.7 m) (Table 5) and the overlying coarse regolith, aquifer vulnerability to contamination is high to moderate in location will deeper and less coarse regolith. Also, well depth has little or no significant relationship with the groundwater yield, whereas there is a moderate and indirect relationship existing between the well discharge and the topography of the area (Fig. 11a, d).

Porphyritic granite terrains

Terrains underlain by porphyritic granite are the least weathered and the least fractured (Figs. 7, 8, 9, 12, and Table 5) across the study area. The overburden thickness was 2.4–20.8 m (11.3 m) compared to the averages of over 18 m in both amphibolite and gneisses and about 13 m in migmatite terrains. Also, the average thickness of the saprolite was just 9.5 m, whereas it was 16.6, 15.8 and 11.3 m

correspondingly in other bedrocks (Table 2). Weathering intensity was not only comparatively shallower in granitic terrains, but the weathered layer also terminates mainly on unaltered or fresh bedrocks. The porphyritic bedrock resistivity was 547–29,903 Ωm at an average of 4601 Ωm , while in other terrains, the averages were 1516, 1815, 1488 Ωm , respectively. Additionally, bedrock of just one location is fractured, and this is at Idere, and the fractured zone occurs at shallow depth of 5.8 m (Table 5, Fig. 9). The bedrocks of just three locations can be said to be slightly weathered, and the rest (that is 80%) are fresh basement (Fig. 12). Therefore, fresh granitic bedrock occurs at shallow depth. However, areas with fairly thick regolith > 10 m are found in areas close to rock contact zones at Idere and other few locations. Notwithstanding, the average S for regolith within the granitic bedrock terrains was 0.15 mhos. This is much lower in comparison with 0.45, 0.28 and 0.23 mhos as the average total longitudinal conductance correspondingly for the regolith layer within other bedrock terrains.

Generally, due to the shallow extent of rock weathering, aquifers are unconfined and occur at shallower depths compared to those within other bedrock terrains. Also, the average yield of 69 m^3/day , which is good, may not be sustainable for longer period. This is as a result of the fact that the underlying granitic bedrocks are typically impermeable and are found at shallow depths. Thereby, the only water-bearing zone is the overlying regolith in granitic terrain, and as a consequence, the groundwater system is exposed to seasonal fluctuations as well as pollution from surface environment. Therefore, the aquifer vulnerability is high (Fig. 10). Additionally, deep wells would not guarantee high yield in granitic terrains as revealed by the strong indirect relationship that existed between groundwater yields and well depths (Fig. 11a). However, area topography has a very strong positive influence on the groundwater yield and highlands areas are characterised by higher yield than lowland areas unlike other bedrocks terrains (Fig. 11d).

The summary of hydrogeological attributes under each bedrock terrain is highlighted in Table 6.

Groundwater prospect is good in areas underlain by amphibolite mainly due to high frequency of bedrock

fractures (Fig. 9). Aquifers within this terrain are characterised by higher yields of 56.0–93.6 m^3/day (av. 72.5 m^3/day). This is despite poor groundwater prospect of the thick and largely fine-grained overlying weathered-regolith. This showed that fractured bedrocks are able to provide better groundwater yield more than the overlying weathered-regolith that is underlain by impermeable crystalline bedrocks.

For areas underlain by gneisses, though, weathering was more intensive, and the recorded yield of 32.8–78.9 m^3/day (av. 53.2 m^3/day) was the lowest in all bedrock setting in the area. This is as a result of fewer developments of bedrock fractures in comparison with those within amphibolite and migmatite regions. Apart from this, the few fractured zones were isolated and not closely packed as in the other two terrains (Fig. 9). Also, the vulnerability of the weathered layer, which is the alternative water-bearing zone is low to moderate (Fig. 10); hence, groundwater occurrence within gneissic terrains is modest. However, groundwater yield of 75.9 m^3/day was obtained in well BH07 in a location close to Alagba where prominent fractures are found. Within migmatite terrain, groundwater yield is higher with 41.9–99.8 (av. 68.3) m^3/day , compared to those in gneisses (i.e. av. 53.2 m^3/day). The more prolific yield in migmatite is attributable to localised higher occurrences of bedrock fractures. This is supported by the groundwater yield > 70 m^3/day that was obtained in wells BH12 and BH13 located within rock contact zones characterised by numerous fractures that are closely spaced (Figs. 4, 9). This also showed that rock contacts promote bedrock fractures, and wells sited within these subsurface discontinuities are most likely to be more productive than those within any typical bedrock terrains.

The granitic aquifers have the second highest yield of 56.8–91.1 (av. 69.0) m^3/day after those of amphibolite. The high yields were from the two wells at Idere, i.e. BH17 and BH18 with yields of 91.1 and 70.4 m^3/day , respectively. The other two wells further north at Ayete and Tapa were characterised by lower yield that is < 60 m^3/day . High groundwater yield at Idere is attributable to topographic effect (Fig. 11d) and nearness to fracture and rock contact zones (Fig. 9). The elevations of wells at Idere are

Table 6 Summary of hydrogeological characterisations of bedrock terrains at Ibarapa region

S/n	Bedrock	Extent and degree of weathering	Predominant saprolite lithology	Bedrock conditions	Aquifer vulnerability	Groundwater yield	Groundwater prospect
1	Amphibolite	High	Clayey	Fractured to unaltered	Low	High	Good
2	Gneisses	High	Sandy and clay	Slightly altered	Low to moderate	Low	Fair
3	Migmatite	Fair	Sandy	Fractured to partly altered	High to moderate	Fairly high	Moderate
4	Porphyritic granite	Low	Sands and clay	Mainly unaltered	High	High at elevated terrains	Fair

both > 200 m, whereas the wells' elevations at Tapa and Ayete are < 160 m (Table 3). Conversely, the possibilities of siting bedrock aquifers are rare on granitic terrain due to paucity of fractures. Nonetheless, from the good yield of the mainly regolith aquifers at elevated granitic terrains, the groundwater prospect is fair. However, the yield will be more sustainable, if there is a source of regular recharge of the groundwater system. Therefore, the sustainability of the weathered-regolith aquifers in granitic areas to a large extent depends on the climatic conditions. Also, the likelihood of contamination of groundwater from surface effluent is high in granitic terrains, since the aquifer system is mainly the saprolite. In addition to this, because weathering is less developed, impermeable granitic bedrock is found at shallow depth and aquifer vulnerability is quite high.

Conclusion

Hydrogeological characterisation of the basement aquifers and their prospects have been investigated from geo-electric studies, groundwater yield tests, and from well inventory data of existing boreholes across the various bedrock terrains.

The strong indirect relationship existing between groundwater discharge and well depth is an indication of shallow occurrence of the water-bearing zones in the basement terrain of Ibarapa region. Hence, for economic considerations, large-diameter shallow hand-dug wells are suitable for sustainable groundwater yield in this region. This is more so in communities such as Ayete, Tapa and Idere with their environs, where the underlying granitic bedrocks are mainly unaltered (fresh) and are found at shallow depths. However, for more sustainability and better groundwater yields, deeper (drilled) wells can be incorporated in areas where the bedrocks are largely fractured and occurred at reasonable depths below the earth surface. This is the scenario in areas underlain by amphibolite at Igboora Township. Also, rock contact zones around Sekere community underlain by migmatite at the south-east and locations within Alagba underlain by banded gneiss within the north-west are local zones with good groundwater prospect within the broad bedrock terrains. Generally, in this region of study, fractured bedrocks are more dominant along zones of rock contacts on migmatite and amphibolite terrains at the south-east region while other fractures are widely spaced across the former and gneissic terrains. Granitic terrains are less fractured, and groundwater yield is better where bedrock fractures, particularly within high topographic areas underlain by granite. For other areas, lowland aquifers are more prolific in respect of groundwater yield. This hydrogeological complexity

demands for a systematic siting of wells for future groundwater development in the area.

Lastly, variance in the intensity of weathering, discrepancies in bedrock fractures, irregularity in area topography and well depth have profound effects on the prospect for groundwater in the area. Methodical siting of wells in line with the present findings will ensure better and more sustainable groundwater yield across the study area. This will also limit the impact of hydrogeological complexity brought about by geological and other natural factors that are beyond human regulations.

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