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Geophysical Characterization of the Basement Rocks and Groundwater Potential Zones Using Electrical Resistivity Sounding Technique

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Abstract
This study characterizes the basement rocks and delineates groundwater potential zones in a basement complex terrain of Adeyemi College of Education, Ondo, Southwestern Nigeria due to its erratic and complex nature of groundwater development. Vertical Electrical Sounding (VES) technique adopting Schlumberger configuration was used to acquire the apparent resistivity data using a resistivity meter. Ten VES stations were established with 100 m spread for half-current electrode spacing. The data were subjected to partial curve matching and computer based iterative interpretations. The generated sounding curves revealed heterogeneous nature of the subsurface geological sequence; topsoil (132-467 Ωm), sandy clay (101-370 Ωm), lateritic clay (347-1133 Ωm), weathered layer (128-750 Ωm), fractured basement (554-5045 Ωm) and fresh basement (14244-24744 Ωm). The results delineated weathered and fractured basements as the aquifer units for the study area. The composite thicknesses of the aquifers were used to characterize the subsurface into high and low groundwater potential zones. VESs 2, 6, 7, 8, 9 and 10 revealed adequate overburden thicknesses (26.5-58.7 m) for groundwater storage, and they were recommended for groundwater exploitation. VESs 3 and 5 revealed low thicknesses (7.1-19.3 m) of the aquifer units, and were regarded as low groundwater potential zones. VESs 1 and 4 revealed fresh basement with thin overburden thicknesses (13.3-10.3 m) and no evidence of fractured and groundwater bearing zones. This study generally revealed high groundwater prospects, and efforts to sink boreholes had been abortive in the past due to lack of adequate knowledge as regards the heterogeneous nature of the subsurface.
Keywords: Basement complex, Heterogeneous nature, Vertical Electrical Sounding, Apparent resistivity, Overburden thickness, Groundwater potential

1. Introduction

Groundwater occurrence in the basement complex terrains such as Ondo could be very irregular due to abrupt discontinuity in lithology, overburden thickness and their electrical properties, and weathered and fractured basements (Badmus & Olatinsu, 2010; Olorunfemi & Fasuyi, 1993; Offodile, 1983; Satpathy & Kanungo, 1976). Groundwater is the water that is held within the subsurface under hydrostatic pressure below the aquifer. Groundwater in sedimentary terrain is less difficult to exploit, while to locate groundwater in basement complex terrains are more challenging (Abdullahi *et al.*, 2015; Fadele *et al.*, 2013; Nwankwo, 2011; K'Orowe *et al.*, 2011). Consequently, an elaborate groundwater exploration scheme within basement region requires appropriate geophysical techniques to effectively characterize the hydro-geologic zones and identify the yielding aquifer units. Efforts to sink boreholes proved abortive most times in basement terrains due to lack of adequate knowledge as regards the heterogeneous nature of the subsurface and groundwater development schemes. Often, drillers find it difficult to hit the aquifers.

Electrical resistivity method involving Schlumberger sounding technique has been widely employed over the years in basement rock characterizations and groundwater investigations (Abdullahi *et al.*, 2015; Badmus & Olatinsu, 2010; Atakpo & Akpoborie, 2008; Olorunfemi *et al.*, 1999; McNeil, 1990; Van Overmeeren, 1989; Zohdy *et al.*, 1974) due to its better depth interpretations. The technique indicates good electrical resistivity contrasts between the saturated and unsaturated zones (Nejad *et al.*, 2011), and it is responsive to water bearing fractured basements due to relatively high electrical conductivities (Asfahani, 2007; Bauer *et al.*, 2006; Corwin & Lesch, 2005; Owen *et al.*, 2005; Chandra *et al.*, 2004; Yoon and Park, 2001). Therefore, this method is found relevant, adequate and appropriate for these investigations. However, geophysical data interpretations could be highly ambiguous if clear correlations between the geophysical attributes observed in the survey, and the geologic and stratigraphic properties of the subsurface are not well studied (Ezomo & Akujieze, 2010).

In any environment, weathering is not uniform since there are numerous agents of weathering. The outcome of weathering most times results into heterogeneous nature and varied hydrological characteristics of the subsurface. The fresh basements are overlain by earth materials which had undergone different stages of weathering. Thus, groundwater availability in the aquifer is attributed to weathering in the overburden and basement surface. The materials in the overburden determine the quantity and quality of the groundwater in the aquifer. Basement weathering revealed the zones of disintegration which appear as region with low electrical resistivity anomalies compare to the surrounding massive basement rocks (K'Orowe *et al.*, 2011). Regions with deep weathered basements are refers to as the points of disintegration which are hydro-geological for groundwater aquifers (K'Orowe *et al.*, 2011). The yearly increases in student's population in Adeyemi College of Education, Ondo forms the main thrust for this investigation. The surface water is inadequate to cater for the needs of staffs and students of this institution. A good number of unproductive boreholes had been sunk in recent time, and in order to avoid further occurrences, a Vertical Electrical Sounding technique had been used to characterize the basement rocks and delineate appropriate aquifer units with a view to produce a blueprint for sitting high yield borehole locations within the institution.

2. The Study Area

The study area is located within Adeyemi College of Education, Ondo, Ondo State Southwestern Nigeria (Fig. 1). It is bounded within latitude N7º 04' 05.10'' and N7º 04' 50.88'', and longitudes E4º 49' 10.21'' and E4º 49' 50.15''. The institution is located to the right of Ondo-Ore road and was established in 1963. Ondo town lies within the basement complex of Southwestern Nigeria (Fig. 2). The topography is very gentle, with surface elevations ranging from 216-242 m above sea level. The town cuts across some rock units such as migmatite, granite-gneiss, quartz-schist and quartzite, porphyritic granite, and charnockite. The basement terrain which comprises igneous and metamorphic basement complex can be found in the central, South-western and South-eastern parts of the country with cretaceous rocks partitioning them into zones. The basement complex of Southwestern Nigeria predominantly composed of Migmatite and Granitic gnesiss; Quartzite; slightly Migmatised to unmagmatised metasedimentary Schist and metaigneous rocks; Charnockitic; Gabbroic and Diorite; and the members of the older Granite suite mainly Granites, Granodiorites and Syenites (Akintorinwa *et al.*, 2010; Obaje, 2009; Rahaman, 1976).

Ondo belongs to rain forest zone characterized by short dry season and a long wet season, with mean annual rainfall ranges between 1270 and 1524 mm, while the mean temperature varies between 27 ºC and 31 ºC with relatively high humidity (Iloeje, 1981). The drainage patterns of the rivers that surround the study area are shown in Fig. 3. The aquifer units in the area and other similar basement complex environments are believed to be derived essentially from the weathered and fractured rocks (Abdullahi *et al.*, 2015; Badmus & Olatinsu, 2010; Bala & Onugba, 2001; Olayinka & Oyedele, 2001; Ademilua & Olorunfemi, 2000). As also observed in this study, the weathered profile developed above the fractured and fresh bedrocks had been documented to comprise of topsoil layer, the saprolite (the product of the in situ chemical weathering of the bedrock, such as sandy clay and lateritic clay) and weathered basement.

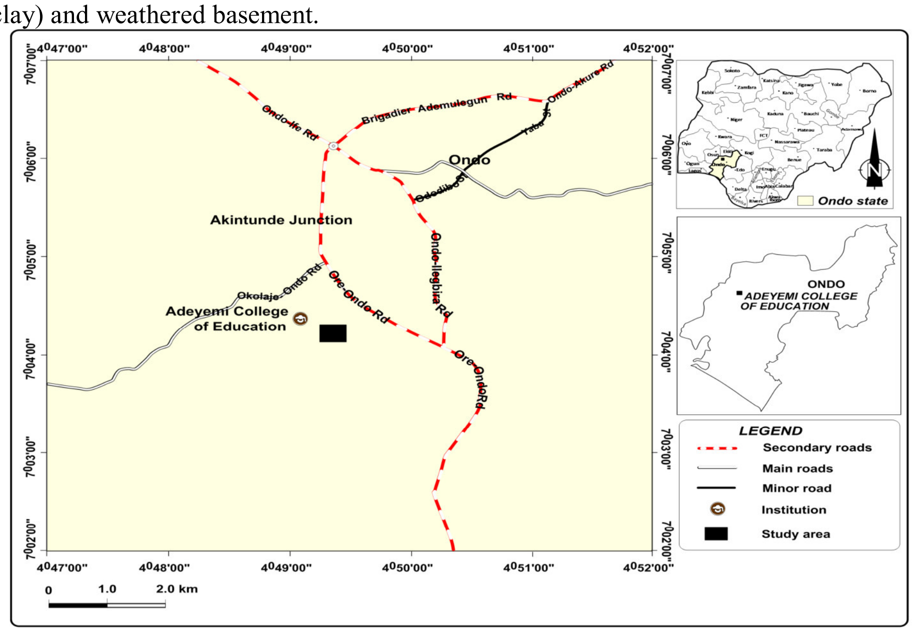

Figure 1: Location map showing the location and access roads to the study area

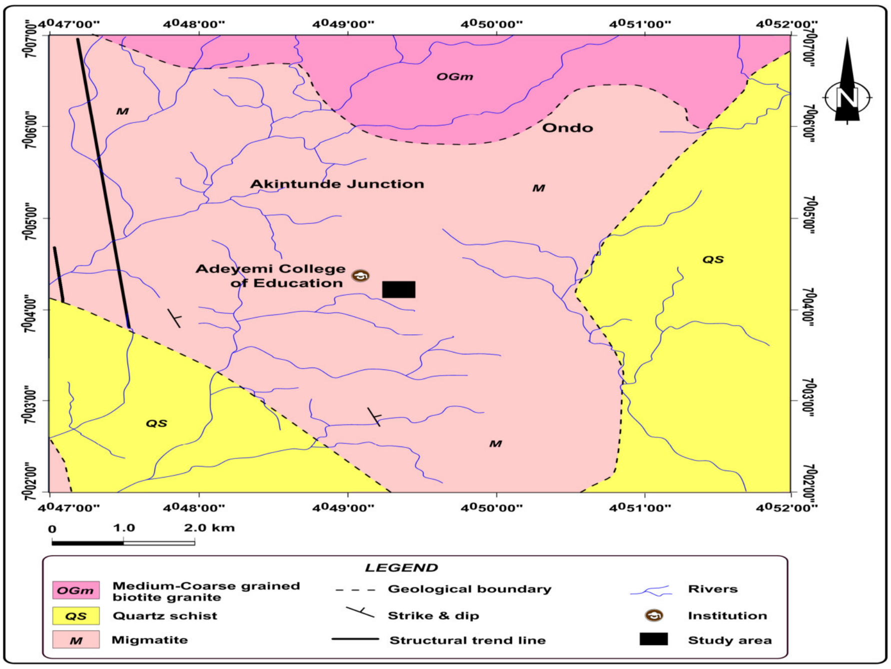

Figure 2: Geological Map of Ondo State showing the study area

3. Methodology

In this study, Vertical Electrical Sounding (VES) using Schlumberger array electrode configuration was engaged by applying current into the ground through two electrodes and then measuring the resultant potential difference across the potential electrodes. Increasing deeper measurements to obtain the information about the stratification of the subsurface were achieved by using wider current electrodes separations (Akintorinwa & Abiola, 2012). The Schlumberger field data were taken in overlapped segments because at each step of current electrodes spacing, the signals of the resistivity meter become weaker. Therefore, potential electrodes spacing was enlarged and two values for the same current electrodes spacing were measured, one for the short and the other for the long potential electrodes spacing. The apparent resistivity values were obtained from the products of the measured resistance and geometric factor. VESs were performed continuously by repeating the Schlumberger configurations with the entire setup moved one step to the side, and the resistivity values along a section were measured (Ojo, 2015; Lowrie, 2011).

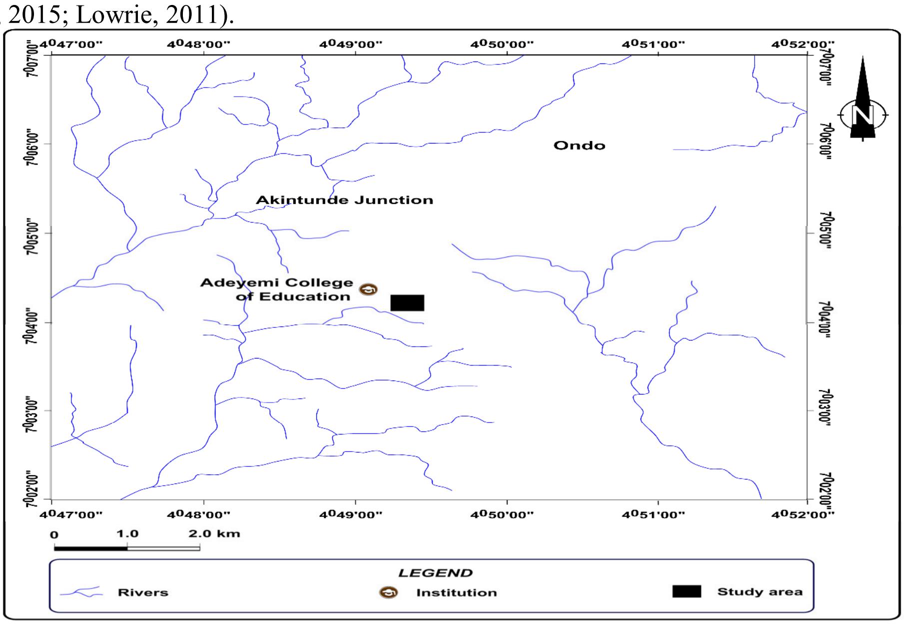

Figure 3: Drainage map showing the drainage pattern of the rivers that surround the study area

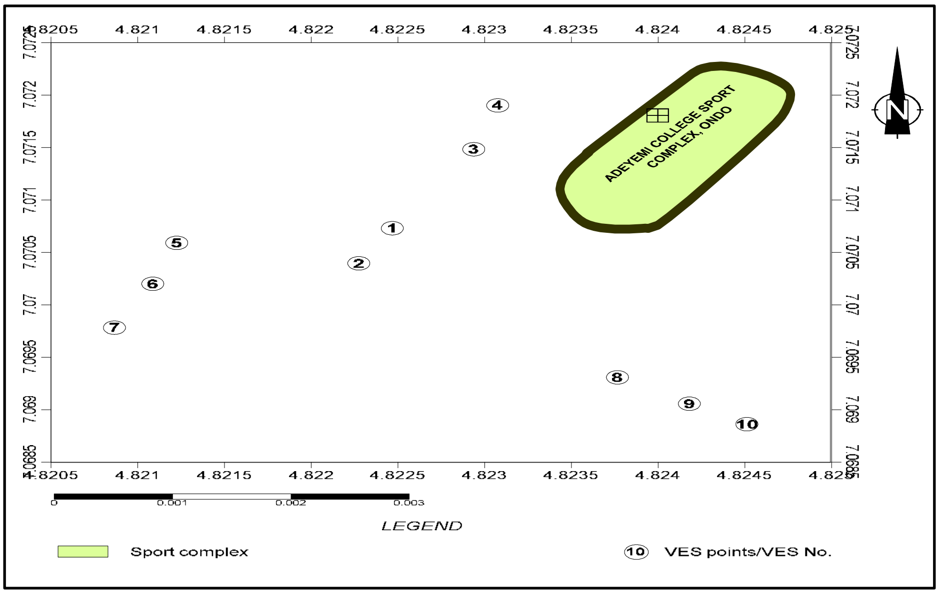

Figure 4: VES Data Acquisition Map

The apparent resistivity data were acquired using Omega resistivity meter and its accessories. The choice of this equipment was based on the fact that it has the capacity to transmit signals to deep depths of the subsurface. The current variation used was in the range of 3-5 A, which is found suitable for sounding surveys in the basement terrain. A total of ten VES point data were acquired (Fig. 4) with 100 m spread for current electrode spacing (AB/2). The coordinates of each station were recorded with their respective elevation above sea levels using Global Positioning System. The apparent resistivity values obtained were plotted against the half-current spacing by subjecting the data to manual interpretation using master curves (Koefeod, 1979; Orellana & Mooney, 1966) and auxiliary point charts (Zohdy *et al.*, 1965; 1974) to determine the earth layers with their resistivity values and thicknesses. To further refine the results obtained from the manual interpretations, computer based iterative interpretations were carried out using WinResist, version 1 (Velpen, 1988). Sounding curves were generated and were carefully interpreted by the trends of the curves to obtain geo-electric parameters needed for the study.

4. Results and Discussion

The geoelectric investigations were presented as sounding curves (Figs. 5-14), and the curves analyses were based on both quantitative and qualitative approaches. The qualitative approach revealed a minimum of three and maximum of five geoelectric layers which were generally identified as topsoil, clayey sand, lateritic clay, weathered layer, fractured basement and fresh basement. The curve types obtained in the sounding curves over a horizontally stratified earth surface were H, AA, KH, HKH and HAA; they were characteristics of a basement complex terrain. The curve type KH occurred frequently in this study and revealed large weathered layer and steady increase in apparent resistivity with depth as the current electrodes distance increased.

Tables 1 and 2 summarizes the geoelectric parameters obtained in the sounding curves. The quantitative analysis revealed three profiles (Figs. 15-17) of geoelectric sections along the VES stations; Profile 1 (VESs 1, 2, 3 and 4) revealed the lithology to depths above 30 m in NNE-SSW direction; Profile 2 (VESs 5, 6 and 7) was in the same direction as profile 1 and indicated geological sequence in the subsurface to depths above 40 m; and Profile 3 (VESs 8, 9 and 10) in NW-SE direction showed the subsurface layers to depths above 50 m. Profile 1 (Fig. 15) revealed clayey sand just beneath the topsoil in VES 3 followed by lateritic clay and weathered regions to depths less than 10 m. VES 2 also revealed a similar lithology as VES 3 with lateritic clay to depths below 20 m, followed by weathered basement to a depth of 30 m. VESs 3 and 2 indicated fractured basements at depths beyond 10 and 30 m respectively, and they could be regarded as water bearing zones with overburden thicknesses 7.1 and 29.9 m respectively. VESs 1 and 4 showed weathered basement beneath the topsoil followed by fresh basement with no evidence of fractured zones, and these stations could not be regarded as water bearing zones.

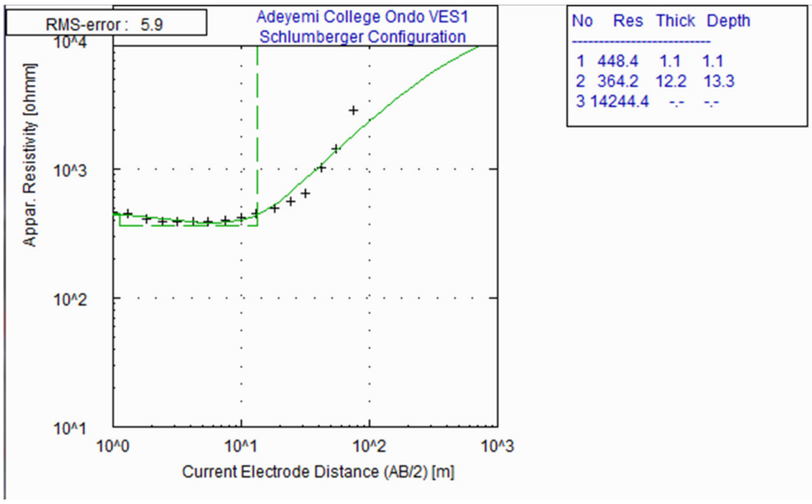

Figure 5: VES 1 Sounding Curve

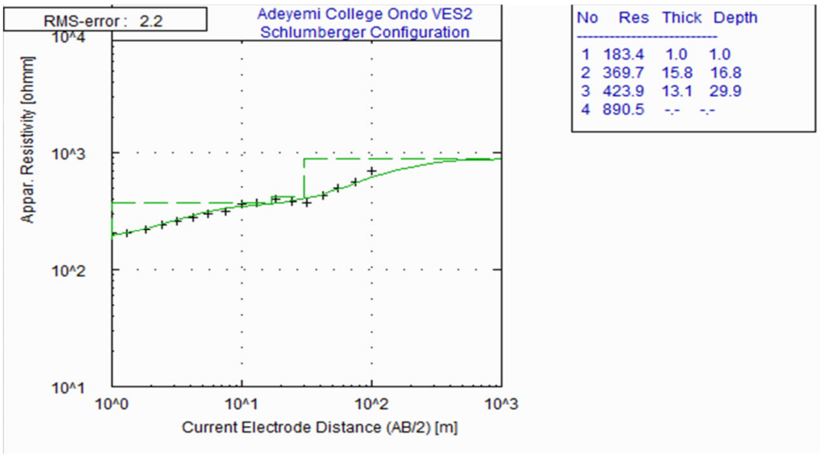

Figure 6: VES 2 Sounding Curve

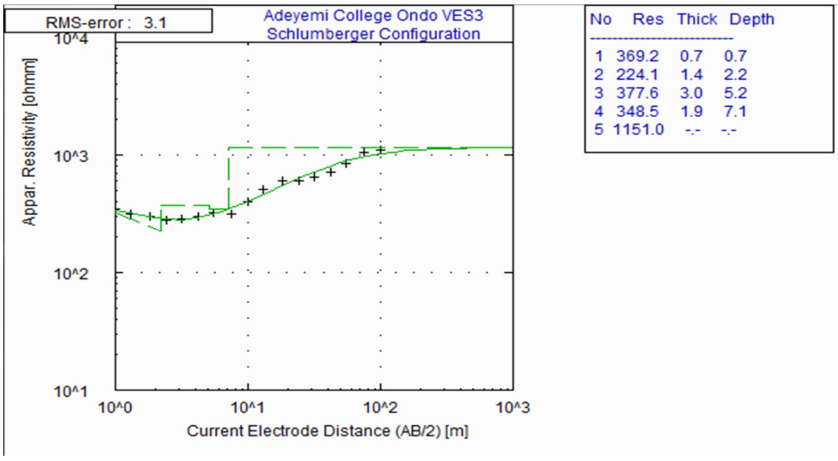

Figure 7: VES 3 Sounding Curve

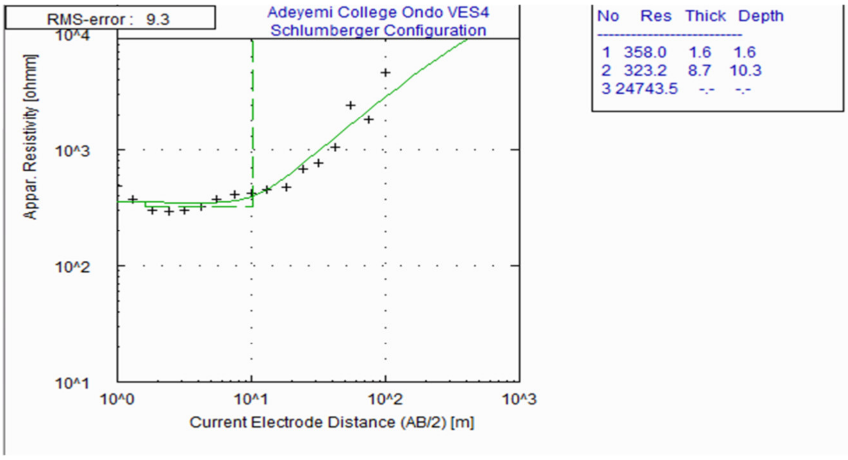

Figure 8: VES 4 Sounding Curve

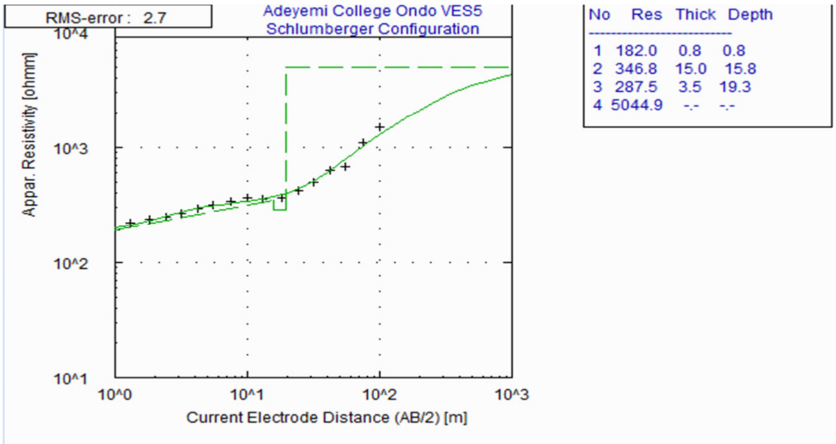

Figure 9: VES 5 Sounding Curve

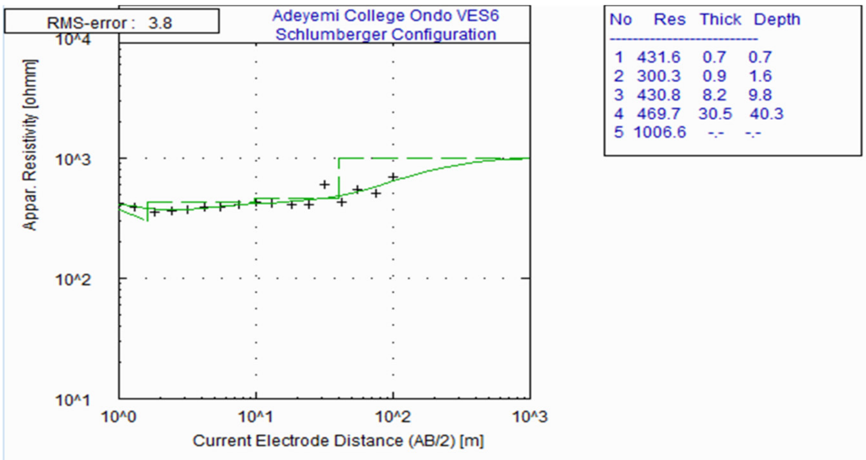

Figure 10: VES 6 Sounding Curve

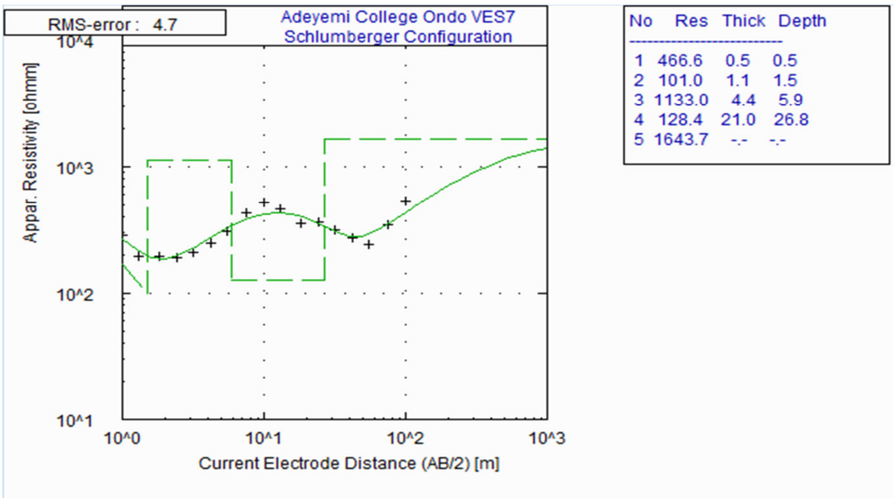

Figure 11: VES 7 Sounding Curve

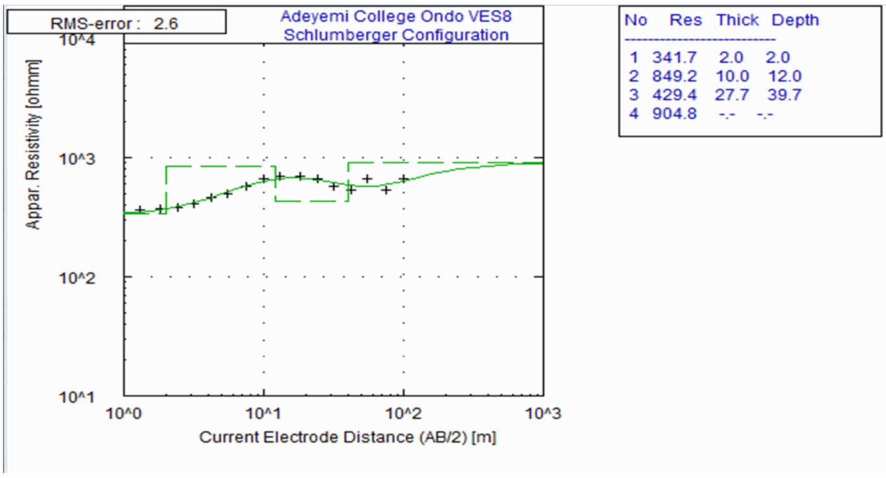

Figure 12: VES 8 Sounding Curve

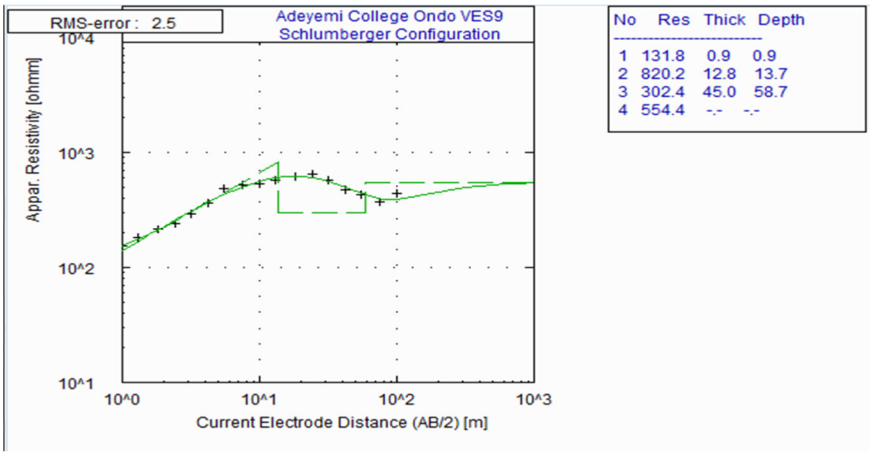

Figure 13: VES 9 Sounding Curve

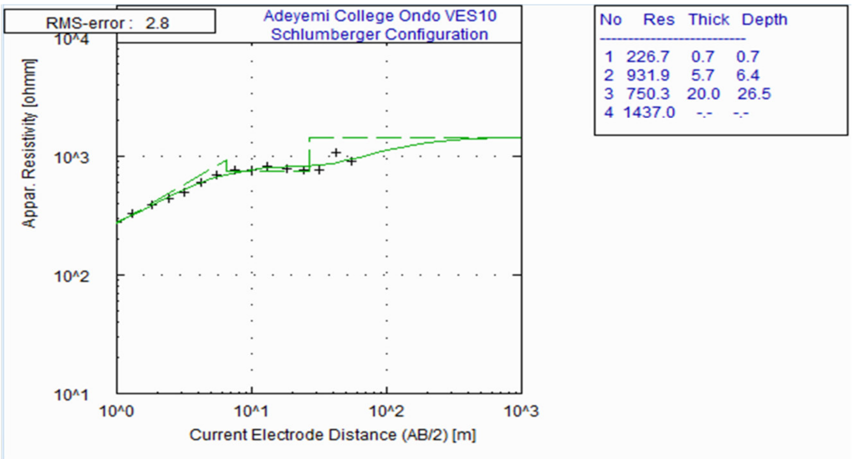

Figure 14: VES 10 Sounding Curve

Table 1: Summary of the geoelectric parameters obtained in the sounding curves for VES 1-5

Station	Layers	Resistivity values (Ωm)	Thickness (m)	Depth (m)	Curve Types	Reflection Coefficient	Probable Lithology
VES 1	1 2 3	448 364 14244	1.1 12.2 -	1.1 13.3 -	H	0.95	Top soil Weathered basement Fresh basement
VES 2	1 2 3 4	183 370 424 891	1.0 15.8 13.1 -	1.0 16.8 29.9 -	AA	0.36	Top soil Clayey sand Weathered basement Fractured basement
VES 3	1 2 3 4 5	369 224 378 349 1151	0.7 1.4 3.0 1.9 -	0.7 2.2 5.2 7.1 -	HKH	0.53	Top soil Clayey sand Lateritic clay Weathered basement Fractured basement
VES 4	1 2 3	358 323 24744	1.6 8.7 -	1.6 10.3 -	H	0.97	Top soil Weathered basement Fresh basement
VES 5	1 2 3 4	182 347 288 5045	0.8 15.0 3.5 -	0.8 15.8 19.3 -	KH	0.89	Top soil Lateritic clay Weathered basement Partially fractured basement

Table 2: Summary of the geoelectric parameters obtained in the sounding curves for VES 6-10

Station	Layers	Resistivity values (Ωm)	Thickness (m)	Depth (m)	Curve Types	Reflection Coefficient	Probable Lithology
VES 6	1	432	0.7	0.7	HAA	0.36	Top soil
	2	300	0.9	1.6			Clayey sand
	3	431	8.2	9.8			Lateritic clay
	4	470	30.5	40.3			Weathered basement
	5	1007	-	-			Fractured basement
VES 7	1	467	0.5	0.5	HKH	0.85	Top soil
	2	101	1.1	1.5			Sandy clay
	3	1133	4.4	5.9			Lateritic clay
	4	128	21.0	26.8			Weathered basement(Clayey)
	5	1644	-	-			Partially fractured basement
VES 8	1	342	2.0	2.0	KH	0.36	Top soil
	2	849	10.0	12.0			Lateritic clay
	3	429	27.7	39.7			Weathered basement
	4	905	-	-			Fractured basement
VES 9	1	132	0.9	0.9	KH	0.29	Top soil
	2	820	12.8	13.7			Lateritic clay
	3	302	45.0	58.7			Weathered basement
	4	554	-	-			Fractured basement
VES 10	1	227	0.7	0.9	KH	0.31	Top soil
	2	932	5.7	6.4			Lateritic clay
	3	750	20.0	26.5			Weathered basement
	4	1437	-	-			Fractured basement

Profile 2 (Fig. 16) revealed thin layers of topsoil and sandy clay with thickness of less than 2 m. The lateritic clay underlies the topsoil with thickness ranging from 5.9-15.8 m followed by massive presence of weathered layer with overburden thickness of 19.3, 40.3 and 26.8 m in VESs 5, 6 and 7 respectively. Varying degree of fractured zones was observed on this profile with no evidence of fresh basement. VESs 5 and 7 revealed partially fractured zones with low groundwater yielding zones, while VES 6 with massive fractured zones showed high groundwater potential zones. This profile generally revealed water bearing zones with varied fractured layers. Profile 3 (Fig. 17) revealed four layers in geoelectric section, comprising of topsoil with thickness 0.9-2.0 m, lateritic clay with thickness 5.7-12.8 m, weathered basement with thickness 20-45 m and fractured basement with overburden thicknesses 39.7, 58.7 and 26.5 m for VES stations 8, 9 and 10 respectively. The sounding curves on this section had the same curve type KH which indicated massive water bearing zones and multiple fractures in the crystalline complex basement. The profile generally revealed high yield of groundwater zones with no evidence of fresh basement layer.

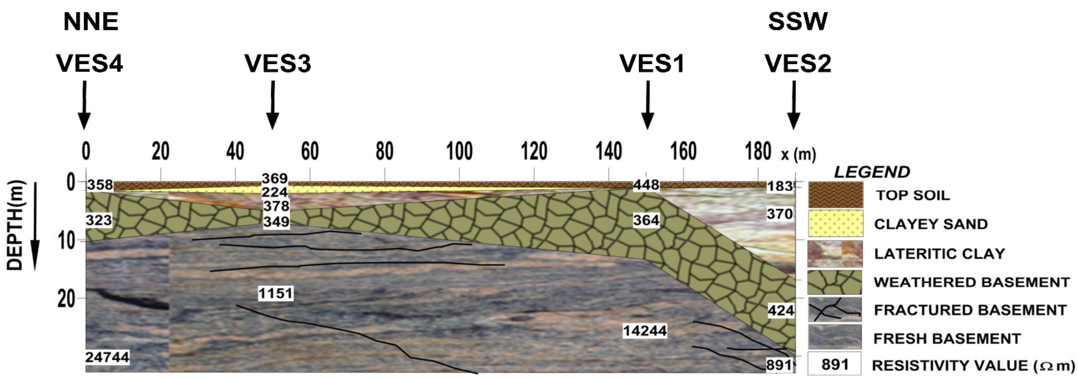

Figure 15: Geoelectric section along Profile 1 (VESs 1, 2, 3 and 4)

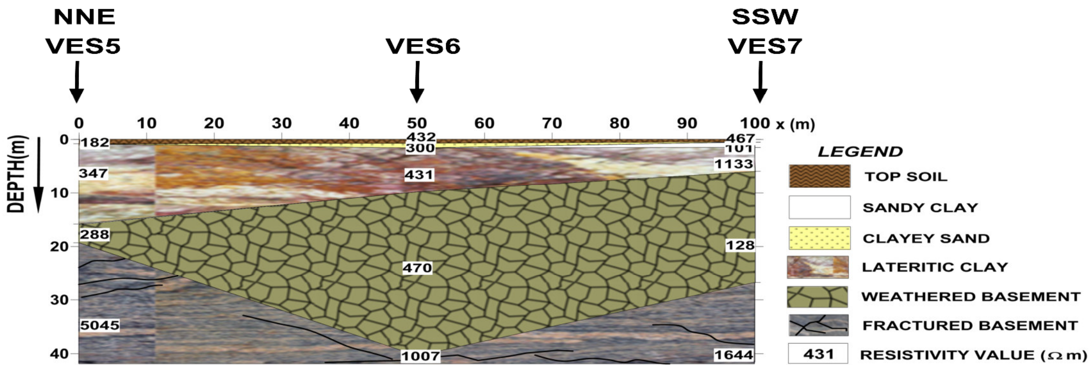

Figure 16: Geoelectric section along Profile 2 (VESs 5, 6 and 7)

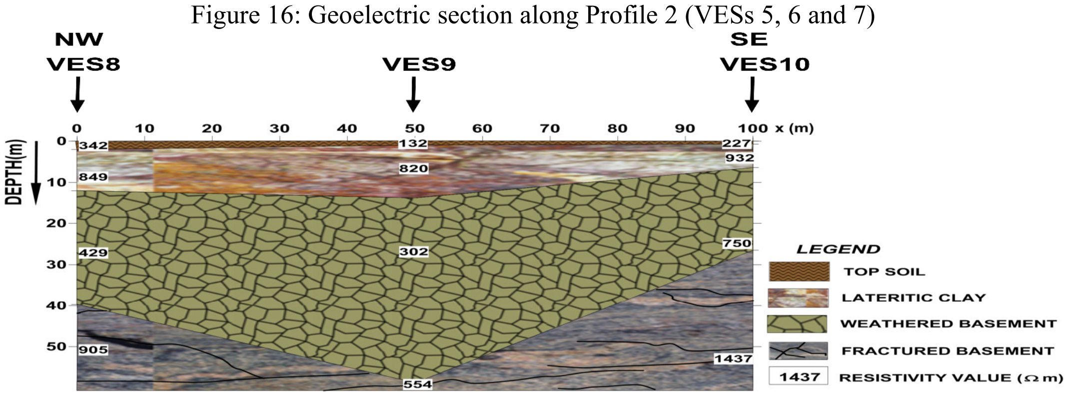

Figure 17: Geoelectric section along Profile 3 (VESs 8, 9 and 10)

The apparent resistivity of the topsoil ranged from 132-467 Ωm revealing mainly sandy clay with maximum and minimum layer thicknesses of 2.0 m (VES 8) and 0.5 m (VES 7) respectively. Fig. 18 showed the variations in the apparent resistivity values of the topsoil, and the differences in the composition of the topsoil were responsible for these variations. The topsoil contributed to groundwater development in the study area due to its high clayey contents which serves as the screening medium for the groundwater flowing into the weathered and fractured basements. The apparent resistivity of the second layer which was mostly sandy and lateritic clay ranged from 101 - 930 Ωm with layer thickness between 1.4-15.8 m.

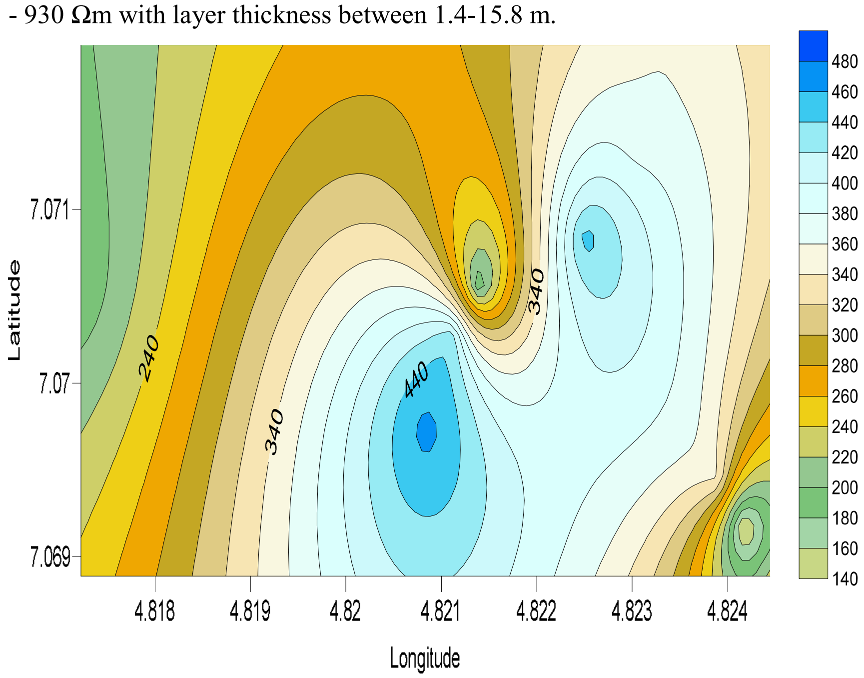

Figure 18: Iso-resistivity map of the topsoil.

VESs 1 and 4 revealed three geoelectric layers in the subsurface; their second layer indicated weathered basements with relatively high resistivity values which were not regarded as water bearing zones due its non-permeate nature. VES stations 1 (14244 Ωm) and 4 (24744 Ωm) revealed fresh basements in the third layer which probably contained high contents of gneisses and granites, with overburden thicknesses 13.3 and 10.3 m, and reflection coefficients 0.95 and 0.97 respectively. The reflection coefficients were too high which indicated that fractures were not observed in these stations and could not be regarded as water bearing zones. In other VES stations, the third layer were mainly composed of the weathered basements with apparent resistivity values ranging from 288-1133 Ωm, and thicknesses ranging from 3.0-45.5 m. On VES stations 5-10, the thicknesses of weathered zones were relatively large. The fractured basements were observed in VESs 2,3,5,6,7,8,9 and 10 with reflection coefficients between 0.29 and 0.89. These values indicated varied fractures with high and low groundwater yield.

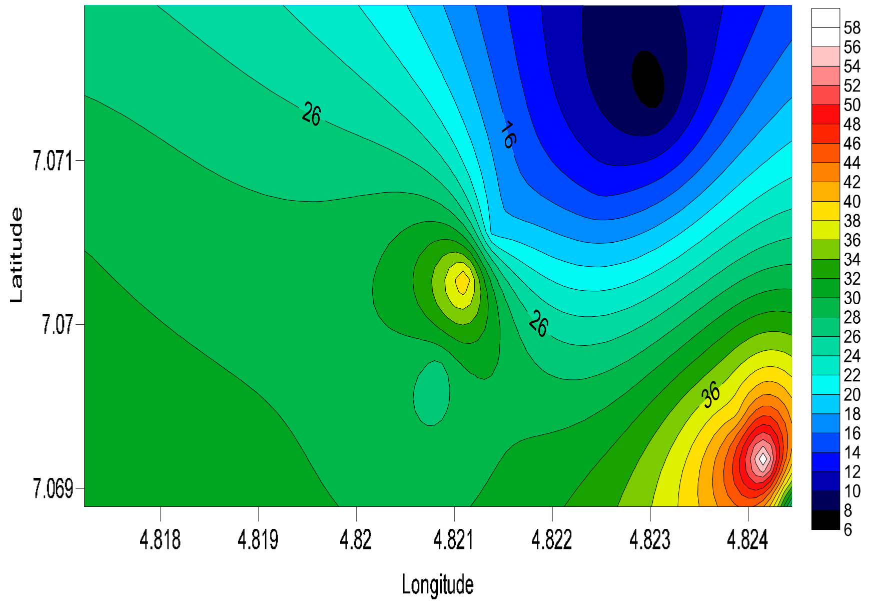

Figure 19: 2D overburden thickness map

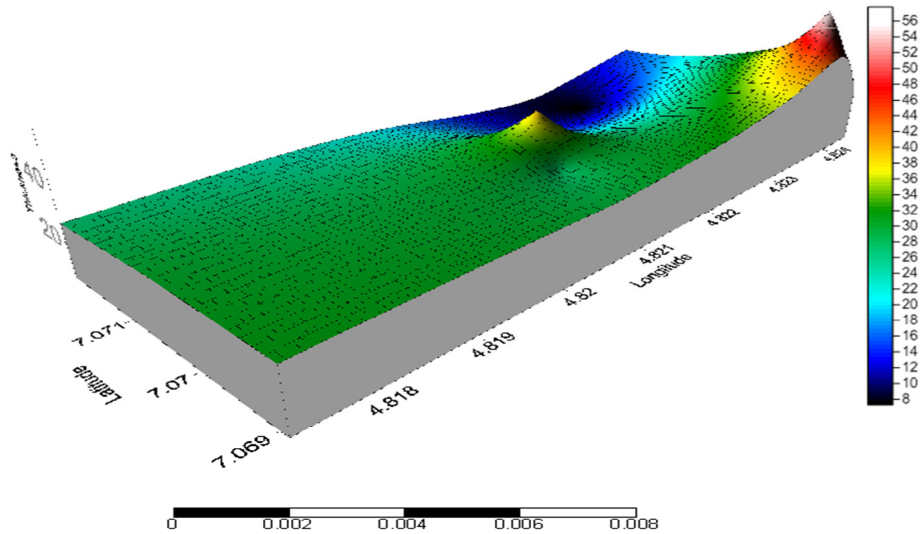

Figure 20: 3D Overburden thickness map. *This figure shows the thickness at different Latitude and Longtitude.*

The overburden thickness of the aquifers enabled the characterization of the subsurface into hydro-geological zones. Hydro-geologic zones with thick overburden thickness were generally considered suitable for groundwater development in the basement terrain (Carruthers *et al.*, 1992). The overburden thickness (depth to fresh basement) is directly proportional to the groundwater storage capacity of the subsurface (Ako & Olorunfemi, 1989). The fractured basement maps of the overburden thickness of the study area are shown in 2D and 3D in figs. 19 and 20 respectively which generally revealed the overview of the regolith variation across the study area. VESs 2, 6, 7, 8, 9 and 10 were regarded as high groundwater potential zones because they revealed adequate overburden thicknesses between 26.5-58.7 m which were suitable for groundwater exploitation. Thus, these sounding stations were strongly recommended for borehole sittings. VES stations 3 and 5 revealved low thicknesses of the aquifer units between 7.1 and 19.3 m, and were regarded as low groundwater potential zones. VES stations 3, 6 and 7 had five geoelectric layers, the fifth layers with apparent resistivity values 1151, 1007 and 1644 Ωm respectively revealed fractured basement to depths at infinity. The weathered and fractured basements were delineated as the aquifer units for the study area. Generally, the study revealed high groundwater prospects which was in agreement with earlier studies by Ahiln & Kumar (2011), Joshua *et al.*, (2011), George *at al.* (2011), Nejad (2009) and Ademilua & Olorunfemi (2000).

5. Conclusion

Geophysical investigation involving electrical resistivity sounding technique has been used to delineate the aquifer units and determine the spatial variations of the overburden thicknesses. The geoelectric parameters obtained from the sounding curves were used to categorize the study area into high and low groundwater potential zones. The geoelectric sections revealed 3-layer (VESs 1 and 4), 4-layer (VESs 2, 5, 8, 9 and 10) and 5-layer (VESs 3, 6 and 7) earth segments which probably indicated topsoil (132-467 Ωm), sandy clay (101-370 Ωm), lateritic clay (347-1133 Ωm), weathered layer (128-750 Ωm), fractured basement (554-5045 Ωm) and fresh basement (14244-24744 Ωm). The results indicated two major types of aquifer units, weathered and fractured bedrocks with low resistivity values which indicated groundwater bearing zones at depths ranging from 7.1 - 58.7 m. The composite thickness of the aquifer units enabled the characterization of the subsurface into hydro-geological zones. VES stations with thick aquifer units had high yield potentials of groundwater, while zones with thin aquifer units had low groundwater potentials. Hydro-geologic zones with thick overburden thickness are generally considered suitable for groundwater development, and VESs 2, 6, 7, 8, 9 and 10 revealed adequate overburden thicknesses between 26.5 - 58.7 m which were good for groundwater storage, these sounding stations were recommended for groundwater exploration. VESs 3 and 5 revealved low thicknesses (7.1 - 19.3 m) of the aquifer units, and were regarded as low groundwater potential zones. VESs 1 and 4 revealed fresh basement with no fractures and thin overburden thickness (10.3 - 13.3 m). These stations could not be regarded as water bearing zones which probably contained high contents of gneisses and granites. Generally, the study revealed high groundwater prospects in the study area.

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