



Application of vertical electrical sounding for groundwater exploration of Cape Coast municipality in the Central Region of Ghana

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Abstract

The focus of this study is to delineate groundwater-bearing zones for the drilling of boreholes to ensure sustainable water supply in the Cape Coast municipality using the vertical electrical sounding (VES) technique. A total of 25 VES points were conducted of which thirteen (13) were test drilled. The VES survey was conducted using the ABEM SAS 1000 Terrameter with the Schlumberger configuration and a maximum half current electrode spacing (AB/2) of 100 m. The VES data were processed and interpreted using the ZONDIP resistivity inversion software. Both qualitative and quantitative interpretations were used to ascertain the best points for drilling a successful borehole (yield > 13 l per minute). The criteria used in selecting a promising site for test drilling are as follows: the nature of the curve (observing the nature of the VES curves), the overburden thickness and the bedrock resistivity. The study revealed a drilling success rate of 90% with an average borehole yield of 118 l/m. A careful review of the resistivity variation with depth revealed that areas with the increasing trend of resistivity from the overburden to the bedrock are most likely to produce unproductive wells whilst areas with decreasing resistivity trend from the overburden to the bedrock are more likely to produce productive wells. The reflection coefficient (Rc) values generally range between -0.8274 and 0.1210 and suggest a highly fractured formation with respect to the Sekondian rocks. Within the granite, the Rc showed more competent formation with values ranging from 0.4040 to 0.6136. A comparison between the depth to bedrock as predicted by VES and the borehole logs was in strong agreement with the correlation coefficient value ($R^2 = 0.9089$). On the other hand, the study revealed a relatively weak correlation ($R^2 = 0.4325$) between the final drilled depth and the borehole yield. The study also finds four major groundwater-bearing zones in the terrain which range between 12 and 28 m, 31 and 40 m, 43 and 59 m, and 80 and 104 m. The bedrock resistivity values most likely to yield productive boreholes with yields greater than 13 l/m range from 54 to 845 ohm-m with a decreasing resistivity between the overburden and the bedrock. Bedrock resistivities more than 900 Ω m with an increasing resistivity between the overburden and the bedrock are most likely to be unsuccessful. Within the terrain, the average depth for drilling productive wells in the Sekodian rocks is 68 m with the final borehole depth ranging from 35 to 120 m. The study therefore has demonstrated the efficacy of the VES technique as a tool in delineating groundwater potential zones for the drilling of boreholes.

Keywords Vertical electrical sounding · Groundwater · Sekondian rocks · Borehole drilling · Cape Coast · Resistivity

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Introduction

Freshwater is essential to human health and national development in accordance with the Sustainable Development Goal 6 (UN General Assembly 2015) (i.e. ensure availability and sustainable management of water and sanitation for all). The distribution of available freshwater within a locality varies enormously with position and time. Access to freshwater is therefore associated with challenges for each alternative source (i.e. surface and groundwater). The Cape Coast municipality and its environs have been facing acute water shortages over the last decade, especially during the peak of the dry

season. This sometimes leads to closure of several educational institutions in the municipality, including the University of Cape Coast and several other second-cycle schools. The recurrence of the water paucity affects institutions and the general public of the municipality. In recent times, surface water which used to be the source of water supply to the communities has been polluted through illegal mining activities. In view of this, surface waters have no longer been relied upon by the communities within the Cape Coast municipality. In an attempt to ameliorate the problem by finding alternative ways of providing water for the populace in the region, the government of Ghana resorted to the use of groundwater resources. After several attempts have been made in drilling 5 unproductive wells by randomly selecting points without the aid of geophysical exploration works, the geophysical team from the Water Research Institute of Ghana was tasked to conduct extensive geophysical survey to locate the best possible drilling sites that could yield substantial volumes of water to ensure sustainable water supply, thereby increasing the drilling success rate. In the light of this, the vertical electrical sounding (VES) technique was the most appropriate geophysical tool chosen for reasons that it is less expensive to conduct per unit length, it is more sensitive to both the vertical and horizontal electrical structures than other one-dimensional methods like the electromagnetic and above all it has the ability to identify subsurface aquifers. Factors including limited space and scattered nature of the settlement ruled out other methods like electromagnetic and electrical resistivity imaging. The electrical resistivity method has proven to be one of the most efficient and economical geophysical methods that is used for the delineation of potential groundwater zones (Ochuko 2013). The resistivity method has received a wide range of applications and this has been reported copiously in literature (Kumar et al. 2010; Bose and Ramkrishna 1978; Chandra et al. 2012; Devi et al. 2001; Francese et al. 2009; Hamzah et al. 2007; Singh et al. 2006; Ebraheem et al. 2012; Owen et al. 2005; Ratna Kumari et al. 2012; Kumar et al. 2014; Zaidi and Kassem 2012; Anechana et al. 2015; Yadav and Singh 2007; Sainato et al. 2003; Sharma and Branwal 2005; Urish and Frohlich 1990). It provides subsurface information with minimal or no destruction to the environment and also gives a contrast between rock layers having different electrical properties (Okrah et al. 2012; Store et al. 2000). Aside from groundwater prospecting, the electrical resistivity method is applied in mineral exploration (Fon et al. 2012) and in slide modelling (Perrone et al. 2004), determining saltwater intrusion (Sherif et al. 2006), environmental pollution (Ogungbe et al. 2012) and in foundation engineering (Olurunfemi et al. 2004). In India, the VES technique has been used successfully to delineate fracture zones (Naziya and Singh 2018). The results from the VES survey revealed the presence of fracture zones oriented in NE-SW and NW-SE direction. In Ghana, the VES technique has been employed

together with other methods as a tool for major groundwater exploration works (Manu et al. 2016; Anechana et al. 2015; Okrah et al. 2012; Sikah et al. 2016). In their work, Sikah et al. (2016) used the integrated geophysical techniques involving the VES and the electrical resistivity imaging to delineate groundwater potential zones. The study revealed three to four geoelectric layers with the aquifer zones located in the third and the fourth layers. Similarly, Anechana et al. (2015) also used a combined method including electromagnetic and vertical electrical sounding techniques to explore for groundwater resources in the Kintampo municipality which is predominantly underlain by Voltaina super group which covers 45% of the entire land mass of Ghana (Dapaah-Siakwan and Gyau-Boakye 2000). The VES revealed three- to four-layered lithological subsurface sequence, indicating the decreasing apparent resistivity with depth. The study again found the aquifer zones lying between 15 and 30 m depth. In a competent granitic environment, Manu et al. (2016) conducted a study within some parts of the basement complex formation in Ghana using the VES and electromagnetic methods (EM). The combined interpretation of the EM and VES results indicated the presence of possible aquifer units comprising the weathered, fractured and fresh bedrock within the subsurface of the study area. The results revealed the presence of three geoelectric layers. It is obvious that in geophysical works, at least two methods are always required in order to validate the results to maximise predictions. However, the current study focuses on using VES as a probing tool to delineate potential groundwater zones. This study also seeks to explore the efficacy of the VES technique as a tool to delineate groundwater potential zones in a crystalline rock environment of Ghana.

The study area

The Cape Coast municipality is bounded on the south by the Gulf of Guinea, west by the Komenda-Edina-Eguafo-Abirem District, east by the Abura-Asebu-Kwamankese District and north by the Twifo-Hemang-Lower Denkyira District. The municipality covers an area of 122 km² and the capital is Cape Coast. According to the 2010 Population and Housing Census of Ghana Statistical Service (GSS 2013), Cape Coast municipality forms about 7.7% of the population of Central Region (2,201,863 people), which makes up 8.9% of Ghana's population. The average household size of the municipality is 3.5 (~4) and the population increase of the region over the past decade is 38.1% with an inter-censal growth rate of 3.1%. The rural population of Cape Coast municipality is 3.4% of the region's 52.9% rural population, whilst the urban forms 12.6% of the region's 47.1% urban population. The Central Region covers an area of 9826 km² forming 4.1% of the land area of Ghana. The population density of the Region is 224.1 people/km² (GSS 2013). The study area consists of undulating plains with isolated hills and occasional cliffs

characterised by sandy beaches and marsh in certain areas and the hinterland, where the land rises between 250 and 300 m above sea level. It lies within the dry equatorial climatic zone and the moist semi-equatorial zone. According to Dickson and Benneh (1995), the annual rainfall ranges from 1000 mm along the coast to about 2000 mm in the interior. The wettest months are May–June and September–October whilst the drier periods occur in December–February. The mean monthly temperature ranges from 24 °C in the coolest month (August) to about 30 °C in the hottest months (March–April) (Dickson and Benneh 1995). The vegetation of the study area is predominantly grassland with few trees.

Geology and hydrogeology

The map showing the geology of the study area is presented in Fig. 1. The geological formation underlying the study area comprises rocks of Sekondian formation, which forms part

of the Coastal Plain Province of the Cenozoic, Mesozoic and Palaeozoic sedimentary strata with sandstone, inter-bedded with undifferentiated shale as the main rock types (Kesse 1985). The Sekondian rocks contain a high degree of shale and clay, mixed with some gravel. The rocks have been subjected to post-depositional igneous activity and a major block faulting and unconformably overlies a complex of granite, gneiss and schist of Precambrian age (Dapaah-Siakwan and Gyau-Boakye 2000). Groundwater occurrence in the area has been said to be dependent on secondary structures which are made up of fractures, joints, shearing and faulting (Banoeng-Yakubo 2000). According to Atobrah (1980), the development of secondary porosities in these rocks is dependent on the nature, aperture, length, density, thickness and degree of interconnection of the fractures as well as the extent of weathering. The rate of drilling successful boreholes in this formation is reported by Dapaah-Siakwan and Gyau-Boakye (2000) to be 78% with a yield ranging from 4.5 to 54 m³/h (average yield 15.6 m³/h). Other areas are underlain by rocks

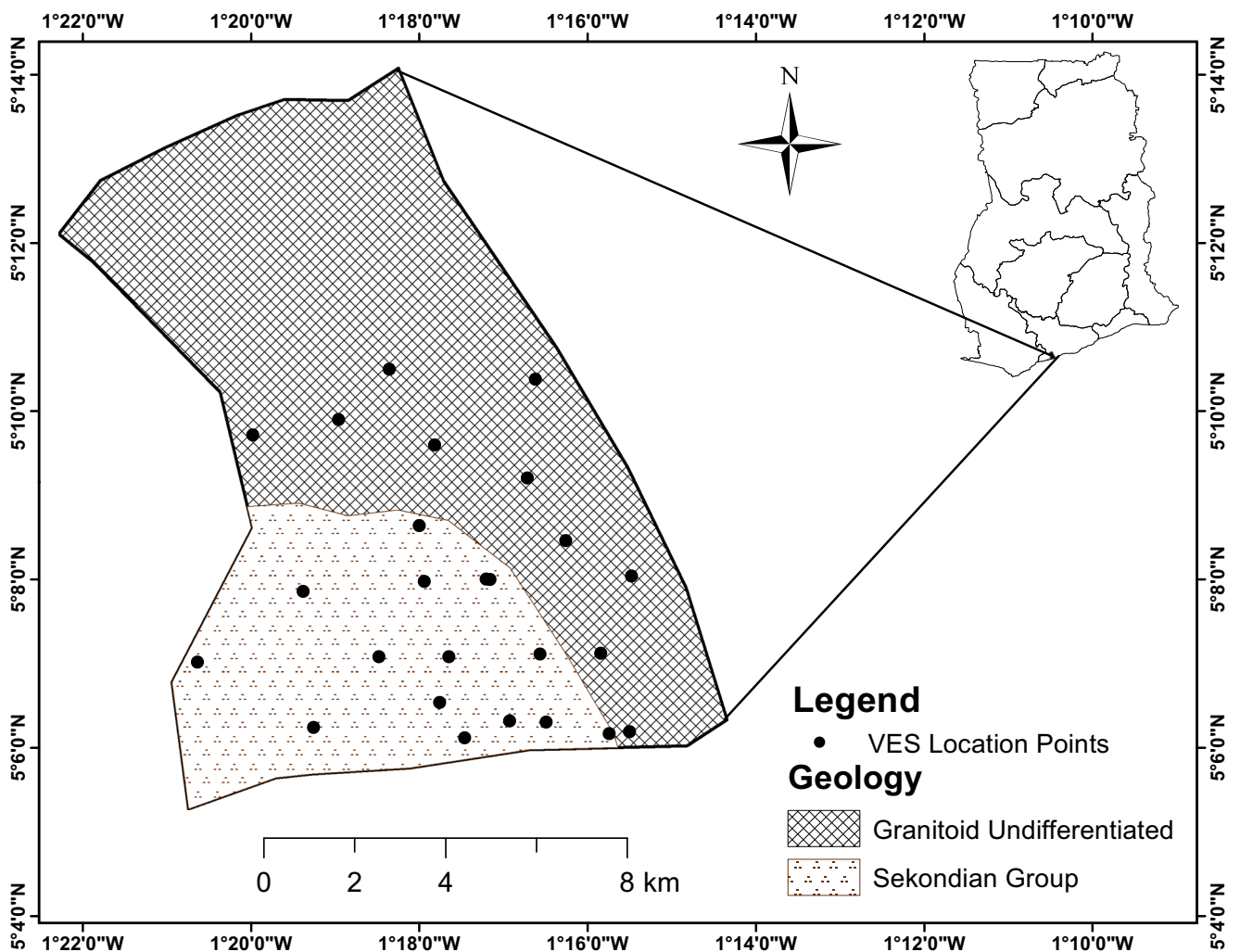


Fig. 1 Geological map of Cape Coast municipality showing the location of VES in the studied area

of Eburnean Plutonic Suite with undifferentiated biotite-granitoid as the main rock type. This rock weathers to form clay and sandy-clay overburden whilst the bedrock is marked with multiple fracture sections. Some assessment carried out on existing boreholes within the neighbourhood of the study area indicated that the success rate of drilling wet well is about 68% with a yield of 1–9 m³/h (Dapaah-Siakwan and Gyau-Boakye 2000).

Materials and methods

In this study, the vertical electrical sounding (VES) technique was employed to delineate potential groundwater-bearing zones. The Schlumberger array configuration with a maximum half current electrode separation of 100 m was adopted for the survey. The rationale of choosing the Schlumberger array over the other arrays (e.g. the Wenner array) was borne out of the fact that fewer electrodes need to be moved for each sounding, the array requires at least three persons for its data collection, it gives better resolution and it has greater probing depth (Keary and Brooks 1984). The Schlumberger array consists of four collinear electrodes separated from each other by some known distance. The outer two electrodes are the current electrodes and the inner ones are the potential electrodes (Sharma 1997). An ABEM SAS 1000 resistivity meter was used to measure the apparent resistivity at each VES station. At every sounding point, the potential electrodes were planted at the middle of the electrode array with the electrode spacing less than one fifth of the spacing between the current electrodes (Sharma 1997). The current electrodes were moved at different distances whilst keeping the potential electrodes constant until the voltage became too small to measure before the potential electrodes were increased accordingly. Field data were recorded and plotted on a graph of apparent resistivity against half-electrode spacing using a bi-logarithmic graph. The generated VES curves were smoothed in order to ensure that all the effects of lateral inhomogeneity and other forms of noisy signatures were minimised (Bhattacharya and Patra 1968). Acceptable readings were obtained at a maximum standard deviation of 8%. At every station, the field data were converted to apparent resistivity by multiplying the resistances by the geometric factor (Sharma 1997). The final computed apparent resistivity data was processed using the ZONDIP 1D software (ZONDIP 2012) to obtain the 1D model of the sounding curve. The interpretation of the final 1D resistivity model provided information about the resistivity of layers, their thicknesses and their depths of occurrence. The geological model was then inferred from these 1D VES models. The data fit was maintained at a reasonable root mean square error (RMS) values of 5–8%. The root mean square is a measure of the closeness of the theoretical curves to the observed field curves as the manual adjustment was done to get

the best fit. Selection of the most promising site for drilling was made by considering factors such as overburden thickness, bedrock resistivity and the nature of the curve. Bedrock with low resistivity is a clear indication of a more loose formation with a high potential of accumulating substantial volumes of groundwater. Consequently, low bedrock resistivity points were given high ranking alongside points with thicker overburden. The thicker the overburden, the higher the potential of water storage in the weathered zone. On the other hand, a rising curve is an indication of a more competent or massive rock, which may not have enough groundwater at storage to produce water in sustainable quantities. In the light of this, curves that show potential decay were also considered as promising points for drilling. All things being equal, a selected point for drilling must have at least two of the factors discussed above. The reflection coefficients (Rc) for all the VES points were calculated using Eq. (1) (Bhattacharya and Patra 1968; Loke 1999).

$$Rc = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \quad (1)$$

where ρ_n is the layer resistivity of the n th layer, and ρ_{n-1} is the layer resistivity overlying the n th layer.

Results and discussions

Figures 2, 3 and 4 show the VES modelled curves for some selected sounding locations in the study area. The quantitative summary of the VES modelled results as well as the drilling results is presented in Tables 1 and 2 respectively. From the VES results, the resistivities of the underlying bedrock generally are relatively low (< 600 Ω m) signifying a more fractured formation with high potential groundwater storage. However, four locations recorded high bedrock resistivities (> 700 Ω m) which indicate a massive crystalline granitic rock with little or no fracture to enhance groundwater development. The granites underlying the southern portions of Ghana are seen to be massive and less fractured with minimal water storage. Okrah et al. (2012) opined that bedrock resistivity greater than 800 Ω m in the granitic environment may lead to dry wells since such areas are seen to have competent underlying rocks with minimal or no secondary porosity. This assertion corroborates the results obtained in three locations where dry wells are well recorded (i.e. Cape Coast Poly, Adisedel College and Aggrey Memorial College). These three areas are underlain by very massive crystalline granitic rocks which have minimal fractures to enhance groundwater development. Although a relatively high bedrock resistivity of 845 Ω m was recorded at UCC Hospital (see Fig. 2d), the first aquifer strike was encountered between 17 and 28 m. This is due to the presence of the relatively thicker overburden (19 m) which could be a

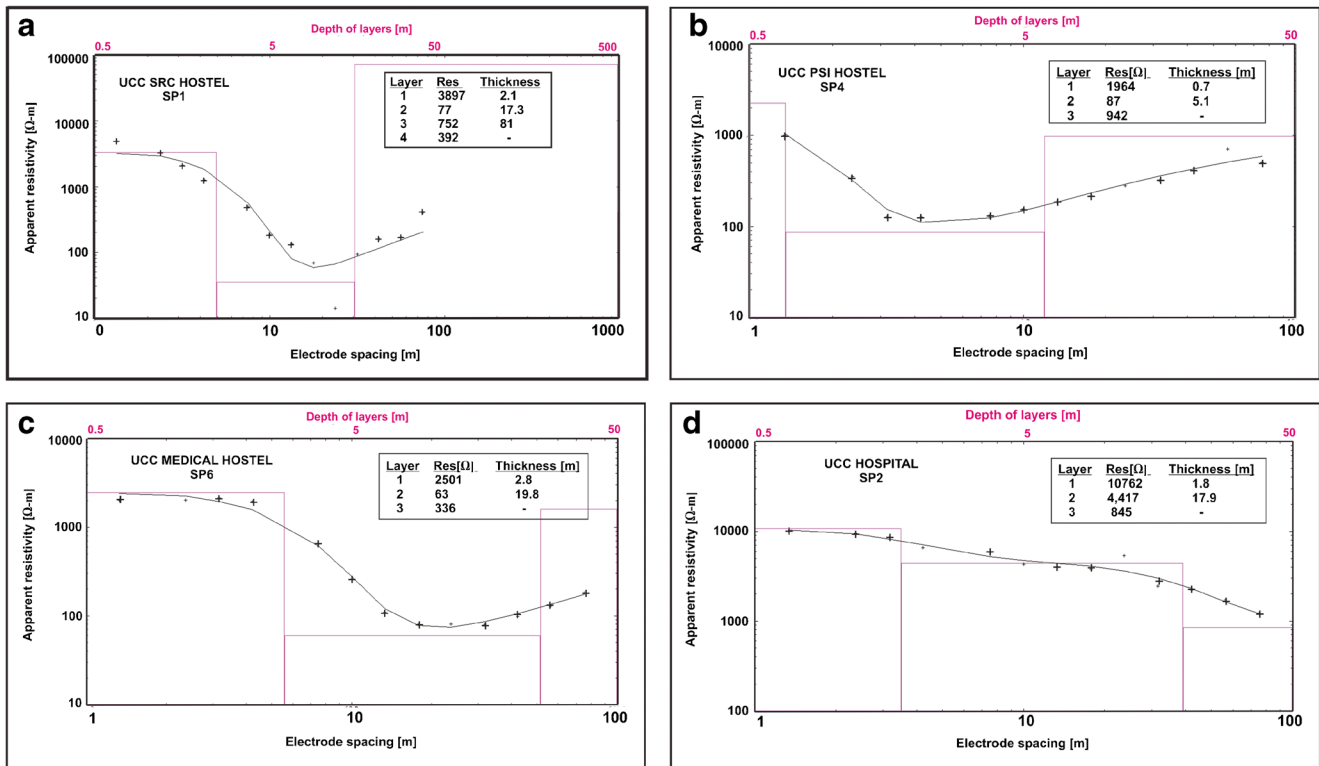


Fig. 2 VES modelled curve at a UCC SRC Hostel SP1, b UCC PSI Hostel SP4, c UCC Medical Hostel SP6 and d UCC Hospital SP2

potential zone for groundwater storage. It can be said that the granite underlying the Cape Coast municipality is massive and competent with minimal fractures to enhance accumulation

and movement of water since all boreholes drilled were dry with no wet sections up to a maximum depth of 120 m. This agrees with earlier suggestions by Yidana et al. (2008). The

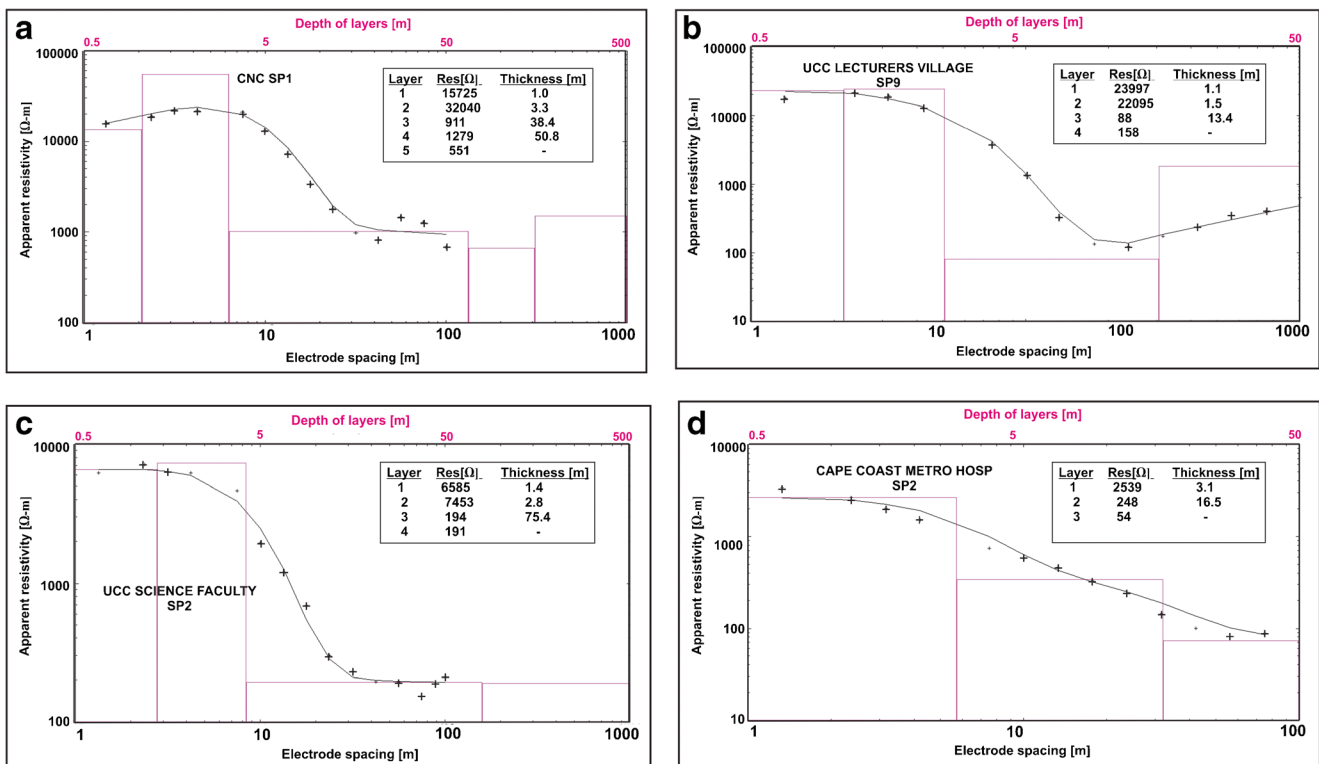


Fig. 3 VES modelled curve at a CNC SP1, b UCC Lecturers Village SP9, c UCC Science Faculty SP2 and d Cape Coast Metro Hospital SP2

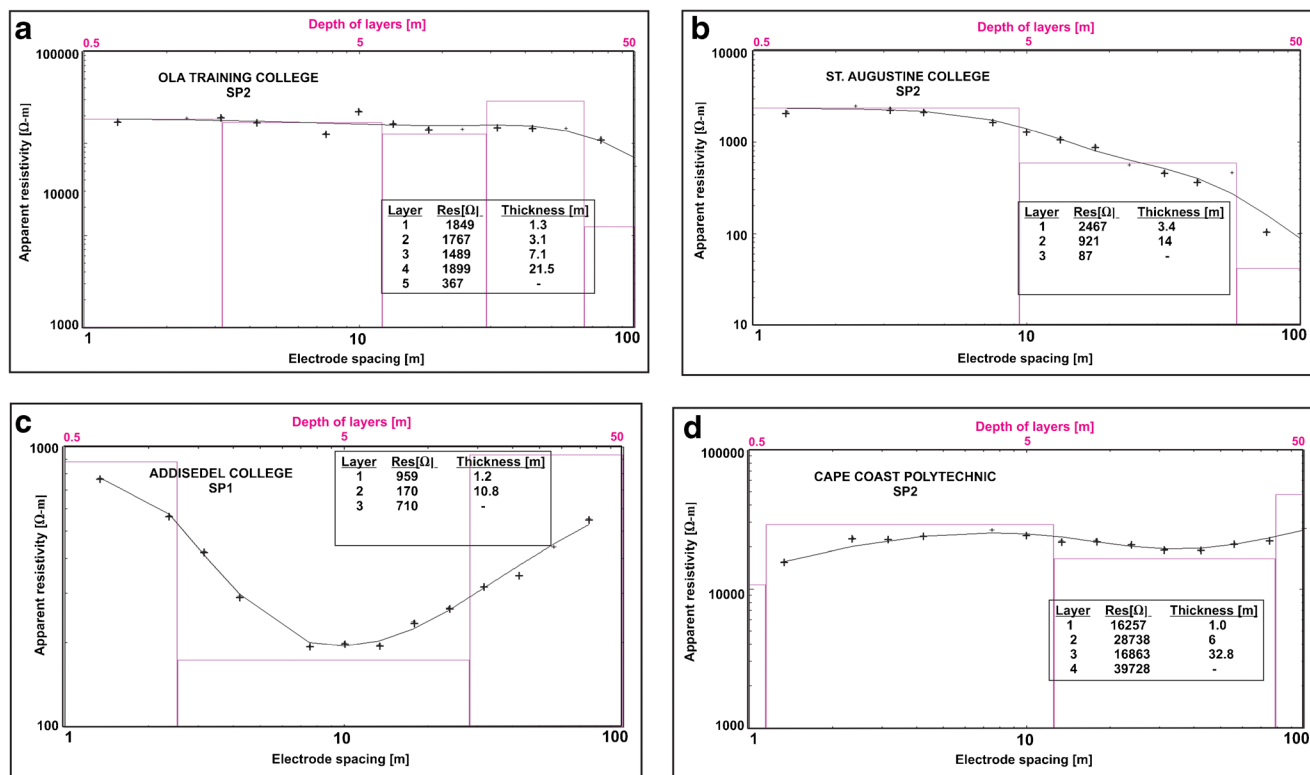


Fig. 4 VES modelled curve at **a** OLA Training College SP2, **b** St. Augustine College SP2, **c** Addisedel College SP1 and **d** Cape Coast Polytechnic SP2

case in the Sekondian rock formation was different. According to Dapaah-Siakwan and Gyau-Boakye (2000), the rocks associated with the Sekondian formation are highly fractured and groundwater development is mainly due to the presence of secondary porosities. The fractures within the rocks serve as groundwater storage points. In view of this, low bedrock resistivity was expected due to the presence of water in the pores. Cape Coast Municipal Hospital recorded the lowest bedrock resistivity in the order of 54 Ωm . This low bedrock resistivity could be attributed to the presence of saline water intrusion since the VES location was just about 100 m away from the Gulf of Guinea. In general, within the Sekondian formation, the resistivity range of 54–600 Ωm is expected to produce productive wells whilst in the Cape Coast granite, bedrock resistivity higher than 800 Ωm may lead to an unproductive well. Another factor that influences groundwater development is the thickness of the overburden. According to Olayinka et al. (1999), only the resistivity of the basement cannot be used to establish the groundwater potential of a promising site and for that matter, overburden thickness and aquifer reflection coefficient should be employed to improve the selection protocols. The reflection coefficient at fresh basement rock interface can provide some insight into the aquiferous nature of the basement rocks (Adeniji et al. 2013; Obiora et al. 2016). The higher the resistivity contrast, the more competent and less fractured the underlying rocks at depth. However, a lower resistivity contrast value exhibits a fracture of the basement rock and, hence, has a higher

groundwater-bearing potential. It is suggested that the aquifer reflection coefficient gives a clearer picture of the degree of fracturing than the basement resistivity (Bayewua et al. 2018). In view of this, reflection coefficient (R_c) less than 0.8 is classified as a good aquifer zone. From the calculated R_c values (see Table 1), areas that recorded lower R_c were inferred as the most fractured or weathered bedrock with the potential of enhancing development of groundwater resources. The lower R_c values (<0.8) were obtained within the Sekondian formation which suggest a fractured bedrock. Areas comprising (SRC, Medical Hostel, UCC Hospital, Science Faculty, OLA, St. Augustine, Lecturers Village) all produced R_c values (<0.8). These points are inferred as a less competent basement with fractures occurring at a depth. The overburden thickness for the study area range between 5.8 and 100 m with the highest thickness recorded at UCC SRC Hostel and the lowest at UCC PSI Hostel. It was observed that the borehole with the highest overburden thickness recorded a yield of 12 l/m whilst the overburden thickness of 19 m produced a yield of 210 l/m. This therefore suggests that groundwater occurrence in the study area is largely dependent on a secondary porosity such as fissuring, fracturing weathering and permeability as underscored by (Banoeng-Yakubo 2000). In general, three (3) to five (5) lithological sequences were predicted by the VES results. The aquifer is located within the third, fourth and five layers with varying degrees of fracturing.

Table 1 VES interpretation and their reflection coefficient (Rc)

Location	No. of layers	Res (ohm-m)	Thickness (m)	Reflection coefficient	Geology
SRC	1	3897	2.1	-0.3147	Sekondian
	2	77	17.3		
	3	752	81		
	4	392			
PSI	1	1964	0.7	0.8309	Sekondian
	2	87	5.1		
	3	942			
Medical Hostel	1	2501	2.8	0.6842	Sekondian
	2	63	19.8		
	3	336			
UCC Hospital	1	10,762	1.8	-0.6788	Sekondian
	2	4417	17.9		
	3	845			
CNC	1	15,725	1	-0.3956	Sekondian
	2	32,040	3.3		
	3	911	38.4		
	4	1279	50.8		
	5	551			
Lecturers Village	1	23,997	1.1	0.2846	Sekondian
	2	22,095	1.5		
	3	88	13.4		
	4	158			
Faculty of Science	1	6585	1.4	-0.0078	Sekondian
	2	7453	2.8		
	3	194	75.4		
	4	191			
Metro Hospital	1	2539	3.1	-0.642	Sekondian
	2	248	16.5		
	3	54			
OLA	1	1849	1.3	0.121	Sekondian
	2	1767	3.1		
	3	1489	7.1		
	4	1899	21.5		
	5	367			
St. Augustine	1	2467	3.4	-0.8274	Sekondian
	2	921	14		
	3	87			
Adissedel College	1	959	1.2	0.6136	Granite
	2	170	10.8		
	3	710			
Cape Coast Poly	1	16,257	1	0.404	Granite
	2	28,738	6		
	3	16,863	32.8		
	4	39,728			

Correlating drilling and geophysical results

The drilling results for the 13 test wells are summarised in Table 2. It consists of borehole data such as static water level, borehole depth, yield, aquifer horizons and depth to bedrock. It was observed that the numbers of layers predicted by the VES in

some cases were not matching the drilling logs. For example, at UCC Lecturers Village, four (4) layers were inferred by the VES interpretation; however, five (5) layers were intercepted after drilling up to a depth of 60 m. In the same vein, the VES inferred layer results at UCC SRC Hostel, UCC Faculty of Science, UCC PSI Hostel, Cape Coast Poly, CNC, Adissedel College

Table 2 Borehole drilling results

Location	BHID	Drilling date	Depth of BH (m)	Depth to bedrock (m)	BH yield (l/m)	Aquifer horizon (m)	Static water level (m)	Status of BH	Geology
UCC Lecturers Village	SP9	08/05/13	60	14.0	55	21–30, 47–54	6.7	Successful	Sekondian
UCC Hospital	SP2	9–10/05/13	43	11.8	210	17–28, 37–43	19.0	Successful	Sekondian
UCC SRC Hostel	SP1	10–14/5/13	120	10.0	12	75–80	6.4	Successful	Sekondian
UCC Faculty of Science	SP2	16/5/13	40	4.1	36	21–26, 34–40	17.0	Successful	Sekondian
UCC Medical Hostel	SP6	15–16/5/13	50	17.3	96	31–48	2.2	Successful	Sekondian
UCC PSI Hostel	SP4	14/05/13	120	5.0	40	80–95	36.0	Successful	Sekondian
Cape Coast Polytechnic	SP2	16/05/13	120	6.4	Dry	–	–	–	Granite
CNC suburb	SP1	24/05/13	108	41.4	75	85–94, 100–104	33.0	Successful	Sekondian
Aggrey Memorial College	SP1	27/05/13	80	8.9	Dry	–	–	–	Granite
Adisadel College	SP1	28/05/13	120	11.0	Dry	–	–	–	Granite
St. Augustine's College	SP2	17–20/5/13	35	17.2	280	12–35	9.3	Successful	Sekondian
OLA Training College	SP2	22–27/5/13	60	9.8	140	20–26, 31–40, 52–59	31.8	Successful	Sekondian
Cape Coast Metropolitan Hospital	SP2	16–17/5/13	40	15.8	240	18–34	1.5	Successful	Sekondian

St. Augustine and OLA deviated from that of the drilling logs. This uncertainty may be attributed to the suppression of thin layers or even thicker layers at larger depths (as the resolution decreases). This problem of suppression occurs when a thin resistive layer is sandwiched between thicker conductive layers and vice versa. In the light of this, thin layers of small resistivity contrast with respect to background will not be detectable (Auken and Christiansen 2004). This is evident in the case of model results from the Addisadel College (Fig. 4c) where a relatively low resistive layer (170 Ω m) of 10.8 m thick is sandwiched by two layers with relatively higher resistivities of

959 Ω m and 710 Ω m respectively. In this case, it may be inferred that there could be other low resistive layers lying between these two layers that may not have been detected as a result of the small resistivity contrast. In view of this, the VES at this point (Addisadel College) predicted 3 layers whilst the drilling results produced 5 layers. This suppression problem and other unforeseen human errors may have accounted for the incongruities in the layer prediction by the VES. Conversely, about 15% of the VES-predicted layers were in agreement with the borehole logs. This is evident in the results obtained at Cape Coast Metro Hospital and UCC Hospital which both predicted 3 layers (see

Table 3 Comparison between drilling logs and geophysical results

Location	VES point	Number of layers		Depth to bedrock (m)		Aquifer horizons (m)	
		Geophysical interpretation	BH drilling interpretation	Geophysical interpretation	BH drilling interpretation	Geophysics results	BH drilling results
UCC Lecturers Village	SP9	4	5	16.0	14.0	10–30, 35–65	21–30, 47–54
UCC Hospital	SP2	3	3	19.8	11.8	15–20, 30–45	17–28, 37–43
UCC SRC Hostel	SP1	4	5	19.4	10	60–70, 80–90	65–75, 78–80
UCC Faculty of Science	SP2	4	3	4.2	4.1	30–50	21–26, 34–40
UCC Medical Hostel	SP6	3	4	21.8	17.3	28–45, 50–83	31–48
UCC PSI Hostel	SP4	3	5	5.8	5.0	75–100	80–95
Cape Coast Polytechnic	SP2	4	6	7.0	6.4	–	–
CNC suburb	SP1	5	3	42.7	41.4	20–60, 80–100	85–94, 100–102
Aggrey Memorial College	SP1	4	5	12.7	8.9	–	–
Adisadel College	P1	3	5	12.0	11.0	–	–
St. Augustine's College	SP2	3	2	17.4	17.2	10–40	12–35
OLA Training College	SP2	5	3	11.5	9.8	30–48, 55–60	20–26, 31–40, 52–59
Cape Coast Metropolitan Hospital	SP2	3	3	19.6	15.8	10–20, 25–50	18–34

Fig. 5 **a** A plot of drilling depth to bedrock (DDB) against geophysics depth to bedrock (GDB). **b** A plot of borehole yield against borehole depth (BHD). **c** A plot of static water level (SWL) against borehole depth (BHD)

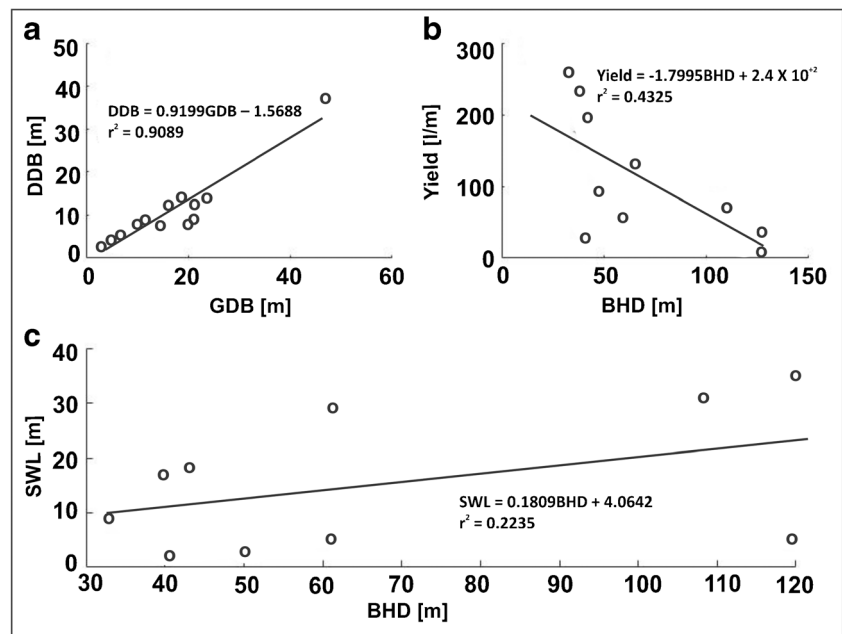


Table 3). The VES and the borehole logs were again compared to ascertain the correlation that exists between the VES predictions on the number of layers, depth to bedrock, overburden thickness and aquifer zones. Figure 5a–c presents the details of the relationship that exists between these aforementioned parameters. It is obvious that there is a strong correlation ($r^2 = 0.9089$) between the VES-predicted depth to bedrock and that of the borehole logs (Fig. 5a). This strong correlation is a result of a strong resistivity contrast between the bedrock surface and the loose overburden material which makes it easy for the VES to locate, unlike layers with similar or slight resistivity variations. There was no significant correlation between the layers predicted by the VES and that of the borehole logs and this has been attributed to suppression of thin layers or as a result of poor resolution at depth. Again, the plot of SWL against borehole depth (Fig. 5c) produced a weak correlation ($r^2 = 0.22$) indicating that depth of boreholes may not necessarily affect the static water levels within the study area. The borehole yield plotted against the borehole depth (Fig. 5b) showed a negative gradient with a significant correlation coefficient ($r^2 = 0.4325$). This perceived reduction in the yield with respect to depth may be due to the sealing of potential fracture zones during borehole construction. It may also suggest that secondary porosity (in the form of fracturing/weathering) of rocks in the area is discrete and occurs at varying depths with varying water holding capacities.

Conclusion and recommendation

The study has demonstrated the versatility of vertical electrical sounding (VES) in adequately delineating water-

bearing fracture zones in a study aimed at improving the water supply system in the Cape Coast municipality. The VES geophysical technique has been fruitful in siting highly productive wells that could yield sustainable water supply for improving the livelihood of the people of the region. The VES modelled results produced three (3) to four (4) geoelectric layers with the aquifer located in the third layer. A careful review of the resistivity variation with depth revealed that an increasing trend of resistivity between the layer overlying the bedrock and the bedrock is not suitable for drilling. On the contrary, most promising groundwater drilling points are associated with a decreasing trend of resistivity between the layer overlying the bedrock and the bedrock. The reflection coefficient (Rc) values generally range between -0.8274 and 0.1210 and suggest a highly fractured formation with respect to the Sekondian rocks. Within the granite, the Rc showed more competent formation with values ranging from 0.4040 and 0.6136 . A comparison between the depth to bedrock as predicted by VES and confirmed by the test drilling was in strong agreement with the correlation coefficient value ($R^2 = 0.9089$). On the other hand, the study revealed a relatively weak correlation ($R^2 = 0.4325$) between the final drilled depth and the borehole yield. The study also finds four major groundwater-bearing zones in the terrain which range between 12 and 28 m, 31 and 40 m, 43 and 59 m, and 80 and 104 m. The bedrock resistivity values most likely to produce productive boreholes with yields greater than 13 l/m range from 54 to 845 Ωm with a decreasing resistivity between the overburden and the bedrock. Bedrock resistivities more than 900 Ωm with an increasing resistivity

between the overburden and the bedrock are most likely to be unsuccessful. The success rate of drilling boreholes within the Sekondian rock (Sandstone) formation is 91% (10 out of 11 boreholes) whilst all three points within the granitic rock formation were unproductive. To improve drilling success in the granitic environment, a 2D resistivity imaging coupled with VES must be employed to provide both the lateral and vertical variations in resistivity with depth in order to obtain clearer information about the extent of fractures within such a hard crystalline rock formation.

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