Geophysical investigation of groundwater potential and aquifer protective capability in selected communities within Cape Coast municipality, Ghana

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Abstract

Application of VES geophysical technique to investigate the groundwater potential and the aquifer protective capability has been carried at Cape Coast Municipality, Ghana. The geology of Cape Coast is mainly made of the Secondian formation and the Eburnean Plutonic Suite. Twenty (20) VES points were selected after the profiling, and Schlumberger array was applied for the conduction of the VES. The PASI Resistivity Terrameter was used, and the maximum current electrode spacing (AB/2) was 100 m. Partial curve matching technique and computer iteration technique were applied in the interpretation data using WINRESIST software. The thematic maps of the parameters were generated to display their spatial variations using Surfer Golden software by the application of appropriate variograms depending on their range of values. The study revealed the presence of three to six layers curve types which include HKH (45%), QH (20%), HA (10%), KH (5%), QHKH (5%), A (5%), AKH (5%) and KHKH (5%) in the study area. The layers include topsoil (31.00–9135.00 Ω m), weathered layer (2.35–60,801.00 Ω m), fractured basement (4.39–32,431.00 Ω m), and fresh basement (59.40–22,521.00 Ω m). About 70% of the resistivities are less than 600 Ω m indicating the possibility of a fractured formation with high potential groundwater storage. The other 30% recorded high bedrock resistivities values of possible massive crystalline granitic rock with a limited fracture. Reflection coefficient and longitudinal conductance were calculated using appropriate equations and parameters. The values of the reflection coefficient ranged from 0.215606 to 0.997049. The study revealed that 20% of the total VES points have high groundwater potential, 65% showed medium potential, 5% showed low potential, while 10% showed very low potential. The study revealed poor (20%), moderate (35%), good (30%), and very good (15%) protective capacity ratings in the area. The technique has been effective in revealing the groundwater potential and the aquifer protective capability of the area. The aquiferous zone of the Secondian formation falls within the range of 17–43 m of depth with a borehole yield of 210–240 l/m. The successful borehole in the granitic rocks shows a low yield of 10 l/m with a water-saturated zone within 20–48 m of depth.

Keywords Geophysical investigation · Groundwater potential · Aquifer protective capacity · Vertical electrical sounding · Cape Coast municipality

Introduction

Water is an essential natural resource that is needed for a healthy living and socio-economic development of every country. As part of the Sustainable Development Goals, availability and sustainable management of water and

sanitation for all occupy goal number 6. Globally, the supply of safe water is not evenly distributed (NGWA 2016). As some countries are able to supply the citizenry with safe water continuously for a long period of time, the story is different in developing countries like Ghana where water supply often does not flow frequently. This observation is a global concern as there is a direct link between public health and the quality of water the public depends on for their water needs. This is why the UN General Assembly (2015) considered the need to ensure the supply of safe water to everyone by the year 2030. In Ghana, Ghana Water Company Limited (GWCL) and Community Water and Sanitation

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Agency (CWSA) are the two government bodies that are responsible for the supply of safe water to the people living in the country. The GWCL is responsible for the water supply in the urban cities, while the CWSA is responsible for the facilitation of the water supply in the rural communities and small towns. Over the years, the two bodies have undergone several reforms to ensure the effective delivery of their task as government bodies. However, there are a lot of places in both the urban cities and the rural communities that are not served with safe water supply. In lieu of this, most non-governmental organizations, religious bodies, cooperate bodies, and individuals have duly played their role by contributing in one way or the other to ensure people in some communities get access to safe water. Ghana is blessed with both surface and groundwater water resources. Unfortunately, the illegal small-scale mining activities have negatively impacted most of our surface water bodies by making them so contaminated to the point of rendering them unfit for certain usage without prior treatment. Therefore, a lot of attention is given to the groundwater which is relatively safer for human consumption and also available in most parts of the country. Manu et al. (2019) report on the challenge of Cape Coast Municipality and its environs face concerning reliable water supply. Hence, the vertical electrical sounding (VES) technique which is less expensive, more sensitive to electrical structures, and has the ability to identify subsurface aquifers was applied to delineate groundwater potential zone in selected areas of their study (Ochuko 2013; Manu et al. 2019). The successful application of the electrical resistivity technique for the delineation of potential groundwater zones and related applications are reported by the different researcher from different part of the world (Olurufemi et al. 2004; Fon et al. 2012; Naziya and Singh 2018; Manu et al. 2016; Manu et al. 2019). As X-ray has advanced the medical world, so geophysical techniques have been in the world of geology. It gives information about subsurface geological layers which aids in groundwater prospecting, mineral exploration, foundation engineering as well as other applications without environmental destruction (Olurufemi et al. 2004; Okrah et al. 2012; Fon et al. 2012). Manu et al. (2019) observed that a combination of two or more geophysical techniques in geophysical works helps in the validation of results to maximize predictions. This study uses VES to assess groundwater potential and aquifer protective capability in selected communities within Cape Coast Municipality. Even though there is available literature on the groundwater resources in the Cape Coast Municipality, little is known on the ability of the overburden rocks to filter the water that percolates through it to the water table from the surface. However, this knowledge is very essential for the proper management of groundwater resources as the various activities such as disposal of oil at mechanic shops, domestic waste disposal and application of agrochemical which are

common in the study area have the potential to contaminate the groundwater when they are dissolved by rainwater and are not filtered by the overburden rocks. Therefore, this study contributes to the knowledge of groundwater resource in the study area and points out how effective the natural filtration process of percolation water occurs.

The study area

The total landmass of the Cape Coast Municipality is about 122 km². It is found within the area bounded by the geographical coordinates 5° 14' 0" N & 5° 4' 0" N and 1° 14' 0" W & 1° 22' 0" W. The area lies within the dry equatorial climatic zone and the moist semi-equatorial zone (GSS 2013). The range of annual rainfall is 1000–2000 mm, and temperature range is 24–30 °C (Dickson and Benneh 1995); the annual rainfall ranges from 1000 mm along the coast to about 2000 mm in the interior.

The geology of Cape Coast is mainly made of the Secondian formation and the Eburnean Plutonic Suite. The Secondian formation occurs in the south-western part of the Municipality, and the rocks are made up of sandstones, shales, siltstone and chalcedonic quartz (Kesse 1985). Fracturing and jointing resulting from tectonic activities exist to varying degrees and depths in the underlying rocks; hence, weathering profiles are also variable in extent (Dapaah-Siakwan and Gyau-Boakye 2000). Groundwater occurrence in the formation is controlled by secondary hydraulic properties (Atobrah 1980; Banoeng-Yakubo 2000). The Secondian rocks with a successful borehole drilling rate of 78% and an average yield of 15.6 m³/h have developed secondary porosities (Dapaah-Siakwan and Gyau-Boakye 2000). The Eburnean Plutonic Suite which is mainly made of biotite-granitoid and marked with multiple fracture sections produces clay and sandy-clay overburden after weathering and has a success rate of 68% for drilling wet well of 1–9 m³/h yield range (GSD 2009; Dapaah-Siakwan and Gyau-Boakye 2000) (Fig. 1).

Materials and methods

The Regional Office of Community Water and Sanitation Agency, Cape Coast, provided the data for this study. The data were taken under a project supervised by a hydrogeologist from Community Water and Sanitation Agency, Cape Coast. Twenty (20) VES points were selected after the profiling, and the Schlumberger array was applied for the conduction of the VES just as it was used for the profiling. The PASI Resistivity Terrameter was used, and the maximum current electrode spacing (AB/2) was 100 m. The limit of the current electrode spacing (AB/2) to a

Fig. 1 Geological map of the study area (modified after GSD 2009)

maximum of 100 m was in line with the original Community Water and Sanitation Agency groundwater exploration project under which the data were generated, however, the data were used for this work due to the lack of funds to conduct a new survey of a high current electrode spacing (AB/2) of more than 100 m. Partial curve matching technique and computer iteration technique were applied in the interpretation data using WINRESIST software which gives the resistivity, thickness, and depth of the various layers. Using the resistivity values of the various lithologies measured from the geoelectric survey (Table 1), evaluations of the total longitudinal conductance and overburden layer were made (1);

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (1)$$

where S is the total longitudinal conductance, Σ is the summation sign, h_i is the thickness of the i th Layer, and ρ_i is the resistivity of the i th layer (Henriet 1976).

The reflection coefficients (r) of the study area were calculated using Eq. (2);

$$r = \left(\frac{\rho_n - \rho_{(n-1)}}{\rho_n + \rho_{(n-1)}} \right) \quad (2)$$

where r is the reflection coefficient, ρ_n is the layer resistivity of the n th layer, and $\rho_{(n-1)}$ is the layer resistivity overlying the n th layer (Bhattacharya and Patra 1968a, b; Loke 1999).

The thematic maps of the parameters were generated to display their spatial variations using Surfer Golden software by the application of appropriate variograms depending on their range of values.

Results and discussion

The quantitative summary of the VES modelled results is presented in Table 1. The study revealed the presence of three- to six-layer curve types which include HKH (45%), QH (20%), HA (10%), KH (5%), QHKH (5%), A (5%), AKH (5%) and KHKH (5%) in the study area. The layers include topsoil (31.00–9135.00 Ω m), weathered layer (2.35–60,801.00 Ω m), fractured basement (4.39–32,431.00 Ω m) and fresh basement (59.40–22,521.00 Ω m). About 70% of the resistivities are less than 600 Ω m indicating the possibility of a fractured formation with high potential groundwater storage. The other 30% recorded high bedrock resistivities values of possible massive crystalline granitic rock with a limited fracture. The study area is underlain by massive and less fractured granitic rocks with limited hydraulic properties. In a granitic environment, resistivity values greater than 800 Ω m indicate the absence of both primary and secondary porosity and permeability (Okrah et al. 2012; Manu et al. 2019). However, in such an environment, the thickness of the overburden can also influence the occurrence of the groundwater as thick overburdens may have the ability to contain

Table 1 The quantitative summary of the VES modelled results

Community	VES station	Layer	Depth (m)	Thickness (m)	App. resistivity (ohm-m)	Curve characteristics	Curve type
Esikafoabantem	A60	1	3.92	3.92	31.6	$P1 > P2 < P3 > P4 < P5$	HKH
		2	7.40	3.48	11.3		
		3	11.8	4.40	7327		
		4	39.5	27.7	121		
		5	–	–	240		
	B100	1	0.83	0.83	53.7	$P1 > P2 < P3 > P4 < P5$	HKH
		2	1.62	0.79	5.59		
		3	4.38	2.76	129		
		4	13.1	8.72	4.39		
		5	–	–	2971		
Kokwaado	A80	1	0.71	0.71	319	$P1 > P2 < P3 > P4 < P5$	HKH
		2	1.53	0.82	18		
		3	3.28	1.75	321		
		4	8.93	5.65	22.3		
		5	–	–	209		
	B100	1	0.24	0.24	4606	$P1 > P2 > P3 < P4$	QH
		2	5.81	5.57	54.5		
		3	12.7	6.89	2.35		
		4	–	–	19.9		
Amamoma	B120	1	0.30	0.30	2499	$P1 > P2 > P3 < P4$	QH
		2	13.8	13.5	85.1		
		3	76.9	63.1	11.9		
		4	–	–	198		
	A92	1	1.26	1.26	34	$P1 < P2 > P3 < P4$	KH
		2	3.35	2.09	398		
		3	30	26.65	4.36		
		4	–	–	294		
Dankwakrom	A115	1	2.36	2.36	83.4	$P1 > P2 < P3 > P4 < P5$	HKH
		2	4.92	2.56	14.0		
		3	14.3	9.38	573		
		4	49.0	34.7	65		
		5	–	–	1151		
	A48	1	1.09	1.09	156	$P1 > P2 > P3 < P4 > P5 < P6$	QHKH
		2	5.88	4.79	36.9		
		3	11.7	5.82	14.8		
		4	23.2	11.5	32,431		
		5	58.1	34.9	164		
		6	–	–	1607		
		1	0.78	0.78	521		
		2	1.48	0.70	50.7		
		3	13.6	12.12	273		
Nyinasin	A98	4	32.6	312.4	52.3	$P1 > P2 < P3 > P4 < P5$	HKH
		5	–	–	22,521		
	A85	1	0.34	0.34	9135	$P1 > P2 < P3 > P4 < P5$	HKH
		2	1.06	0.72	86.7		
		3	3.00	1.94	887		
		4	7.16	4.16	17.6		
		5	–	–	9018		
Kyirakomfo	A50	1	3.68	3.68	284	$P1 < P2 < P3$	A
		2	37.7	34.02	852		
		3	–	–	60,801		
	A90	1	0.64	0.64	316	$P1 < P2 < P3 > P4 < P5$	AKH
		2	4.99	4.26	794		
		3	6.20	1.30	4154		
		4	20.2	14.00	955		
		5	–	–	1480		

Table 1 (continued)

Community	VES station	Layer	Depth (m)	Thickness (m)	App. resistivity (ohm-m)	Curve characteristics	Curve type
Wesley Girls SHS	A115	1	0.75	0.75	325	$P1 > P2 < P3 > P4 < P5$	HKH
		2	1.52	0.77	95.4		
		3	9.41	7.89	220		
		4	36.5	27.09	19.8		
		5	—	—	3879		
	A74	1	0.38	0.38	543	$P1 > P2 > P3 < P4$	QH
		2	16.3	15.92	61		
		3	34.0	17.70	14.5		
		4	—	—	6981		
Abura Roman Hill	A160	1	0.46	0.46	93	$P1 < P2 > P3 < P4 > P5 < P6$	KHKH
		2	2.64	2.18	450		
		3	7.08	4.44	90.4		
		4	17.5	10.42	6575		
		5	66.7	49.20	59.4		
		6	—	—	691		
	A98	1	1.71	1.71	1446	$P1 > P2 < P3 < P4$	HA
		2	2.84	1.13	236		
		3	30.1	27.26	544		
		4	—	—	2961		
Nkanfoa new site	A142	1	1.26	1.26	205	$P1 > P2 < P3 > P4 < P5$	HKH
		2	2.28	1.02	55.4		
		3	8.13	5.85	728		
		4	10.4	2.27	92		
		5	—	—	596		
	A62	1	0.34	0.34	2113	$P1 > P2 > P3 < P4$	QH
		2	2.25	1.91	147		
		3	16.2	13.95	27.1		
		4	—	—	5597		
Kyirakomfo	A80	1	3.75	3.75	72	$P1 > P2 < P3 > P4 < P5$	HKH
		2	7.28	3.53	2.54		
		3	18.8	11.52	4725		
		4	44.7	25.9	66.7		
		5	—	—	342		
	A110	1	0.60	0.60	170	$P1 > P2 < P3 < P4$	HA
		2	1.57	0.97	3.22		
		3	17.9	16.33	45		
		4	—	—	4501		

groundwater. The groundwater occurrence of the area is controlled by secondary hydraulic properties (Banoeng-Yakubo 2000). The connection of thick overburden and fracture zone within crystalline basement rocks improves the success rate of groundwater exploration (Olayinka 1999; Omosuyi 2000).

Therefore, knowing the depth of the overburden layers of basement rock and the reflection coefficient values is very essential for identifying potential points for groundwater exploration. Areas of high overburden thickness (> 13 m) and low reflection coefficients (< 0.8) serve as promising high-yield aquiferous zones. High overburden thickness (> 13 m) and high reflection coefficients (≥ 0.8) reveal medium-yield aquiferous zones. Areas of low overburden thickness (< 13 m) and high reflection coefficients (≥ 0.8) serve as low-yield aquiferous zones. Areas of low overburden thickness (< 13 m) and low reflection coefficients (< 0.8)

serve as very low aquiferous zones. The reflective coefficient values reveal the basement since it depends on the rock's competency (Olayinka, 1996). The values of the reflection coefficient range from 0.215606 to 0.997049. Low (< 0.8) reflection coefficient values reveal fracture/weathered bed-rock areas. The low values were observed at A60 (resistivity of 240 Ω m; thickness of 39.5 m), B100 (2971 Ω m; 12.7 m), A90 (1480 Ω m; 20.2 m), A98 (2961 Ω m; thickness of 30.1 m), A142 (596 Ω m; 10.4 m) and A80 (342 Ω m; thickness of 44.7 m). This indicates that basement rocks underlying the points above are less competent due to fracturing; hence, they may have secondary hydraulic properties that enhance the groundwater occurrence, especially when the thickness is high (> 13 m). This accounts for the high rating of groundwater potential at A60, A90, A98, and A80 (Table 2). Points B100 and A142 are rated medium and very

Table 2 Groundwater potential yield and protective capacity ratings of the VES points

VES Station	N	W	Overburden thickness (m)	Reflection coefficient (r)	Groundwater potential yield	S(Ω)	Protective capacity rating
A60	5.37194	1.35472	39.5	0.32964	High	0.661541	Moderate
B100	5.37472	1.35250	13.1	0.997049	Medium	2.164508	Good
A80	5.15861	1.36056	8.93	0.807177	Medium	0.306596	Moderate
B100	5.24778	1.43417	12.7	0.788764	Very low	3.034169	Good
B120	5.31750	1.44361	76.9	0.886613	Medium	5.461278	Very good
A92	5.30861	1.44306	30	0.970774	Medium	6.154695	Very good
A115	5.37222	1.45222	49	0.893092	Medium	0.761371	Moderate
A48	5.38028	1.44639	58.1	0.814794	Medium	0.7432	Moderate
A98	5.24111	1.54139	32.6	0.995366	Medium	6.032931	Very good
A85	5.23750	1.54778	7.16	0.996104	Low	0.246893	Moderate
A50	5.40444	1.37778	37.7	0.972361	Medium	0.052887	Poor
A90	5.39806	1.37028	20.2	0.215606	High	0.022363	Poor
A115	5.31639	1.50722	36.5	0.989843	Medium	1.414424	Good
A74	5.31056	1.50889	34	0.995854	Medium	1.482373	Good
A160	5.16333	1.31028	66.7	0.841684	Medium	0.888773	Good
A98	5.16389	1.30528	30.1	0.689586	High	0.056081	Poor
A142	5.32056	1.45139	10.4	0.732558	Very low	0.057268	Poor
A62	5.31639	1.43833	16.2	0.990363	Medium	0.527914	Moderate
A80	5.15472	1.48417	44.7	0.673599	High	1.832591	Good
A110	5.15028	1.48361	17.9	0.980202	Medium	0.667661	Moderate

low (Table 2) even though they have low reflective coefficients because of the low respective thicknesses. High (> 0.8) reflection coefficient values show massive bedrock areas. The higher values were observed at A80, B100, B120, A92, A115, A48, A98, A85, A50, A115, A74, A160, A62 and A110. This means the underlying basement rock is highly competent with less secondary developed hydraulic properties. The study revealed that 20% of the total VES points had high groundwater potential, 65% showed medium potential, 5% showed low potential, while 10% showed very low potential. The drilling results presented in Table 3 show that the groundwater exploration in the Secondian formation results in successful boreholes of good yield, while the drilling of boreholes in the granitic rocks resulted in either

a dry well or borehole of low yield. The aquiferous zone of the Secondian formation falls within the range of 17–43 m of depth with a borehole yield of 210–240 l/m. The successful borehole in the granitic rocks shows a low yield of 10 l/m with a water-saturated zone within 20–48 m of depth. This observation agrees with the findings of Manu et al. (2019). In their study, all three borehole drilling attempts in the granitic rocks failed, while all the ten drilling attempts in the Secondian formation were successful and had good yields (Manu et al. 2019). Again, from Fig. 2b the thickness of the overburden rocks is higher at the northing part and the south-western part of the study area. This shows that the two major geological formations in the study area show variations in the overburden rock thickness in the study area. The

Table 3 Selected borehole drilling results of the study area

Community	VES Station	Borehole depth	Depth to bedrock	Borehole yield	Aquifer horizon	Static water level	Status of borehole	Geology
Amamoma	B120	80	25				Unsuccessful	Granite
	A92	80	20				Unsuccessful	Granite
Nkanfoa new site	A142	49	35	10 l/m	20–48	20	Successful	Granite
	A62	75	37				Unsuccessful	Granite
Ola Madina	BH1	40	15.8	240	18–34	1.5	Successful	Secondian
UCC Campus	BH2	43	11.8	210	17–28, 37–43	19.0	Successful	Secondian

Fig. 2 Spatial variation of **a** longitudinal conductance, **b** overburden thickness, **c** reflection coefficient of the study area

area underlain by the Secondian formation generally shows low overburden rock thickness. This may be due to the presence of a shallow water table. From Fig. 2c, the reflection coefficient of the study area is highest in the eastern part. The low reflection coefficient and high thickness at the point close to the north-eastern corner of the study area make it a potential site for drilling a high-yielding borehole. However, the study area generally has a medium groundwater potential.

The use of longitudinal conductance to assess aquifer protective capacity is common in the literature (Bhattacharya and Patra 1968a, b; Olayinka 1996; Loke 1999; Golam et al. 2014; Oborin and Udom 2014). The values of the longitudinal conductance of the aquifer reveal its protective capability; higher values of longitudinal conductance indicate stronger protective capability. The study area showed poor (20%), moderate (35%), good (30%), and very good (15%) protective capacity ratings. Areas of low conductance values are vulnerable zones that are prone to groundwater contamination due to a high infiltration rate; hence, the aquifer needs to be protected from the negative impacts of anthropogenic activities such as the application of agrochemicals on farmlands, improper waste disposals and mining activities. From Fig. 2a, the longitudinal conductance is very high at the easting part of the study area and the values reduce from there towards the south-western part. This observation is in line with the geology of the study area as the south-western part is underlain by the Secondian, while the easting part is underlain by hard granitic rocks (Fig. 1).

Conclusion

Application of VES geophysical technique to investigate the groundwater potential and the aquifer protective capability has been carried out at selected communities within the Cape Coast Municipality. The study revealed the presence

of three to six layers curve types which include HKH (45%), QH (20%), HA (10%), KH (5%), QHKH (5%), A (5%), AKH (5%) and KHKH (5%) in the study area. While 30% of the total VES locations recorded high bedrock resistivity values of possible massive crystalline granitic rock with limited fracture, about 70% of the resistivity values were less than 600 Ω m indicating the possibility of a fractured formation with high-potential groundwater storage. The study revealed that the area generally has medium groundwater potential and moderate aquifer protective capability; hence, the technique has been effective in the assessment of groundwater potential and the aquifer protective capability of the area. The study reveals the high potential of the Secondian formation as compared to the Cape Coast granite. The aquiferous zone of the Secondian formation falls within the range of 17–43 m of depth with a borehole yield of 210–240 l/m. The successful borehole in the granitic rocks shows a low yield of 10 l/m with a water-saturated zone within 20–48 m of depth.

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Declarations

Conflict of interest The author declares that he has no conflict of interest.

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