Hydrogeophysical characterization of aquifers in Upper Denkyira East and West Districts, Ghana

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Abstract

Hydrogeophysical assessment of aquifers in the Upper Denkyira East and West Districts of Ghana has been carried out for groundwater potential and protective capacity of the overburden rocks determination. The data for the study were obtained from the Regional office of Community Water and Sanitation Agency (CWSA), Cape Coast. A total of thirty-seven VES probed using a Schlumberger array with maximum current electrode spacing (AB/2) of 100 m at each point using the Abeam Terameter was used. The data were interpreted using the partial curve matching and WINRESIST computer iteration program techniques. The thickness and resistivities of the various overburden layers, basement resistivity, reflection coefficient and longitudinal conductance were used for the assessment of the groundwater potential and the protective capability of the overburden layers. The study revealed three-to-six layers with an average of four (4) layers including laterite (0.34–3.57 m); clay (0.64–8.84 m); sandy-clay (0.67–27.09 m) and slightly-to-highly weathered bedrock which includes phyllites and granite (3.09–86.89 m) that show high level of heterogeneity of electrical resistivity of the geologic materials within the study area. The weathered layers serve as the aquiferous zones. About 21.6%, 62.2%, 2.7% and 13.5% showed high, medium, low and very low potential for groundwater, respectively, with higher groundwater potentials at the western and south-eastern corner of the study area underlain by the Birimian and Tarkwaian formations, respectively, indicating that the two formations have similar groundwater potentials in the study area. The lowest groundwater potential was observed at the point underlain by the granitic intrusion. The assessment of the protective capacity of the aquifer showed very good (5%), good (27%), moderate (19%), weak (22%) and poor (27%) indicating that the study area is overlain mostly by materials of different protective capacities. This study presents information on the aquifer protective capacity evaluation by using geophysical technique and it has revealed that the Birimian formation has a good aquifer protective capacity than the Tarkwaian formation and has also confirmed the effectiveness of using geophysical techniques in ground investigation.

Keywords Groundwater potential · Aquifer protective capacity · Vertical electrical sounding · Birimian supergroup · Upper Denkyira East and West Districts

Introduction

Over the years, there have been challenges in meeting the water demand in all parts of the world. The continuous increase in the uncertainty of water availability due to the impacts of factors such as high population growth rate, climate change and improved technology that demands water resources. Effective water resource management is the key to ensure the sustainability of natural resources. This

management is dependent on the available data for making informed decisions on the water resources. Some researchers have characterized aquifers in different parts of the world using evidence from hydrogeological data acquired using VES which were interpreted to reveal the characteristics of the aquifer as well as the subsurface lithological succession (Clark 1985; Jones 1985; Olayinka 1996; Oladapo and Akintorinwa 2007; Golam 2014; Ogunrayi et al. 2016). Different geoelectric layers and curve types may be obtained across a study area. Layer resistivities and thicknesses can be used to deduce parameters such as transverse resistance (T), longitudinal conductance (S), coefficient of anisotropy (I), and reflection coefficient (r) (Bhattacharya and Patra 1968; Henriot 1976; Loke 1999). The existence of human

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being depends on the availability of safe water, and the total dependence on water for life calls for a continuous supply of potable water. There is a need to improve the techniques in the groundwater search due to the continuous loss of surface water to contamination and/or climate change. The high cost of treating highly polluted surface water makes the groundwater an ideal source for domestic, industrial and other water needs; hence, the exploration of groundwater is very essential.

Besides the use of groundwater for drinking and domestic purposes, it is also used for irrigation and other agricultural purposes in all parts of the world due to irregular natural rainfall pattern (Margat and Gun 2013). The global demand for groundwater for water needs is reaching an alarming rate and gives a bad signal for the future danger which may be worsened by climate change and increased population size (EEA 1999; UNECE 1999). For effective water resource management, there is a need for the availability of information on water quality and quantity and their change with time and space. Natural pores and fractured zones within rocks serve as the channel for the flow of groundwater below the surface of the earth (Golam 2014). In a typical basement environment, the flow of the groundwater occurs within the weathered, fractured faulted zones. However, the flow occurs through porous and permeable layers of the saturated zone in sedimentary rocks.

Over the years, the application of geophysical methods in groundwater exploration has gain popularity, and there has been great advancement in data acquisition, processing and interpretation. Several geophysical methods are used in different areas and for different purposes. The vertical electrical-sounding geophysical technique is one of the techniques that is widely used in groundwater exploration globally due to its efficiency. It is one of the oldest geophysical techniques used in the studying of the earth and is still being used. Schlumberger and Wenner started using the method in 1912 and the method has gone through advancement in instrumentation, data acquisition, processing and interpretation. According to Pous et al. (1996) in the early years, the major research focus on VES was to minimize the effects of surface inhomogeneities and two-dimensional bodies. A lot of experimentation took place until the problem was solved by the recent advent of the resistivity imaging technique. Abbas et al. (2004) applied geoelectric sounding taking account of near-surface inhomogeneities in the semi-arid and arid area characterized by a sequence of sedimentary rocks formed over a long geologic period with an unconformity that separates it from the underlying igneous and metamorphic rocks in Egypt. The alluvium fan of Wadi Watir is of quaternary age, and it is the major water-bearing formation and groundwater that occur in different types of lithological compositions under unconfined and confined conditions. Abbas et al. (2004) attempted the use of one-dimensional VES in cases

where neither two-dimensional nor three-dimensional survey equipment was not available nor this has improved the one-dimensional survey technique by better estimation of geoelectrical parameters known as the Dar Zarrouk parameters. They also provided a method of studying the geologic conditions of the study area by the use of a two-dimensional representation of the number of the VES that have the same range of resistivity values at discrete half current electrode distance ($AB/2$) and the plot revealed the dominant curve type for the area which indicated is interpreted the presence of continuous geologic structures. They calculated Dar Zarrouk parameters calculated for the aquifer to examine its quality where the values of transverse resistance greater than $9000 \Omega\text{-m}^2$ were considered to indicate saltwater and this approach help them to successfully identify areas of preferable groundwater exploration and drilling. Application of VES in groundwater exploration occurs all over the world over the years (Henriet 1976; Clark 1985; Ogunrayi et al. 2016). The application of the VES technique using the Schlumberger array method was carried out at 16 VES points to determined resistivities and thicknesses of the subsurface layers and their hydrogeological properties. This study aimed at evaluating the groundwater potential of the area, establishing the aquifer protective capacity of the overlying formations, especially its isolation from contamination, and recommending suitable points for borehole drilling. The application of VES in groundwater studies is well documented in the literature (Keller and Frischknecht 1966; Keller 1967; Henriet 1976; Koefoed 1979; Kosinski and Kelly 1981).

In Ghana, groundwater is mainly used for the domestic purposes since there is no supply of treated water in villages and small towns, and most of the surface water bodies are contaminated. The major source of water in the Upper Denkyira East and West Districts is the groundwater. However, the district is also rich in gold mineralization which has attracted both large scales, small scale and illegal mining activities. These activities together with other anthropogenic activities such as agriculture in the district present major challenges in the groundwater management. The increasing demand for groundwater in the district calls for means to guarantee effective management of the groundwater resources and to ensure that the groundwater supplied for use by the public meets the drinking, domestic and irrigation water quality standards. It is, therefore, necessary to assess the groundwater resources potential and the protective potential of the overburden layers that protect the aquifer from being contaminated by fluids from the surface. However, there is limited information on the local aquifers' groundwater potentials and their protective capacities. Therefore, this study seeks to characterize the aquifers in the study area to assess their groundwater potentials and their protective capacities. Locally, the occurrence of groundwater in the study area is controlled by the underlying Birimian

meta-sediments and the Tarkwaian formation which hydraulic properties dependent on the secondary permeability created by fractures, quartz stringers, veins and shear zones that improve groundwater flow and storage. With the dependence on the secondary hydraulic properties coupled with the heterogeneity of the aquifer, groundwater flow within the aquifers occurs mainly in the fractures and other discontinuities rather than as interstitial flow. The overlying shallower weathered bed-rock profiles tend to form a confining unit to this aquifer, and the shallow quaternary sediments associated with drainage lines, if saturated, would be too thin to form useful aquifers but may form perched aquifers that support remnant vegetation. At least on a large scale, the groundwater flow would be heterogeneous and fracture-flow dominated and may also be compartmentalized into separate strip aquifers across the site (CAGL 2010). Coffey (2007) conducted terrain analysis of the regional topography and concluded that the groundwater in the study area flows toward the Offin River. However, the analysis of static water level of twenty-five inclined exploration holes drilled by Sun Gold Limited showed that the groundwater flow is radial within the study area (CAGL 2010). According to Jay Minerals Services Limited (1993), the estimated aquifer recharge of the area is 3–5% of the total annual rainfall. However, CAGL (2010) reported an estimated recharge of 15% of the total precipitation which varies locally and regionally from 1 to 20%. Examination of drilled logs of exploration holes depth of aquiferous zone to range between 6 and 92 m with a mean of 22.4 m revealing the presence of both shallow and deep-seated aquifers in the study area (CAGL 2010). Hydrogeological studies of the weathered rock in the existing pits in the study area indicated rock mass permeability in the order of 0.1–0.01 m/day where higher values were associated with the structural features within the pits which indicate that the rock mass permeability as a whole is probably as low as 0.001 m/day (CAGL 2010). In November 2006, a site audit by a team from the European Union identified elevated levels of arsenic in seepage from sections of the heap leach pads and recommended that although elevated arsenic concentrations are not widespread, the situation warrants further observation and possible mitigation measures in the study area (CAGL 2010). This study aims to understand the groundwater potentials of the aquifers of the study area and the natural capabilities of the overburden rocks to prevent contaminant fluids from polluting the groundwater from the surface.

Study area

The study area is under a forest-dissected plateau, rises to about 250 m above sea level and generally has undulating relief with pockets of steep-sided hills that alternate with flat-bottomed valleys. The district is drained by the River Dia, River Offin and several streams such as the Subin Ninta,

Afiefi and Subin which are tributaries of the two rivers. The districts fall within the semi-equatorial zone with mean annual temperatures 30 °C and 26 °C on the hottest and the coolest months, respectively. It has two rainfall regimes with total annual mean rainfall ranging between 1200 and 2000 mm which spans from May to June, and from September to October, respectively, while the dry season occurs from November to February. The area is favorable for cocoa production; hence, the district is one of the leading producers in the region. The area is endowed with Gold and other natural mineral resources, and this has attracted more than ten mining companies that are currently operating in the districts. Also, many small-scale mining companies operate in the districts.

The study area is underlain by the Middle Precambrian hydrogeological unit which is extensively dominated by Birimian and Tarkwaian formations aligned in the north-eastern and south-western directions (Fig. 1). Both Birimian and Tarkwaian formations consist of phyllite in relative abundance but they differ in age. The Birimian rocks are made up of metamorphosed volcanic and sedimentary rocks. They have been folded, metamorphosed under the greenschist-facies condition and invaded by granitoids during the Eburnean (Junner 1935; Leube et al. 1990). Abouchami et al. (1990) suggest that the rocks were deposited on deformed and metamorphosed basement rocks of not more than 50 Ma old. The Birimian supergroup is made up of two major lithostratigraphic units, namely Birimian Sedimentary Basin and Birimian Volcanic Belts (Kesse 1985). The rocks of the Birimian formation are folded, foliated and these together with the faults, folds, foliations and joints of the formation enhance the permeability for groundwater, storage and transmission in the rocks (Junner 1935). The contact zone between the Birimian rocks and the granitoids is highly sheared; showing formed foliations oriented N–S. Also, aligned parallel to the plane of shearing is quartz and pegmatite veins. The rocks of the Birimian Sedimentary Basin are represented by a great thickness of isoclinally folded, steeply dipping, alternating phyllites, schistose greywackes, sheared conglomerates, slates and argillaceous beds with some tuffaceous schist and lava. As a result of the extensive shearing, schists dominate at the contact between the Birimian Sedimentary Basin rocks and granitic intrusives. The rocks are of polygenic origin, having been mud and silts with beds of coarser sediments (Kesse 1985). The Dixcove granite (G2) is a complex rock that intrudes into the Birimian metavolcanic and hence is volcanic belts granitoid. These rocks consist of soda-rich hornblende, biotite granite or granodiorites which grade into quartz diorite and hornblende diorite and are commonly tonalitic in composition. The rocks found in the study area include greywackes, phyllites, slates, schists, tuffs, conglomerate, mudstone, siltstones, granite and sandstones. Therefore, some common

Fig. 1 Geological map of the study area (Okrah et al. 2012)

minerals in the area include orthoclase, plagioclase, quartz, biotite, muscovite, amphibole, hornblende, calcite, silica and chlorite. Anornu et al. (2009b, a) observed that there were poor relations between borehole yield and depths in the Birimian rocks. They concluded that the transmissivity of the boreholes varies between 0.12 and 125 m²/day from pumping test data. According to the Ghana Geological Survey Department (GSD 2009), whereas the synvolcanic intrusive rocks were formed within the Birimian supergroup period (2195–2135 Ma), the undifferentiated intrusive granitoids were formed in the Eburnean Plutonic Suite period (2120–2115 Ma) as a result of partial melting of slightly older Birimian sediments during the Eburnean tectono-thermal event. The synvolcanic granitoids yield a significant amount of groundwater than the undifferentiated intrusive granitoids, which is because the former has well-developed and connected fractures than the latter (Kesse 1985).

The Tarkwaian Group is made of a variety of sandstones, conglomerates and argillites, and its occurrences have been found on the eastern margin of the Sefwi Belt, in the Kibi-Winneba belt and the northern Nangodi Belt beside the study area (Griffis et al. 2002). The Tarkwaian is subdivided into four major units, which are, from the base to the top:

the Kawere Group; the Banket Series; the Tarkwa Phyllite; and the Huni Sandstone. The conglomeratic units of the Tarkwaian Group is interpreted as having been deposited in alluvial fans and then reworked by braided stream channels (Griffis et al. 2002). The latter is thought to have concentrated fine particles of gold within the channel conglomerates. The Tarkwaian is folded along the north-eastern axis which enhances the groundwater potential (Kesse 1985). Moreover, according to the CSIR-WRI Database (2007), the Birimian and Tarkwaian formations of the area are marked with extensive weathering, availability of quartz vein and the presence of buried river channel (Dickson and Benneh 1980) as contributory factors to promote groundwater potential in the terrain (Kortatsi 1994).

Methodology

The data for this study were taken from the Regional Office of community water and sanitation Agency, Cape Coast. The data were taken by qualified professionals who observed the appropriate protocols to ensure the accuracy of data. Originally the data were taken under a project aimed to supply

water to some selected communities within the districts. The data were taken Abeam Terrameter which principle of operation is the determination of subsurface resistivity variation with depth by the measurement of the resistance of the various lithologies for the generation of the apparent resistivity of the lithologies. A total of 37 VES points were probed in the study area using the symmetrical Schlumberger electrode spread technique with maximum electrode spacing ($AB/2$) of 100 m. The resistance recorded from the machine at each point was multiplied by the geometric factor k for the electrode separation to get the apparent resistivity. The apparent resistivity values were plotted against $AB/2$ on logarithmic forms for the preview of the aquifer characterization and noise minimization by the repetition of measurements until acceptable readings were obtained at a standard deviation in the order of $10^{-2}\%$ as the curves were interpreted by partial curve matching technique. The geoelectric parameters from the partial curve matching served as the input model for computer-assisted iteration using WINRESIST. The existing boreholes in the study area were calibrated to assess the groundwater potential at the local hydrogeological unit and thereby estimate the success rate of the drilling program. Longitudinal conductance of the overburden rock units was used to evaluation of aquifer protective capacity. The longitudinal unit conductance gives a measure of the impermeability of the confining clay layer, which has low resistivity and low hydraulic conductivity. The longitudinal layer conductance (S) of the overburden at each station was obtained from Eq. (1)

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

where S is the total longitudinal conductance, Σ is 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) below.

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

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

Results and discussion

The use of the geoelectrical resistivity method in groundwater studies including the assessment of groundwater potential and the aquifer protective capabilities is well documented in the literature (Golam et al. 2014; Keller and Frischknecht

1966; Koefoed 1979; Olorunfemi et al. 1998; Henriet 1976). Table 1 gives a summary of the geoelectric parameters of the study area. The characteristic curves include KH (17), HKH (3), K (1), KHKQ (1), KQ (1), KQH (2) QHK (1), KHKH (1), KHK (1), QH (1), KHA (2), AA (1), HA (1), A (1), AKH (3). The study revealed three-to-six layers with an average of four (4) layers according to the geophysical analysis of the weathered overburden zone in the formation including laterite (0.34–3.57 m); clay (0.64–8.84 m); sandy-clay (0.67–27.09 m) and slightly to highly weathered bedrock which includes phyllites and granite (3.09–86.89 m) which reveals a high level of heterogeneity of electrical resistivity of the geologic materials within the study area and the weathered layers serve as the aquiferous zones. The abundance of the four-layer lithologies, especially in the Birimian formation, agrees with the observation of Okrah et al. (2012), .

Groundwater potential of the study area

According to Okrah et al. (2012), the geophysical interpretation of the Tarkwaian formation of the study area shows that it consists of four layers of sandy-clay, laterite, weathered phyllite and granite and the aquiferous zone located in the third or fourth layer with a characteristic average resistivity of 415.05 Ω m, borehole located at 122–148 m above mean sea level, average resistivity and thickness of the overburden rocks being 491.82 Ω m and 2.38 m, respectively, while the depth of the borehole ranges between 40.0 and 75.0 m with an average of 55.0 m. The first layer consists of an average 3 m sandy-clay and laterite patches; the bedrock is phyllite and granite buried within the ranges of 3–24 m with an average of 16 m deep and shows different degrees of weathering at different locations. The average potential yield of a borehole is 19 L/min ranging between 12 and 30 L/min. CSIR-WRI Database (1996) recorded depths to aquifer range of 6–69 m with a mean of 37 m, Coffey (2007) reported a range of 13–60 m, while CAGL (2010) reported a range of 6–92 m with a mean of 22.4 m. This reveals the presence of both shallow and deep-seated aquifers in the study area. The Birimian is characterized by structural features such as well-developed joint and fracture systems as well as quartz veins within the phyllite bodies. These structural features, as well as the extent of weathering, determine groundwater occurrence in the Birimian system. The best aquifers are located where significantly decomposed materials have been accumulated, which are usually along the slopes of the synclinal troughs (Dapaah-Siakwan and Gyau-Boakye 2000). The predominantly argillaceous sediments have metamorphosed into schist, slate, phyllite and greywacke. The tuff and lava range from mafic to silicic composition with many of the mafic extruded underwater. The contact between the saprolite and

Table 1 Summary of the geoelectric parameters of the study area

Community	VES station	Layer	Depth (m)	Thickness (m)	App. resistivity (Ω -m)	Curve characteristics	Curve type
Akwaboso	A60	1	0.96	0.96	80	P1 < P2 > P3 < P4	KH
		2	9.80	8.84	233		
		3	84.2	74.4	9		
		4	—		410		
	A140	1	0.34	0.34	2043	P1 > P2 < P3 > P4 < P5	HKH
		2	1.81	1.47	111		
		3	2.48	0.67	4069		
		4	83.0	80.52	9		
		5	—		410		
	B78	1	0.72	0.72	39	P1 < P2 > P3 < P4	KH
		2	1.91	1.19	2720		
		3	88.8	86.89	26		
		4	—		284		
	A182	1	3.57	3.57	304	P1 < P2 > P3 < P4	KH
		2	8.25	4.68	1080		
		3	30.9	22.65	10		
		4	—		539		
Efefiso	D78	1	1.28	1.28	517	P1 < P2 > P3	K
		2	16.2	14.92	1017		
		3	—		161		
	Existing BH	1	0.71	0.71	220	P1 < P2 > P3 < P4 > P5 > P6	KHKQ
		2	1.47	0.76	1327		
		3	3.07	1.6	181		
		4	6.16	3.09	815		
		5	52.0	45.84	166		
		6	—		4.76		
	C52	1	1.19	1.19	82	P1 < P2 > P3 < P4	KH
		2	4.81	3.62	390		
		3	16.3	11.49	141		
		4	—		737		
Dominase	C188	1	1.16	1.16	80	P1 < P2 > P3 < P4	KH
		2	3.34	2.18	652		
		3	9.54	6.2	23		
		4	—		40		
	B50	1	0.43	0.43	305	P1 < P2 > P3 > P4	KQ
		2	1.07	0.64	2983		
		3	7.52	6.45	237		
		4	—		54		
	B76	1	1.21	1.21	570	P1 < P2 > P3 > P4 < P5	KQH
		2	2.27	1.06	2991		
		3	9.59	7.32	107		
		4	40.3	30.71	35		
		5	—		2751		
	Existing BH	1	1.06	1.06	20	P1 < P2 > P3 < P4	KH
		2	3.55	2.49	98		
		3	6.92	3.37	13		
		4	—		104		

Table 1 (continued)

Community	VES station	Layer	Depth (m)	Thickness (m)	App. resistivity (Ω -m)	Curve characteristics	Curve type
Kwameprakrom	B145	1	0.57	0.57	12	P1 < P2 > P3 < P4	KH
		2	1.75	1.18	1002		
		3	6.52	4.77	4		
		4	–		143		
	C150	1	1.41	1.41	105	P1 < P2 > P3 < P4	KH
		2	4.35	2.94	1154		
		3	26.6	22.25	16		
		4	–		4432		
	A130	1	0.43	0.43	130	P1 < P2 > P3 < P4	KH
		2	4.61	4.18	569		
		3	31.7	27.09	23		
		4	–		5507		
	A88	1	0.56	0.56	24	P1 < P2 > P3 < P4	KH
		2	6.53	5.97	153		
		3	17.7	11.17	8		
		4	–		4231		
	C80	1	3.30	3.30	74	P1 < P2 > P3 < P4	KH
		2	7.72	4.42	356		
		3	23.5	15.78	14		
		4	–		5668		
	A168	1	1.61	1.61	741	P > P > P < P > P	QHK
		2	7.99	6.38	64		
		3	16.6	8.61	15		
		4	25.8	9.2	88		
		5	–		17		
	A52	1	0.43	0.43	253	P < P > P < P > P < P	KHKH
		2	1.50	1.07	637		
		3	2.67	1.17	8		
		4	7.02	4.35	100		
		5	29.4	22.38	22		
		6	–		54		
	C62	1	1.81	1.81	54	P < P > P < P > P	KHK
		2	3.50	1.69	766		
		3	8.30	4.8	38		
		4	18.1	9.8	502		
		5	–		31		
	A142	1	1.69	1.69	543	P > P > P < P	QH
		2	8.10	6.41	58		
		3	10.7	2.6	15		
		4	–		37		
	B75	1	0.47	0.47	263	P < P > P > P < P	KQH
		2	1.40	0.93	1344		
		3	7.14	5.74	118		
		4	12.2	5.06	12		
		5	–		39		

Table 1 (continued)

Community	VES station	Layer	Depth (m)	Thickness (m)	App. resistivity (Ω -m)	Curve characteristics	Curve type
	A100	1	0.46	0.46	41	P < P > P < P < P	KHA
		2	1.58	1.12	634		
		3	3.48	1.9	4		
		4	83	79.52	45		
		5	–		90		
Agyiempaboa	C115	1	0.53	0.53	173	P > P < P > P < P	HKH
		2	1.41	0.88	39		
		3	4.53	3.12	1184		
		4	32.8	28.27	58		
		5	–		3940		
Akropong	C65	1	0.61	0.61	74	P < P < P < P	AA
		2	2.92	2.31	157		
		3	30.1	27.18	381		
		4	–		8750		
	D98	1	1.60	1.60	15	P < P > P < P	KH
		2	14.3	12.7	22,261		
		3	43.6	29.3	622		
		4	–		21,889		
	D42	1	4.67	4.67	40	P < P > P < P	KH
		2	27.1	22.43	98,100		
		3	38.7	11.6	491		
		4	–		21,889		
	C115	1	0.40	0.40	829	P > P < P < P	HA
		2	6.55	6.15	112		
		3	25.2	18.65	268		
		4	–		75,845		
Adwumam	A172	1	0.49	0.49	15	P < P > P < P	KH
		2	0.77	0.28	5609		
		3	25.8	25.03	241		
		4	–		21,889		
	B60	1	2.44	2.44	57	P < P < P	A
		2	21.6	19.16	235		
		3	–		52,660		
	A95	1	1.97	1.97	432	P < P > P < P < P	KHA
		2	3.79	1.82	1442		
		3	9.53	5.74	512		
		4	52.7	43.17	2043		
		5	–		48,529		
	A130	1	0.63	0.63	78	P < P > P < P	KH
		2	4.44	3.81	1508		
		3	23.5	19.06	733		
		4	–		290,000		

Table 1 (continued)

Community	VES station	Layer	Depth (m)	Thickness (m)	App. resistivity (Ω -m)	Curve characteristics	Curve type
Buaben	A42	1	1.89	1.89	37	P < P > P < P	KH
		2	5.27	3.38	10,448		
		3	56.6	51.33	479		
		4	–		1898		
	B112	1	1.87	1.87	170	P < P > P < P	KH
		2	4.09	2.22	6423		
		3	27.8	23.71	530		
		4	–		34,546		
	A240	1	1.00	1.00	410	P < P < P > P < P	AKH
		2	8.14	7.14	1003		
		3	15.1	6.96	2060		
		4	34.4	19.3	376		
		5	–		94,881		
	A110	1	0.31	0.31	6122	P > P < P > P < P	HKH
		2	1.11	0.8	98		
		3	2.37	1.26	6052		
		4	33.3	30.93	603		
		5	–		130,000		
	Existing BH (304 BU1)	1	0.66	0.66	152	P < P < P > P < P	AKH
		2	4.78	4.12	280		
		3	7.02	2.24	3312		
		4	83	75.98	1333		
		5	–		27,753		
	B68	1	0.90	0.90	15	P < P < P > P < P	AKH
		2	3.19	2.29	97		
		3	4.87	1.68	100,000		
		4	77.7	72.83	12,723		
		5	–		1,100,000		

the saprock is the most productive groundwater zone within the Birimian system as they usually complement each other in terms of permeability and storage (Carrier et al. 2008a, b). The fracture systems within the granitoids are localized with overlying porous weathered profiles serving as a storage reservoir. Dapaah-Siakwan and Gyau-Boakye (2000) upon analysis of borehole data in Ghana concluded that the mean depth of boreholes in the Lower Birimian rocks and the associated granites was 35 m and 60 m, respectively. They estimated the yield of boreholes in the Birimian to be about 212 l/min (12.7 m³/h). Bayewu et al. (2018) observed that the use of the thickness of overburden rocks and the

reflection coefficient is good in estimating the groundwater potential in a typical basement terrain.

In this study, thirty-seven potential points selected after the horizontal profiling were probed by using the Schlumberger technique for the determination of the vertical variation of rock resistivity with depth to identify the thickness of the regolith and possible aquiferous zone.

Existing boreholes were added to the selected points for calibration as evidence of the hydrogeological conditions of the study area. Groundwater potential of the area was classified as high, medium and low regarding the overburden thickness and reflection coefficient values. The study revealed that the areas of highest groundwater yield are characterized

by thick overburden (> 13 m) overlying the fractured zone which showed low reflection coefficients ($r < 0.8$). About 21.6% showed a high groundwater potential. When the overburden rock is thick (> 13 m) and the reflection coefficient is high ($r > 0.8$) the area is said to have medium groundwater potential and 62.2% of the total VES points were found in this category. An area of thin layer and high reflection coefficient shows low potential, while an area of thin layer and low reflection coefficient shows very low potential. The study shows that about 2.7% and 13.5% of the VES points have low and very low potentials, respectively, which agrees with the previous studies of the area. Spatially, the thickness of the overburden rocks is higher in the northernmost and the south-eastern corner of the study area, while the lowest is seen close to the center of the study area (Fig. 2a). However, the reflective coefficient of the study area is higher at the western and southern parts of the study area (Fig. 2b). The point that shows the lowest overburden also shows a lower reflective coefficient. The point is underlain by a granitic intrusion (Fig. 1) which is the cause of such occurrences. To display the spatial variation of groundwater potential of the study area, numerical weight was assigned to the various rating as shown in Table 2. Based on the weight assigned to the various potential yields, a thematic map of the groundwater potential of the study area was generated (Fig. 2c) which reveals that the groundwater potential is higher at the western and south-eastern corner of the study area.

The western side of the study area is mainly underlain by the Birimian, while the south-eastern corner is underlain by the Tarkwaian indicating that the two formations have similar groundwater potential in the study area. The point of lowest groundwater potential is the point underlain by the granitic intrusion. The observations in this study agree with that of previous studies. According to previous studies, phyllite is the major rock type of the Birimian and the Tarkwaian formations which underlain the study area which is strongly foliated, fractured, weathered, contains quartz vein, the possible presence of buried river channel which has a relatively rich aquifer of 0.3–250 L/min borehole yield with an average yield of 12.7 L/min, a success rate of 75%, borehole depth of 34–60 m with an average of 53 m, hence, drilling to the right depth results to borehole success (Wyllie 1963; Kesse 1985; Dickson and Benneh 1980; Kortatsi 1994; Dapaah-Siakwan and Gyau-Boakye 2000; CSIR-WRI Database 2007; Okrah et al. 2012). Some studies and available data have suggested the yield of 4–250 L/min, 5.0–7.0 L/min which still supports the high groundwater potential of the study area (GSD 2012; Okrah et al. 2012). The undulating topography influences the thickness which controls the aquifer horizon at any site in the study area. Okrah et al. (2012) observed laterite, clay, sandy-clay and bedrocks made of partly weathered or fresh phyllite and granite in the Birimian environment. They reported on 100% borehole drilling success rate with a drilling yield

range of 12.0–60.0 L/min and an average depth of successful boreholes of 38.8 m within the study area and comparison of the geophysical analysis and the borehole drilling logs (Table 3) revealed that the number of layers obtained from the geophysical analysis was not the same as those obtained from the drilling logs and they attributed this occurrence to the ambiguities existing among the adjoining beds. However, they observed that the aquiferous horizons predicted from the geophysical interpretation were confirmed by the water-bearing zone shown by the logs (Table 4) indicating the appropriateness of the use of the geophysical technique to generally present adequate information on the subsurface condition useful for resources exploration. CSIR-WRI (1996) recorded a borehole yield range of 10.0–136.7 L/min with an average of 45.0 L/min, while Coffey (2007) recorded a borehole yield range of 11.7–179.8 L/min with a mean of 45 L/min. This reveals that the average borehole yield of the study area is around 45 L/min. Coffey (2007) reported that the aquifers of the study area have a limited areal extent, low storage capacity, a transmissivity range of 1.7–3.7 m²/day and an average of 2.98 m²/day. He also recorded a static water level range of 1.7–23.3 m with a mean of 9.16 m, while CAGL (2010) recorded a range of 1.7–26.6 m with a mean of 12.62 m in the inclined holes.

Aquifer protective capacity evaluation

In the absence of an impermeable overlying layer such as clay, the aquifer becomes vulnerable to the inflow of contaminated fluid. Naturally, the earth materials filter contaminated fluids as they percolate through them to the groundwater and this defines their protective capacity which can be assessed by the geoelectrical method (Olorunfemi et al. 1998). The assessment of aquifer protective capability depends on the natural laws by which the environment protects the groundwater from surface contamination to some degree through filtration. Henriet (1976) showed that the longitudinal conductance (S) can be used to evaluate the hydrologic properties of an aquifer and the protective capacity of an overburden rock is considered to be proportional to the longitudinal unit conductance in mhos (Olorunfemi et al. 1998). Due to the large-scale mining, illegal small-scale mining ('galamsey') and farming activities that are common in the study area the groundwater can easily be contaminated and consequently pollute the whole aquifer system within the catchment area, and hence, there is a need to assess the capability of the rocks to prevent such contaminations from mining, farming and other anthropogenic sources. The longitudinal conductance was evaluated from the thickness and resistivity values of the various geoelectric layers, and the values were used in the classification of the aquifer protective capacity of the VES locations. Impervious materials

show high longitudinal conductance values as a result of their low resistivity values, while permeable ones have low longitudinal conductance values due to their high resistivity values. High longitudinal conductance values indicate excellent aquifer protective capacity, while low values reveal poor protective capacity. The longitudinal unit conductance values which reveal very good to poor capacities of the overburden materials in the study area are shown in Table 5. The various VES points showed the capacities as very good (5%), good (27%), moderate (19%), and weak (22%) and poor (27%). High longitudinal conductance indicates

relatively high protective capacity of the overburden rocks. The areas of weak and poor aquifer protective capacities are potential zones of high infiltration rates from liquid from the surface; hence, they are areas vulnerable to leachate and other surface contaminants. The study reveals that generally, the overburden layer can protect the groundwater system from infiltration of fluid contaminants. However, there were weak and poor zones that can serve as vulnerable zones for contamination. These poor zones revealed areas of thin overburden rocks and high electrical resistivities. The variation in the aquifer protective capacities within the study

Fig. 2 Thematic map showing the spatial distribution of **a** overburden thickness and **b** reflective coefficient, **c** groundwater potential yield rating and **d** longitudinal unit conductance in the study area

area agrees with the observation of Okrah et al. (2012) that the rock formation in the study area is highly anisotropic with varying petrophysical properties like the attitude of the bedding plane, texture, sorted grains, pore size and interconnection between pores or fractures which are influenced by agents such as weathering, sedimentation, compaction or crystallization to define the characterization of the formation which calls for a careful selection appropriate geophysical technique to be employed for a successful groundwater investigation. The spatial variation of the aquifer protective capacity of the area is shown in Fig. 2d. The higher capacity values are seen in the north-western corner of the study area, while the lowest values are seen in the south-western corner of the area. The Tarkwaian formation shows poorer aquifer protective capacity as compare to the Birimian formation. It is, therefore, important for the groundwater resources to

be protected from surface contaminates in the study area, especially in the Tarkwaian formation.

Conclusion

After extensive geophysical exploration for groundwater within the study area, the predictions were validated from previous studies. The study revealed that the characteristic curves include KH (17), HKH (3), K (1), KHKQ (1), KQ (1), KQH (2) QHK (1), KHKH (1), KHK (1), QH (1), KHA (2), AA (1), HA (1), A (1), AKH (3). The study revealed three-to-six layers with an average of four (4) layers according to the geophysical analysis of the weathered overburden zone in the formation including laterite (0.34–3.57 m); clay (0.64–8.84 m); sandy-clay (0.67–27.09 m) and slightly to highly weathered bedrock which includes phyllites and granite (3.09–86.89 m) which reveals a high level of heterogeneity of electrical resistivity of the geologic materials within the study area. The weathered layers serve as the aquiferous zones. About 21.6%, 62.2%, 2.7% and 13.5% showed high, medium, low and very low potentials for groundwater, respectively, with higher groundwater potentials at the western and south-eastern corner of the study area underlain by the Birimian and Tarkwaian formations, respectively, indicating that the two formations have similar groundwater potentials in the study area. The lowest groundwater potential was observed at the point underlain by a granitic

Table 2 Numerical weight of groundwater potential yields

Groundwater potential yield	Numerical weight
Very low	1
Low	2
Medium	3
High	4

Table 3 Comparison between drilling and geophysical results (Okrah et al. 2012)

Community	VES point	No of layers		Depth to bedrock (m)			Aquifer horizon (m)	
		Geophysical interpret	Borehole drilling	Geophysical interpretation	Borehole drilling		Geophysical interpretation (estimated)	Borehole drilling
					weathered	Hammed		
Buabinso	B30	3	4	2.7	18.0	Deep-seated	40.0–50.0	25.0–36.0
	C100	4	4	0.7	3.0	7.0	20.0–40.0	32.0–39.0
Congo No.1	B80	3	5	42.8	18.0	Deep-seated	15.0–40.0	17.0–23.0
Zion No.1	A40	3	4	27.9	24.0	33.0	40.0–60.0	31.0–40.0
Achiase	B100	4	5	3.0	7.0	19.0	10.4–extended	20.0–38.0

Table 4 Correlating lithology deduced from geophysics with the drilling results (Okrah et al. 2012)

Borehole site		Drilling log		Geophysics		
Community	VES Point	Lithology	Thickness (m)	Resistivity (Ω m)	Thickness	Layer
Community	B30	Sandy-clay and gravel	0–2	147.7	2.7	1
		Sandy-clay	2–10			2
		Sandy-clay and gravel	10–18			3
		Rusty weathered phyllite	18–38	57.7	15.9	–
		Weathered granite	27–33			
		Fresh granite	33–51			

Table 5 Longitudinal unit conductance, aquifer protective capacity and groundwater potential of the study area

VES station ID	N	W	S (Ω)	Protective capacity rating	Overburden thickness (m)	Reflection coefficient	Groundwater potential yield	Numerical weight
A60	6.228567	2.035633	8.316607	Very good	84.2	0.957041	Medium	3
A140	6.227917	2.035967	8.960241	Very good	83	0.957041	Medium	3
B78	6.228833	2.035900	3.360822	Good	88.8	0.832258	Medium	3
A182	6.227583	2.036150	2.281077	Good	30.9	0.96357	Medium	3
D78	6.213717	2.044633	0.017146	Poor	16.2	-0.72666	High	4
Existing BH	6.211567	2.045283	0.292576	Moderate	52	-0.94425	High	4
C52	6.209400	2.045933	0.105284	Weak	16.3	0.678815	High	4
C188	6.049683	1.958400	0.287409	Moderate	9.54	0.269841	Very low	1
B50	6.061333	1.941533	0.039564	Poor	7.52	-0.62887	Very low	1
B76	6.058167	1.958450	0.948317	Good	40.3	0.974874	Medium	3
Existing BH	6.047983	1.960600	0.337639	Moderate	6.92	0.777778	Very low	1
B145	6.054500	1.958883	1.241178	Good	6.52	0.945578	Low	2
C150	6.049283	1.958683	1.406601	Good	26.6	0.992806	Medium	3
A130	6.044233	1.964450	1.18848	Good	31.7	0.991682	Medium	3
A88	6.044617	1.964567	1.458603	Good	17.7	0.996226	Medium	3
C80	6.049283	1.959317	1.184153	Good	23.5	0.995072	Medium	3
A168	5.958567	1.822500	0.780406	Moderate	25.8	-0.67619	High	4
A52	5.959483	1.831250	1.210402	Good	29.4	0.421053	High	4
C62	5.965733	1.827333	0.181562	Weak	18.1	-0.88368	High	4
A142	5.958783	1.830900	0.286963	Moderate	10.7	0.423077	Very low	1
B75	5.958850	1.830783	0.47279	Moderate	12.2	0.529412	Very low	1
A100	5.959117	1.831050	2.255097	Good	83	0.333333	High	4
C115	5.965583	1.823667	0.515677	Moderate	32.8	0.970985	Medium	3
C65	5.925050	1.689483	0.094295	Poor	30.1	0.916548	Medium	3
D98	5.922617	1.691900	0.154343	Weak	43.6	0.944738	Medium	3
D42	5.923033	1.691767	0.140604	Weak	38.7	0.956122	Medium	3
C115	5.924200	1.714500	0.124983	Weak	25.2	0.992958	Medium	3
A172	5.927917	1.677333	0.136576	Weak	25.8	0.97822	Medium	3
B60	5.923617	1.698183	0.124339	Weak	21.6	0.991114	Medium	3
A95	5.927567	1.705167	0.038164	Poor	52.7	0.919204	Medium	3
A130	5.927833	1.707167	0.036606	Poor	23.5	0.994958	Medium	3
A42	5.880817	1.759150	0.158565	Weak	56.6	0.596971	High	4
B112	5.880117	1.758883	0.056081	Poor	27.8	0.96978	Medium	3
A240	5.879067	1.758900	0.064266	Poor	34.4	0.992106	Medium	3
A110	5.880150	1.759567	0.059716	Poor	33.3	0.990766	Medium	3
Existing BH	5.879067	1.758233	0.076732	Poor	83	0.908341	Medium	3
B68	5.880050	1.759283	0.089349	Poor	77.7	0.977132	Medium	3

intrusion. The assessment of the protective capacity of the aquifer showed very good (5%), good (27%), moderate (19%), and weak (22%) and poor (27%). The study area is overlain mostly by materials of different protective capacities. The study shows that the Tarkwaian formation has poorer aquifer protective capacity as compare to the Birimian formation. It is, therefore, important for the groundwater resources to be protected from surface contaminates in the study area, especially in the Tarkwaian formation. This is

because the groundwater in the formation is vulnerable to surface contaminants such as mining waste, sewage, effluent and indiscriminate waste disposal in the study area. The study has confirmed that geophysical techniques are an effective scientific tool in groundwater exploration.

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Declaration

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

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