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CASE STUDY

Using electrical resistivity imaging technique for borehole calibration in selected communities in Asutifi North District, Ghana

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Abstract

This study has investigated the use of Electrical Resistivity (ER) technique for siting suitable groundwater points in selected communities within the Asutifi North District of Ghana where borehole drilling success rate has been low, leading to water shortages in the dry season. The study method employed involved 2D Electrical Resistivity Imaging (2D ERI) survey along existing boreholes in the area using the dipole-dipole array and correlating the outputs with existing 1D Vertical Electrical Sounding (1D VES) data and its corresponding borehole logs of the area to delineate the potential groundwater zones. The results from the 2D ERI survey showed the potential groundwater zones to be at depths of 14.7 to 58.9 m with resistivity values ranging from 2.08 to 156 Ωm while that for the 1D VES were at depths of 20 to 60 m with resistivities ranging from 67.10 to 545.28 Ωm. Also, the delineated potential groundwater zones from the 2D ERI showed a positive linear correlation with the observed aquifer zones from the borehole logs at a correlation coefficient (R^2) of 0.72, whereas no correlation was observed when the observed aquifer zones from the borehole logs were compared to potential groundwater zones from the 1D VES data. Additionally, the 2D pseudo-sections from the 2D ERI survey aided in categorising the different potential groundwater zones in the area as good, moderate, fair and poor. Thus, the 2D ERI technique provided more detailed information on the subsurface in the area than the 1D VES approach and would be more reliable for subsequent groundwater exploration projects in the area and similar geological terrains.

Keywords: Groundwater, Electrical Resistivity Imaging, Vertical Electrical Sounding, Ghana

Introduction

The development of groundwater resources is essential in the delivery of safe drinking water in most rural communities and small towns in Ghana since it is relatively abundant, cheap to develop, and needs little to no treatment, unlike surface water (Nazifi, 2021). Also, nearly one-third of the population in the world depends on groundwater for drinking (Tay, 2021). This notwithstanding, about 44 % of rural Africa still has no access to sustainable and affordable safe drinking water (Agyekum and Asare, 2016). According to the Community Water and Sanitation Agency (CWSA) rural water coverage report for 2020, about 38 % of the rural population in Ghana is unserved with clean water. Furthermore, it is estimated that over 58 % of the rural population in the Asutifi North District has no access to reliable and affordable drinking water services mainly due to poor borehole drilling success rate in some communities within the district coupled with high levels of iron, manganese, and fluoride in the groundwater beyond permissible limits for drinking in some communities (CWSA, 2012). These challenges have significantly contributed to the low rural water coverage resulting in acute water shortages and overcrowding at the few functional point sources, especially during peak hours of fetching, which often compels many people to resort to polluted and untreated water sources, exposing them to water-related diseases (like cholera, typhoid fever, dysentery, etc.) and their repercussions. The unpredictability of rainfall and the high cost of treating surface water sources make development of groundwater resources the most viable option for the attainment of the Sustainable Development Goal (SDG) 6.1, particularly, in the study area.

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However, the availability of groundwater in any area depends largely on the recharge and hydrogeological conditions of the area (Aning *et al*., 2019). In Ghana, groundwater in economic quantities within crystalline basement formation, underlying the area, is mostly associated with the presence of joints, fractures, and weathered zones (Issah, 2015; Aning *et al*., 2019). This is because the occurrence and movement of groundwater in the rock types of this formation are largely controlled by secondary pores (Yeleliere, 2018). Also, according to Aning *et al*. (2019), the secondary pore spaces within this geologic formation differ from one place to another at varying depths; hence, the aquifers are more discontinuous and localized. Therefore, the main challenge in developing groundwater resources in areas underlained by such geologic formations is identifying the appropriate locations for the drilling of productive boreholes.

Generally, detailed geophysical investigations are often required in locating suitable sites for the secondary pores (i.e., fractures, joints, and weathered zones) and delineating the potential aquifer zones before drilling boreholes in such geological formation. The available geophysical techniques used for such purpose include Electrical Resistivity (ER), Electromagnetic (EM), Seismic, Gravity, and Ground Penetration Radar (GPR) (Maxwell *et al*., 2021). These techniques measure variations in physical properties such as resistivity, conductivity, velocity, density, and dielectric permittivity of the geologic media, which are influenced by porosity, degree of saturation, and quality of the water it contains. Among the geophysical techniques for groundwater prospecting, electrical resistivity (ER) and electromagnetic (EM) methods are the most popular techniques used for siting boreholes in Ghana (Aning *et al*., 2019; Issah, 2015).

The EM technique is commonly used for mapping and detection of conductive zones and has been used to explore groundwater successfully in different hydrogeological formations (Maxwell *et al*., 2021). However, the depth of investigation is limited when conductive superficial interference layers are present (Maxwell *et al*., 2021). The ER technique, on the other hand, can probe deeper depths and the physical property measured could be directly related to the presence of pore spaces and degree of saturation. In the ER survey, the electrical resistivity profile at depth can be acquired by employing the 1D VES or the 2D ERI (Maxwell et al., 2021). The 1D VES technique measures the resistivity of the subsurface as a function of depth while the 2D ERI produces discrete resistivity measurements of the subsurface through various points at different depths, which are interpolated to provide continuous 2D images of the subsurface, making it possible to analyze the variation of the electrical resistivity laterally and with depth. The 2D ERI data acquisition is relatively cheaper, and a large amount of data can be acquired over a vast area with limited time and labour. Additionally, 2D ERI outputs give detailed information on subsurface geological features such as the presence of dykes, fractures, and their orientations unlike the traditional 1D VES data.

The 1D VES technique, in particular, has been used widely used for the delineation of aquifers in different geologic formations (Ewusi and Kuma, 2011; Aning *et al*., 2019; Raji and Abdulkadir, 2020; Abdulrazzaq *et al*., 2020). Although this technique has been suitable and successful in siting boreholes in other parts of the country, it was unable to efficiently delineate suitable sites for drilling successful boreholes in some areas in the Asutifi North District. For instance, out of a total of 10 points selected for boreholes using the VES technique in the study area by Comwasan Consult Limited in 2012, only 4 yielded successful boreholes after drilling (CWSA, 2012). However, the 2D ERI technique has proven to be more effective in delineating aquifer zones successfully in different geological formations, including the crystalline basement rocks in other parts of the country with similar hydrogeological characteristics (Ewusi *et al*., 2009; Ratnakumari *et al*., 2012; Issah, 2015; Sikah *et al*., 2016; Aning *et al*., 2019).

Thus, this study seeks to establish the extent to which the 2D ERI can aid delineate aquifer zones and improve the borehole drilling success rate in the Asutifi North District, which is underlained by the crystalline basement complex formation. The approach employed includes comparative analysis and interpretation of survey data from 2D ERI, 1D VES, and borehole drilling logs in selected communities within the study area. It is envisaged that the study would provide useful practical information to enhance groundwater exploration and aid improve borehole drilling success rates for water supply.

Materials and Methods

Study area

The study area, Asutifi North District of Ghana, is located between latitudes 6°40' and 7°15' North and Longitudes 2°15' and 2°45' West. The population of the district is estimated to be about 73,556 with 51.2 % males and 49.8 % females (Ghana Statistical Service, 2021). Additionally, the district lies within the Wet Semi-Equatorial Zone, which is marked by a dual raining season from May to July and from September to October with a varying mean annual rainfall ranging between 125 cm and 200 cm (Ghana Statistical Service, 2010). According to the Ghana Statistical Service (2010), the relative humidity of the district is generally high and ranges from 75 % to 80 % during the two rainy seasons and 70 % to 80 % during the rest of the year. The mean monthly temperature ranges from 23 °C in August to 33 °C in March and April (Tay, 2021). The topography of the study area is generally characterized by an undulating landscape with elevations between 200 and 467 m above sea level (Tay, 2021). Furthermore, the area is drained by River Tano and its tributaries while the vegetation is a moist semi-deciduous forest with flora ranging from shrubs and climbers to timber trees such as ceiba pentagram, tripolichiton scleroxylon, and militia excelsa (Tay, 2021).

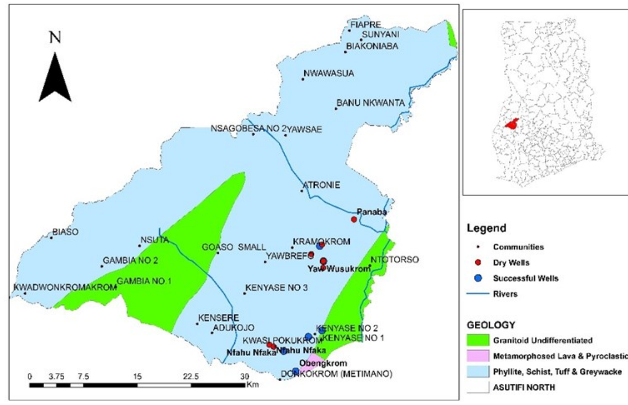

Figure 1 Study area with borehole locations and underlying geology

The area is underlained by igneous and metamorphic rocks of the crystalline basement complex formation comprising phyllite, schists, and other metasediments with granitoid intrusions as shown in Figure 1 (Geological Survey Authority, 2009). These rocks commonly possess low primary porosity but exhibit deformational features such as low-high grade metamorphism, folding, foliation, jointing, fracturing, and intense weathering, which introduces secondary pores in them and control the occurrence and movement of groundwater in the crystalline basement rocks (Aning *et al*., 2019). Data from seventeen (17) borehole logs drilled under the *Agence Française de Développement* (AFD) Project in the district (CWSA, 2012) indicate the presence of both weathered and fractured aquifers in the area with yields, hydraulic parameters, and depths of boreholes varying significantly from one place to another. This is similar to the observation made by Aning *et al*. (2019) in a comparable hydrogeologic setting in the Bole District. According to Erdlyi (1965), the varying characteristics of the aquifer system within the crystalline basement complex are caused by varying intensities of weathering and the anisotropic nature of the fracture systems.

Collation of 1D VES and borehole logging data

Borehole siting and drilling records from 2010 to 2012 conducted under the AFD peri-urban, rural, and small-town water supply and sanitation projects were collated from hydrogeological reports from CWSA, Bono Regional Office. Information obtained from the reports included GPS coordinates, 1D VES data, and borehole drilling records. The 1D VES data were acquired using the OYO McOhm Resistivity Meter and the Dipole-Dipole electrode configuration was used to site the thirty (30) points, in total, spread across eight communities in the district (i.e., Akantansu, Kenyasi By-Pass, Obenkrom, Yakuba Village, Kofi Manukrom, Nfahu-Nfaka, Panaba, Yaw Wusukrom, and Kokofu). The VES data were thoroughly reviewed and then re-processed for analyses following standard procedures observed in previous studies (Ewusi and Kuma, 2009; Ratnakumari *et al*., 2012; Aning *et al*., 2019; Raji and Abdulkadir, 2020; Abdulrazzaq *et al*., 2020;) Abdulrazzaq *et al*., 2020;)

The drilling records for the 16 borehole logs and their corresponding 1D VES data points were organized into parameters such as observed aquifer zone (screen position), depth to bedrock, well status, and predicted aquifers zone. The stratigraphic and lithological descriptions obtained from the boreholes logs were laterite, clay, phyllite, granite, and metamorphosed lava. The phyllite, granite, and metamorphosed lava were confirmed to be the major rock types in the study area from the geology of Ghana (Geological Survey Authority, 2009). The borehole data were validated by conducting a field reconnaissance survey to confirm the existence of all the drilled borehole points in the communities.

2D ERI survey measurements

The 2D ERI survey was conducted on 12 traverse lines. Eight (8) of the traverses were along existing boreholes at Akantansu, Kofi Manukrom, Panaba L1 & L2, Yaw Wusukrom, Kenyasi, Obengkrom and Yakuba Village whereas three of the survey traverses were along previously drilled dried wells at Kokofu, Nfahu-Nfaka, and Panaba L3 while the last traverse line was used to investigate a possible drilling point at a public institution (DA Girls), which had no access to potable water. The length of each traverse line and centre of the spread was decided based on the location and position of the previously drilled hole in each community. Figure 2 shows the traverse lines used for the 2D ERI survey.

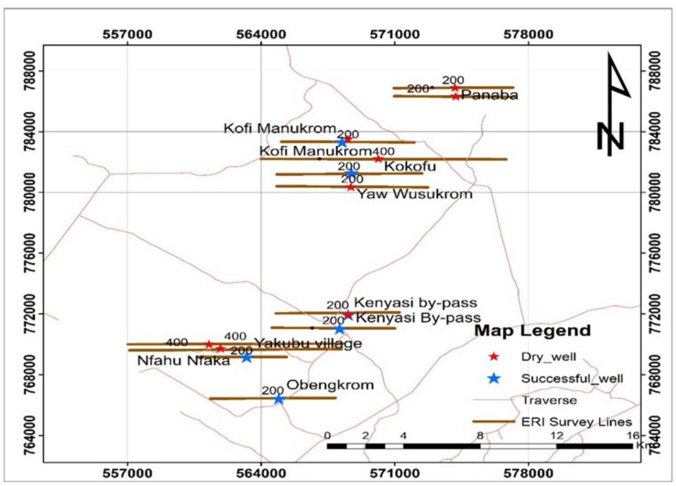

Figure 2 Distribution of the traverses for the 2D ERI survey

The 2D ERI survey was carried out using the ABEM Terameter LS of cable length 400 m with 81 electrodes, 2 cable connectors, and in the dipole-dipole configuration. Traverse line of 200 m was used at Akantansu, Kofi Manukrom, Yaw Wusukrom, Kenyasi By-Pass, Obengkrom, Yakuba Village, Panaba L1 and L2, 320 m for DA Girls and 400 m for Kokofu, Nfahu-Nfaka, and Panaba L3. The inter-electrode spacing of 2.5 m, 3 m, and 5 m were used for the traverse lines 200 m, 320 m, and 400 m, respectively. The spacings were defined considering the depths of investigation (depth of each hole). The ERI data obtained from the survey were processed by using the RES2DINV software (version 4.8.10 dated 20-05-2018) to a Root Mean Square (RMS) error ranging between 7.8 and 18.8 % after iterations. The procedures for processing the 2D ERI data and interpretations were in line with standards observed in similar studies (Okrah and Danuor, 2012; Sikah *et al*., 2016; Noye *et al*., 2017).

Correlation of geophysical data and borehole logs

Qualitative and quantitative methods were used to obtain aquifer zones, resistivities, and thickness as well as establish the relationships between the 1D VES and 2D ERI survey data and the borehole logs as well as the level of closeness of the predicted aquifer to the screen positions. The qualitative approach was used to describe and obtain the aquifer zones from the 2D pseudo-sections of the 2D ERI survey, classify overburden materials and aquifer position from the borehole logs.

Additionally, the quantitative technique was used to determine the average depth to bedrock, aquifer resistivities, aquifer thickness, boreholes yield, and correlation between the geophysical data and well logs. Also, the relationship between the predicted aquifer zones (via the 1D VES and 2D ERI data) and observed aquifer zones of the productive boreholes, and the relationship between the observed and 2D ERI predicted regolith thickness were investigated using scatter plots with the aid of Microsoft Excel. Finally, the mean depth to bedrock, aquifer resistivity and thickness, yield, and percentage borehole success rate values were all estimated.

Results and Discussion

Evaluation 1D VES and borehole data

Table 1 presents the geologic layers from the borehole logs and their corresponding apparent resistivities from the previous 1D VES survey data as well as other information from the boreholes. It was observed that the regolith materials consist of laterite and clay, which are underlained by slightly weathered to fractured basement rock of phyllite or granitic rock. This stratagraphic sequence in the study area is similar to the succession pattern reported by Okrah and Danuor (2012) in the Upper Denkyira District in the Central Region and Noye *et al.* (2017) in the Sissala East District of the Upper West, which were all within the crystalline basement complex. The observed average depth to bedrock is about 30 m with varying thicknesses, ranging from 7 to 40 m as shown in Table 1. The depth to bedrock observed is not different from the overburden thickness reported by Nyako *et al.* (2016) in the crystalline basement formation in Ghana. Additionally, the resistivity of the laterite ranges from 428.18 to 1450.59 Ωm whereas the resistivity of the clay ranges from 14.93 to 1066.28 Ωm; these are not too different from the resistivity ranges of laterite and clay reported by Okada *et al.* (2019) in a similar geological formation in Nigeria.

Also, the yields of the boreholes range from 15 to 50 l/min with an average yield of 24. 85 l/min, which is lower than the average yield of 58 l/min reported by Noye *et al*. (2017) in the crystalline basement complex in the Sissala East District of Ghana with a similar mode of groundwater occurrence. Additionally, the boreholes yields are higher than the 0.41 to 29.8 l/min reported by Kankam-Yeboah *et al.* (2003) in the crystalline basement complex in Ghana. Furthermore, the depth of boreholes ranges from 40 to 61 m with an average depth of 48.5 m. The depth range is comparable to the depth range of 50 to 70 m reported by Aning *et al.* (2019) in the crystalline basement rocks in the Bole District of the Savannah Region. Furthermore, 8 out of 18 drilled holes in the area yielded more than 13.5 l/min, indicating a success rate of 44.44 %, which is relatively lower in comparison to the success rates achieved in the Tano North and South, Asutifi South, Asunafo North and South under the AFD Projects in the Tano Basin with similar modes of groundwater occurrence (CWSA, 2012).

Table 1 Summary of geologic layers and other information in the borehole logs of the study area and their corresponding apparent resistivities

Town	Geologic layer thicknesses from borehole logs (m)			Apparent resistivities from the 1D VES for geologic layers (Ωm)			Borehole data		
	Laterite	Clay	Fractured rock	Laterite	Clay	Fractured rock	Aquifer zone (m)	Borehole Depth (m)	Yield (l/min)
Akantansu (S1C)	0 – 7	7 - 21	21 - 42	1450.59	124.05 - 545.28	63.34 - 124.05	32 - 41	42	20
Kenyasi By-Pass(S1C)		0 - 7	7 - 82		157.00	156.25 - 798.12	Not applicable	82	
Kenyasi By-Pass(S1B)		0 - 14	14 - 55		86.46 - 274.28	183.69 - 1184.51	39 - 45 & 48 - 54	55	50
Obenkrom (S1B)		0 - 7	7 - 52		14.93	24.51 - 114.02	31 - 37 & 43 - 49	52	30
Yakuba Village(S1B)		0 - 35	35 - 61		70.73 - 708.65	50.67 - 390.61	45 - 60	61	17
Manukrom(S1C)		0 - 30	30 - 84		108.59 - 116.13	149.91- 874.02	Not applicable	84	
Manukrom (S1D)	0 – 4	4 - 21	21 - 40		The esoteric method was used		27 - 39	40	40
Kokofu (S1A)		0 - 36	36 - 87		166.08 - 760.38	185.50 - 409.62	Not applicable	87	
Kokofu (S1D)		0 - 26	26 - 41		The esoteric method was used		34 - 40	41	20
Nfahu-Nfaka(S1A)	0 – 7	7 - 27	27 - 85	428.18	620.23 - 1066.28	177.36 - 532.08	Not applicable	85	
Nfahu-Nfaka (S1D)	0 – 4	4 - 20	20 - 90		The esoteric method was used		Not applicable	90	
Panaba (S1C)		0 - 21	21 - 82		151.23 - 285.04	67.11 - 430.73	Not applicable	82	
Panaba (S1B)		0 - 32	32 - 87		101.61 - 208.66	175.25 - 420.49	Not applicable	87	
Panaba (S1D)		0 - 35	35 - 90		The esoteric method was used		Not applicable	90	
Wusukrom (S1C)		0 - 32	32 - 84		273.73 - 492.89	304.84 - 381.64	Not applicable	84	
Wusukrom (S1D)		0 - 40	40 - 49		The esoteric method was used		Not applicable	49	
Wusukrom (S1E)		0 - 14	14 - 49		The esoteric method was used		33 – 42& 45 - 48	49	20
Panaba L2		Not applicable			The esoteric method was used		30 - 48	48	25

Interpretation of the 2D ERI and 1D VES data

Figures 3a and 3b show the pseudo-section and log-log curve of the 2D ERI and 1D VES surveys conducted at Akantansu. The 2D ERI modelled section illustrates varying resistivity values ranging between 9.65 to 11015 Ωm with relatively low resistivity values from 9.65 to 72.1 Ωm (deep and sky blue colour portions) at depths of 7.35 to 46.3 m as shown in Figure 3a. Notably, the delineated aquifer zone on modelled section is shown by black horizontal lines with an estimated aquifer thickness of 29 m with 7 m depth to groundwater and resistivity values ranging from 9.65 to 72.1 Ωm. The aquifer resistivity in this profile line is similar to the aquifer resistivities reported by *Noye et al*. (2017) in the basement complex. Furthermore, the 2D pseudo-section depicts high isolated resistivity signatures (green and red colour areas), particularly at stations 103 and 153 at depths ranging from 0.43 to 7.35 m with resistivity values varying between 4029 to 11015 Ωm but with no clear indication of the presence of basement rock even though the drilled logs indicates a depth to bedrock of 30 m. Also, the black vertical arrow located at station 93 indicates the existing borehole location whereas the orange vertical lines on the log-log curve marked the aquifer zone delineated by the 1D VES survey as shown in Fig. 3b. The 1D VES survey mapped the resistivity distribution from 63.34 to 545.28 Ωm. Significantly, the 1D VES survey mapped the aquifer zone from 20 to 50 m with resistivity values also ranging from 63.34 to 545.28 Ωm. Although both techniques nearly missed out on the observed aquifer zone (screen position) at 32 to 41 m, the 1D VES survey comparatively matches better than the 2D ERI survey. Moreover, the moderately weathered zone contributed to the development of groundwater at Akantansu with an estimated borehole yield of 20 l/min.

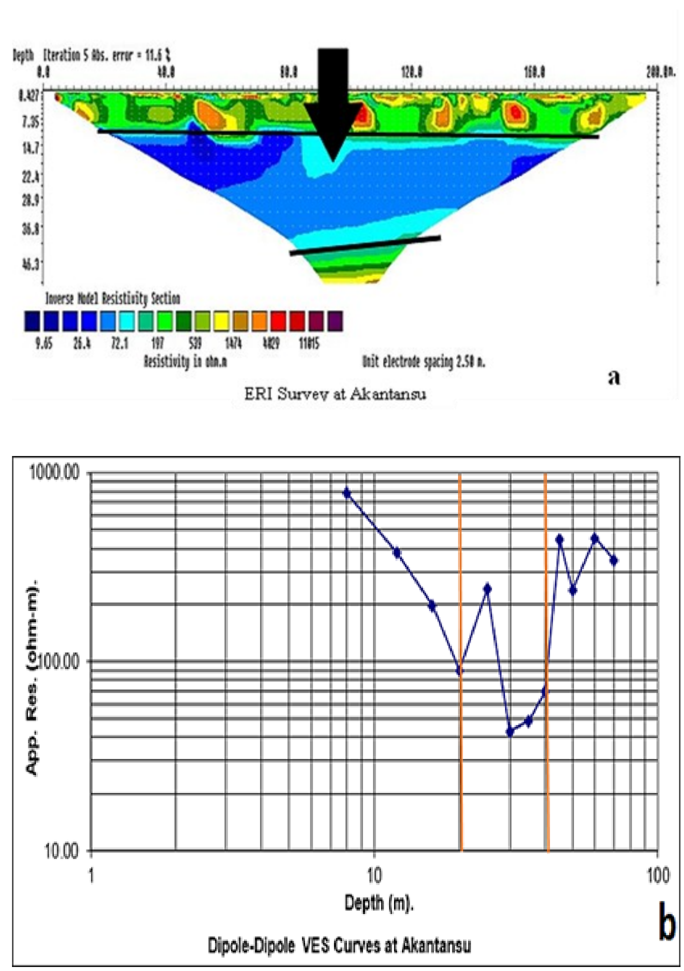

Figure 3 (a) 2D ERI Survey at Akantansu, and (b) 1D VES curves at Akantasu

Figure 4a and 4b illustrate the pseudo-section and log-log curve of the 2D ERI conducted at Kofi Manukrom. The 2D ERI modelled section in Fig. 4a shows varying resistivity values ranging between 11.00 to 7785 Ωm with moderately low resistivity values between 75.40 to 156.00 Ωm (deep blue colour portions) at depths of 22.4 to 46.3 m. Furthermore, the delineated aquifer zone on the 2D modelled section is marked by black horizontal lines with an estimated thickness of 17m and a delineated depth to groundwater of about 29m. Importantly, the 2D pseudo-section depicts high (red colour areas) pocket resistivity signatures at station 133 at a depth ranging from 7.35 to 11.7 m, and station 160 at a depth ranging between 14.7 to 22.4 m with resistivity values varying between 6026 to 12507 Ωm but with no clear indication of the presence of bedrock although the drilled logs indicate a depth to bedrock of 33 m. Also, the black vertical arrow located at station 93 indicates the existing borehole location, whereas the orange vertical lines on the log-log curve marked the aquifer zone delineated by the 1D VES survey as shown in Fig. 4b. The 1D VES survey predicted aquifer zone is from 20 to 60 m with a similar resistivity range of 149.29 to 159.66 Ωm. Both survey predictions partially correlated with the observed aquifer zone of 27 to 39 m. Finally, the slightly weathered zones significantly contributed to the development of groundwater at Kofi Manukrom with an estimated borehole yield of 40 l/min.

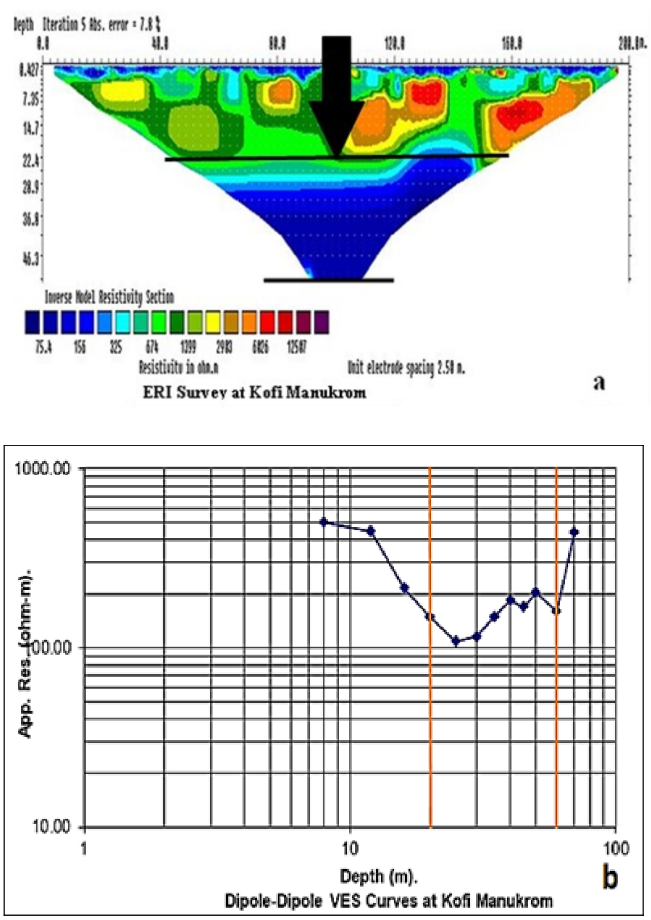

Figure 4 (a) 2D ERI Survey at Kofi manukrom, and (b) 1D VES curve at Kofi Manukrom

Figure 5a and 5b present the pseudo-section and log-log curve of the 2D ERI survey conducted at Yaw Wusukrom. The 2D ERI modelled section shows varying resistivity values ranging between 21.02 - 84747 Ωm with relatively low (aquifer) resistivity values between 21.00 - 68.90 Ωm (deep blue colour portions) at depths of 7.35 - 46.3 m as shown in Fig. 5a. Significantly, the delineated aquifer zone is represented by black horizontal lines with an estimated aquifer thickness of 38.8 m, delineated depth to groundwater of 7 m and resistivity values ranging from 21.00 - 68.90 Ωm. Furthermore, the 2D pseudo-section shows no clear indication of bedrock even though the drilled logs indicated a depth to bedrock of 33 m. Also, the black vertical arrow located at station 98 indicates the existing borehole location, whereas the orange vertical lines on the log-log curve marked the aquifer zone delineated by the 1D VES survey as shown in Fig. 5b with delineated aquifer zones ranging from 20 to 30 m and 35 to 70 m. The 1D VES survey comparatively matches the observed aquifer zone of 33 to 42 m and 45 to 48 m better than the 2D ERI survey. Similarly, the slightly weathered phylitte layers contributed to the development of groundwater at Yaw Wusukrom with an estimated borehole yield of 20 l/min.

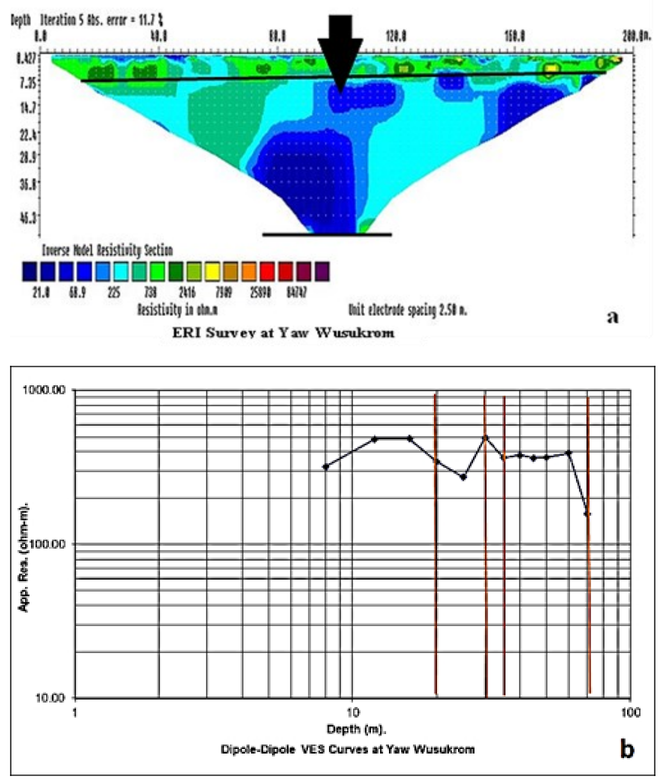

Figure 5 (a) 2D ERI Survey at Yaw Wusukrom, and (b) 1D VES at Yaw Wusukrom

Figures 6a and 6b present the 2D pseudo-section and log-log curve of the 2D ERI and 1D VES surveys conducted at Kenyasi By-Pass. The 2D ERI modelled section shows varying resistivity values ranging between 2.68 to 9479 Ωm but with no obvious resistivity anomaly zone as shown in Fig. 6a. The depth to the basement rock is 5.89 m with resistivity values of less than 286 Ωm and basement rock resistivity ranges between 2958 to 9479 Ωm. Similarly, the black vertical arrow located at station 98 indicates the existing borehole location, whereas the orange vertical lines on the log-log curve marked the aquifer zone at depths of 20 to 40 m with resistivity values ranging between 156.25 to 798.12 Ωm. The 1D VES survey completely missed out on the observed aquifer position of 39 to 45 m and 48 to 54 m. Fractured basement rock of granite contributed to the development of groundwater at Kenyasi By-Pass with an estimated borehole yield of 50 l/min.

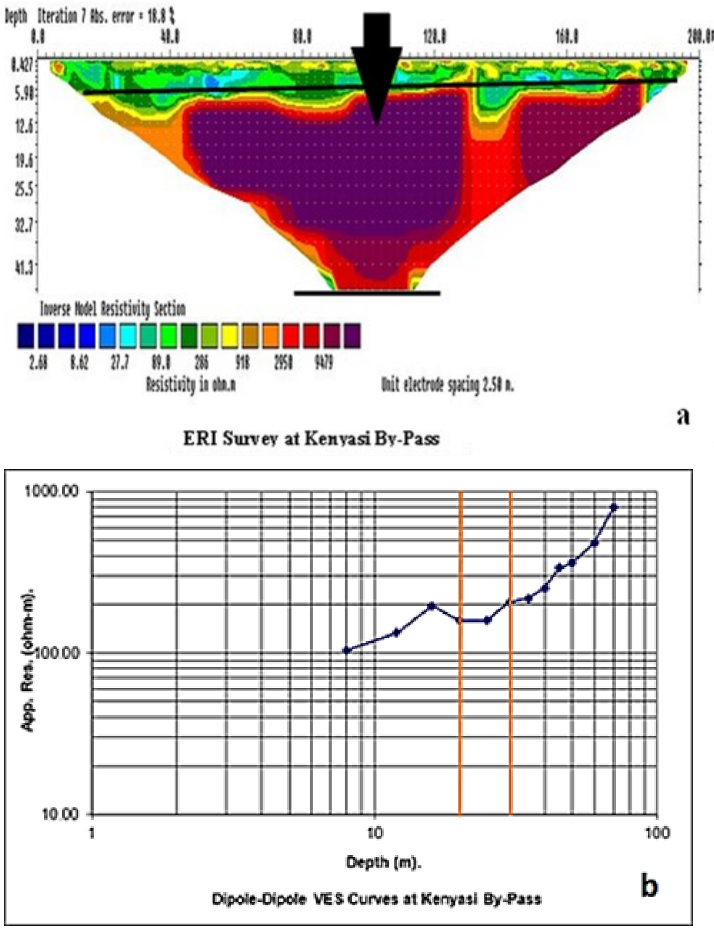

Figure 6 (a) 2D ERI Survey at Kenyasi By-Pass, and (b) 1D VES curve at Kenyasi By-Pass

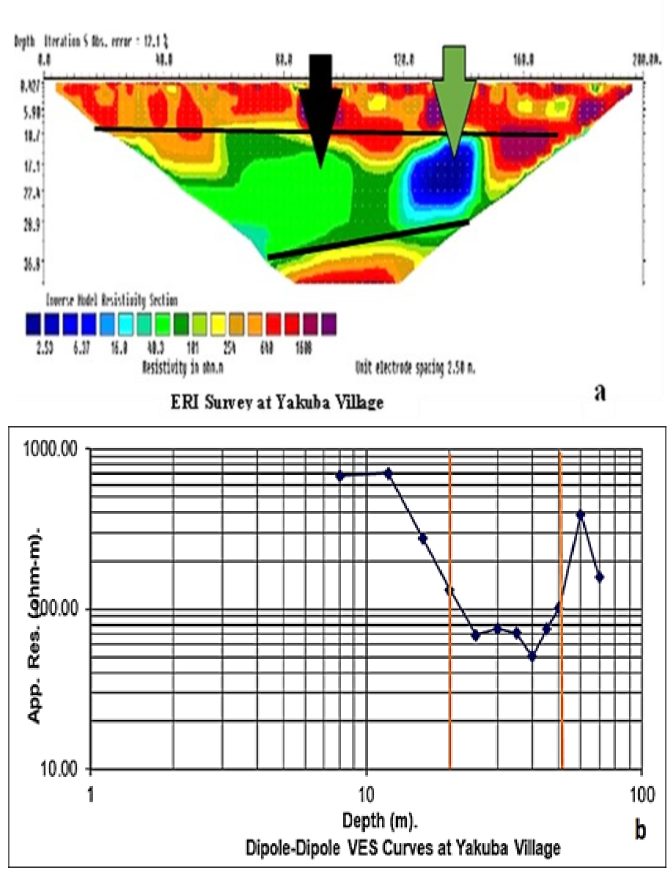

Figure 7 (a) 2D ERI Survey at Yakuba Village, and (b) 1D VES curve at Yakuba Village

Figures 7a and 7b present the 2D pseudo-section and log-log curve of the 2D ERI and 1D VES surveys conducted at Yakuba Village. The 2D ERI modelled section shows varying resistivity values ranging between 2.53 to 1600 Ωm with resistivity anomaly values between 2.53 to 16.00 Ωm (deep blue and light green colour portions) at depths between 10.7 to 28.9 m as shown in Fig. 7a. Notably, the delineated aquifer zone is indicated by horizontal lines with an average aquifer thickness of 18.2 m and delineated depth to groundwater of 11 m. Furthermore, the 2D pseudo-section depicts high resistivity signatures of surficial materials up to about 11 m and a basement rock at a depth of 36.8 m with resistivity values varying between 640 to 1600 Ωm. Furthermore, the black vertical arrow located at station 100 indicates the existing borehole location while the green arrow located at station 135 shows good possible borehole drilling point. Also, the 1D VES survey delineated aquifer zone from 20 to 50 m is indicated by orange vertical lines as shown in Fig. 7b with resistivity values ranging from 2.53 to 16.00 Ωm. The 1D VES survey comparatively matches the observed aquifer zone of 33 to 42 m and 45 to 48 m better than the 2D ERI survey. Lastly, the moderately weathered granite layers contributed to the development of groundwater at Yakuba Village with an estimated borehole yield of 17 l/min.

Figures 8a and 8b illustrate the 2D pseudo-section and log-log curve for the 2D ERI and 1D VES surveys conducted at Obengkrom. The 2D ERI modelled section shows generally low resistivity values varying between 0.072 to 201 Ωm with no obvious resistivity anomaly zone as shown in Fig. 8a. Moreover, the 2D pseudo-section indicates the presence of basement rock up to about 22 m with relatively low resistivity values that ranges from 64.9 to 201 Ωm although the observed depth to bedrock is 20 m. The existing borehole location at station 98 is marked by the black vertical arrow whereas the 1D VES survey delineated aquifer zone from 20 to 50 m is marked by the vertical orange lines as shown in Fig. 8b and falls within the observed aquifer zone of 31 to 37 m and 43 to 49 m. Lastly, the moderately weathered phylitte layers with quartz vein contributed to the development of groundwater at Obengkrom with an estimated borehole yield of 30 l/min.

Figures 9a and 9b present the 2D pseudo-section and log-log curve of the 2D ERI and 1D VES surveys conducted at Kokofu. The 2D ERI modelled section shows varying resistivity values ranging between 2.08 to 1707 Ωm with resistivity anomaly values ranging from 2.08 to 36.90 Ωm (sky blue colour portions) at depths between 29.5 to 73.6 m as shown in Fig. 9a. Furthermore, the 2D pseudo-section depicts high resistivity signatures of surficial materials up to about 15 m and a basement rock at a depth of 45 m with resistivity values varying between 251 to 1707 Ωm even though the observed depth to bedrock is 36 m. The delineated aquifer zone is marked by black horizontal lines with an average aquifer thickness of 18 m and a delineated depth to groundwater of 30 m. The existing borehole location is marked by the black vertical arrow, whereas the dry hole location (Kokofu S1A) is marked by the green arrow. The 1D VES survey delineated aquifer zones from 20 to 30m and 35 to 60m with resistivity values of 328.74 to 409.56 Ωm are marked by the vertical orange lines as shown in Fig. 9b.

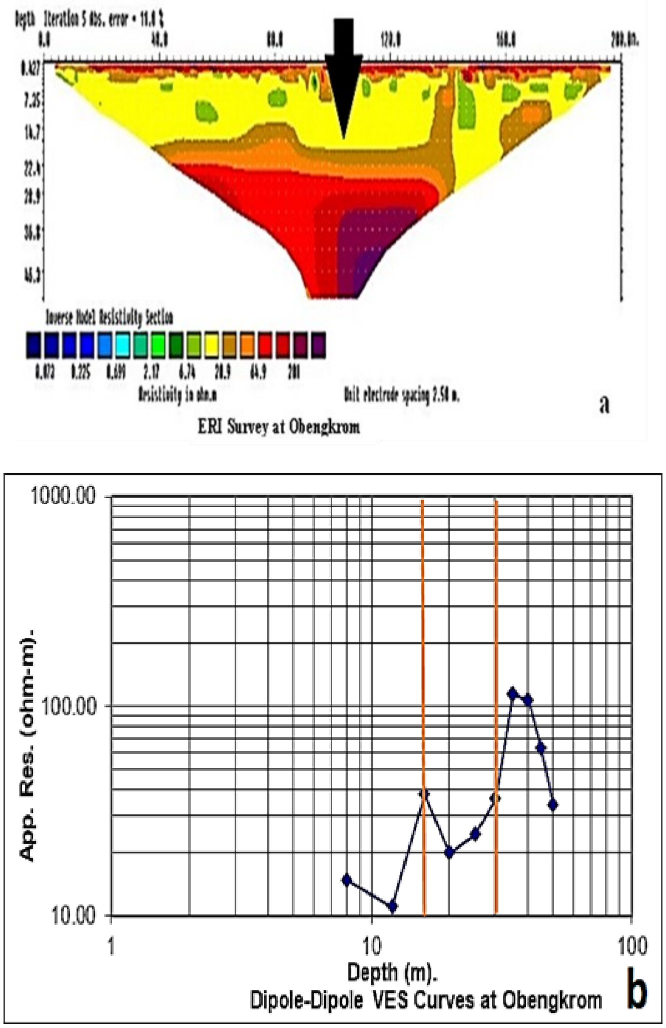

Figure 8 (a) 2D ERI Survey at Obengkrom, and (b) 1D VES curve at Obengkrom

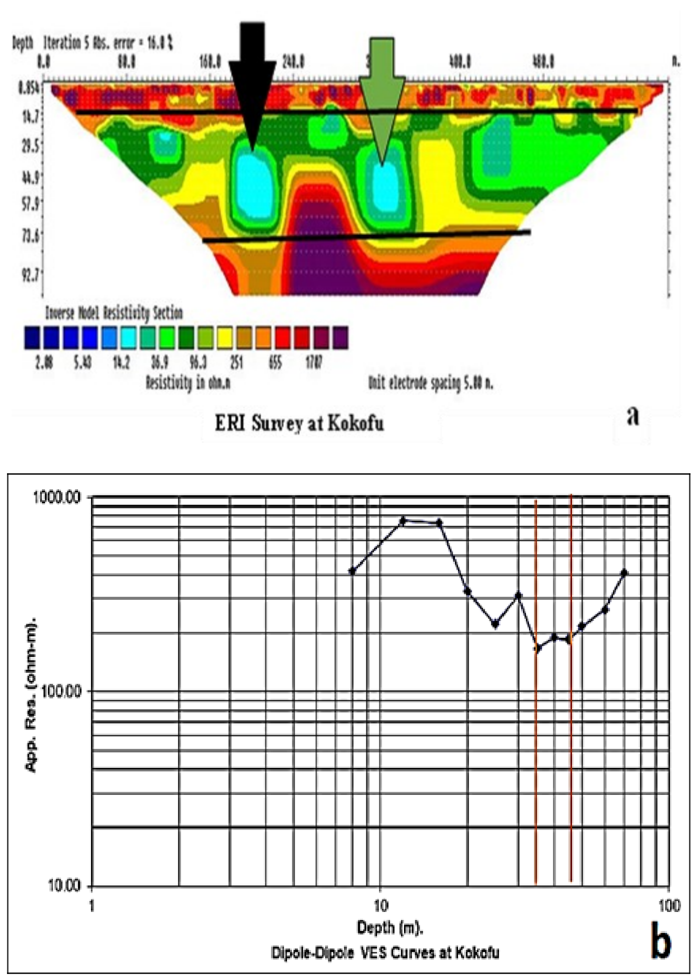

Figure 9 (a) 2D ERI Survey at Kokofu, and (b) 1D VES curve at Kokofu

However, the 1D VES survey prediction at Kokofu S1A resulted in unproductive (dry) holes whereas the esoteric technique predicted aquifer zone at Kokofu S1D resulted in a productive borehole. Finally, the 2D ERI survey aquifer zone correlate with the observed aquifer zone of 34 to 40 m. Similarly, the moderately weathered phyllite layers with quartz vein also contributed to the development of groundwater at Obengkrom with an estimated borehole yield of 20 l/min. Figures 10a and 10b present the 2D pseudo-section and log-log curve of the 2D ERI and 1D VES surveys conducted at Nfahu-Nfaka. The 2D ERI modelled section shows varying resistivity values ranging of 42.7 to 15345 Ωm with resistivity anomaly values ranging from 42.7 to 114 Ωm (deep and sky blue colour portions) at depths between 14.7 to 44.9 m as shown in Fig. 10a. Significantly, the 2D pseudo-section depicts high resistivity signatures of surficial materials and a basement rock down to about 58 m with resistivity values varying between 6622 to 15345 Ωm even though the observed depth to bedrock is 20 m. The 2D ERI survey delineated aquifer zone is marked by black horizontal lines with an average aquifer thickness of 30 m and a delineated depth to groundwater of 15 m. The dry hole location is marked by a black arrow whereas the 1D VES survey delineated aquifer zone from 25 to 60 m with resistivity values ranging from 182.09 to 334.39 Ωm is marked by vertical orange lines as shown in Fig. 10b.

Figures 11a, 11b, 12a and 12b present 2D pseudo-sections and log-log curves for the 2D ERI and 1D VES surveys conducted at Panaba L1 and L3. The 2D ERI modelled sections illustrate varying resistivity values and signatures. Fig. 11a shows varying resistivity values ranging between 15.6 to 6649 Ωm with resistivity anomaly values ranging from 15.6 to 88.1 Ωm (deep and sky blue colour portions) at depths of 23.6 to 58.9 m. Also, the 2D pseudo-section depicts isolated high resistivity signatures at stations 128, 162, 192, 210, 256 and 292 with resistivity values ranging between 2801 to 6649 Ωm down to about 24 m. Meanwhile, Fig. 12a indicates resistivity distribution ranging between 15.9 to 1081 Ωm with resistivity anomaly values ranging from of 42.70 to 99.10 Ωm (deep and sky blue colour portions) at depths of 14.7 to 44.9 m. Significantly, modelled sections depict high resistivity signatures of surficial materials and basement rock at different depths with resistivity values of more than 2800 Ωm. The 2D ERI delineated aquifer zones are marked by black horizontal lines with an average aquifer thickness of 35 m for Panaba L1 while the estimated average aquifer thickness of Panaba L3 is 30 m. The dry hole location Panaba L1 and L3 are marked by light blue arrows while another possible borehole drilling point at station 250 is marked by the black arrow at L3. The 1D VES survey delineated the aquifer zone to be 20 to 50m with resistivity values of 67.10 to 92.74 Ωm at L1 while the aquifer zone was from 30 to 50 m with resistivity values of 187.74 to 402.44 Ωm at L3, which resulted in unproductive holes.

Figures 13a and 13b present the 2D pseudo-section for the 2D ERI survey conducted at Kenyasi DA Girl and Panaba L2. The 2D ERI modelled section for Fig. 13a illustrates varying resistivity values ranging between 11.00 to 7785 Ωm with resistivity anomaly values ranging between 11.00 to 71.80 Ωm (blue, and sky blue colour portions) at depths between 28.7 to 65.5 m. Notably, the delineated aquifer zone is marked by black horizontal lines with an estimated average aquifer thickness of 36.8 m and delineated depth to groundwater of 28.7 m. The possible borehole drilling points are indicated in black vertical arrows. Also, the 2D pseudo-section depicts high isolated resistivity signatures at stations 168, 216, 263, and 280 at depths ranging from 10.2 to 31.9 m with resistivity values varying between 3050 to 7785 Ωm. Furthermore, the 2D ERI modelled section for Fig. 13a illustrates the delineated aquifer zone at Panaba L2 is from 22.4 to 36.8 m with resistivity values, which range between 15.9 to 183 Ωm. The existing borehole location is marked by the black arrow whereas the aquifer zone is marked by horizontal black lines. The 2D ERI survey delineated the aquifer zone of 22.4 to 37 m to be fairly matched to the observed aquifer zone of 30 to 48 m. Furthermore, the 2D pseudo-section depicts higher resistivity signatures at stations 120 and 160 with resistivity values between 4260 to 10812 Ωm at a depth range of about 7 to 15 m and 8 to 14 m respectively but with no indication of the presence of bedrock up to the 46.3 m investigated depth.

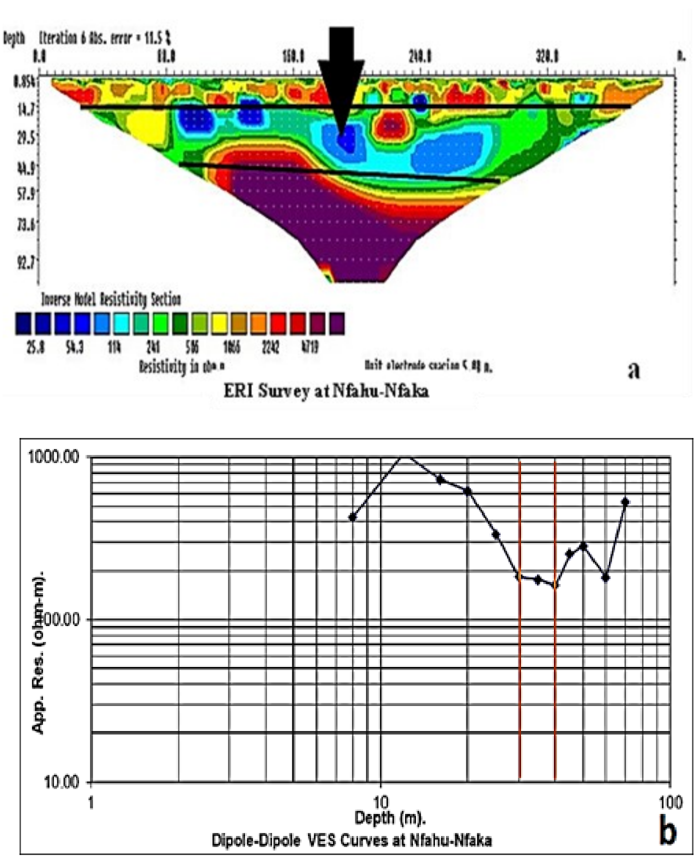

Figure 10 (a) 2D ERI Survey at Nfahu-Nfaka, and (b) 1D VES curve at Nfahu-Nfaka

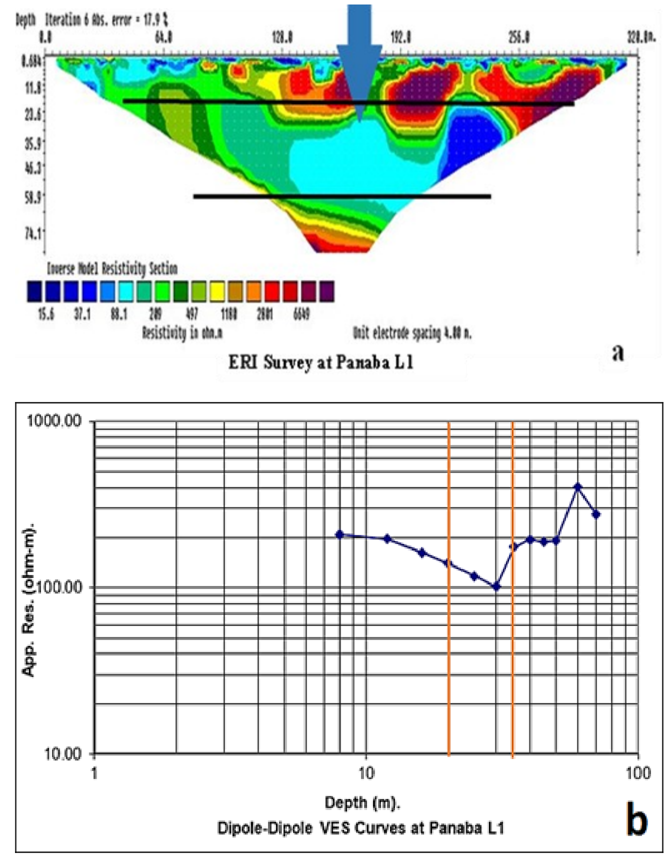

Figure 11 (a) 2D ERI Survey at Panaba L1, and (b) 1D VES curve at Panaba L1

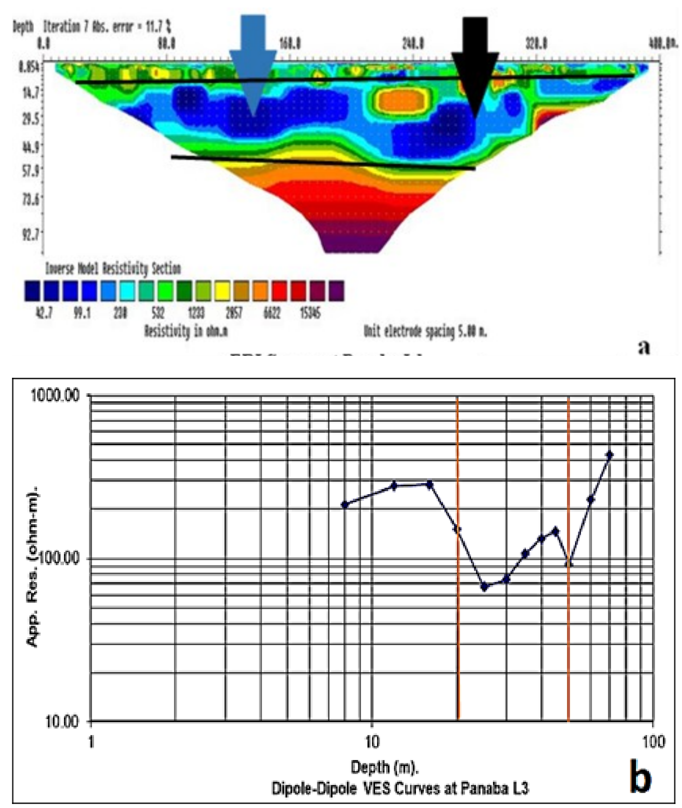

Figure 12 (a) 2D ERI Survey at Panaba L3, and (b) 1D VES curve at Panaba L3

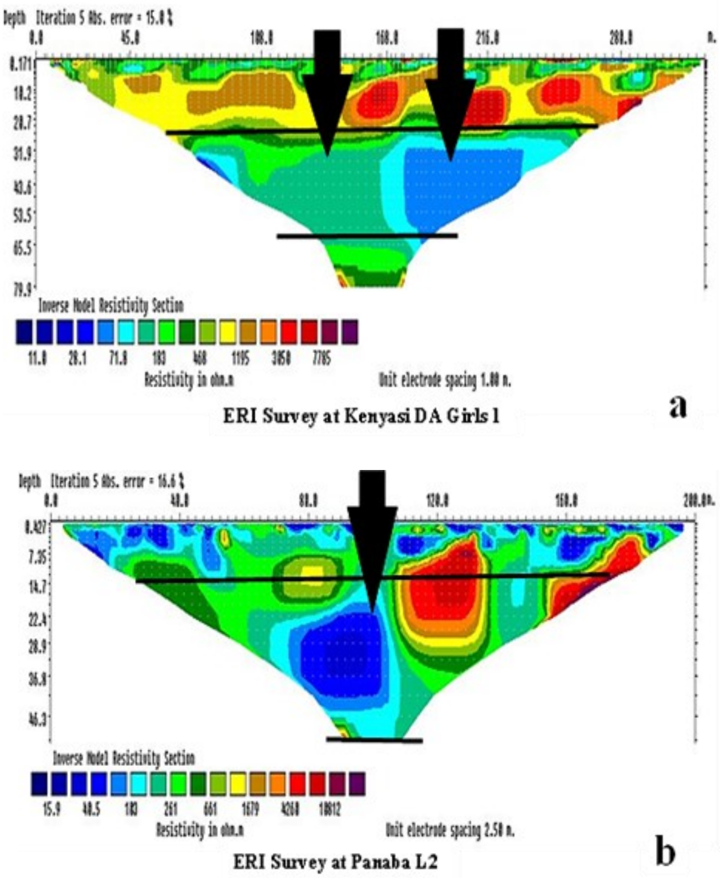

Figure 13 (a) 2D ERI Survey at Kenyasi DA Girl 1, and (b) 2D ERI Survey at Panaba L2

Correlation of the geophysical and drilling results

Table 2 presents the observed aquifer zones from the previous drilling well logs and predicted aquifer zones from the geophysical survey data. The 2D ERI predicted aquifer zones at Akantansu (S1C), Kofi Manukrom (S1D), Kokofu (S1A), Panaba L2, Yakuba Village (S1B) and Yaw Wusukrom (S1E) falls within the observed aquifers zones of the successful boreholes, whereas the 1D VES predicted aquifer zones at Akantansu (S1C), Yakuba Village, and Manukrom (S1D) falls within the observed aquifer zones. Furthermore, the 2D ERI did not detect any obvious aquifer zone at Kenyasi By-Pass (S1B) and Obengkrom (S1B) although the boreholes are productive. Also, the predicted aquifer zones at Kokofu (S1A), Nfahu-Nfaka (S1A), Panaba (S1C/L1), and Panaba (S1B/L3) by both techniques did not result in productive boreholes.

Additionally, correlation analysis between the geophysical data and observed aquifer zones showed a strong linear relationship between the observed and 2D ERI predicted aquifer zones but no relationship between the observed and 1D VES predicted aquifer zones as shown in Fig. 14. Additionally, analysis and interpretation of the well logs and the 1D VES data revealed that the observed aquifer zones are between 27 to 60 m with resistivity values of less than 150 Ωm except for Kenyasi By-Pass where the resistivity of the aquifer is between 196.34 to 206.50 Ωm, which is similar to the 20 to 50 m aquifer zones observed by Okrah and Danuor (2012) in the Precambrian Provinces of the Upper Denkyira. It is observed that the application of the 1D VES technique in the area contributed to only 4 productive boreholes out of the 12 drilled holes, which represents 33 % success rate. According to Okrah *et al*. (2012), the 1D VES has a higher success rate in this type of geologic formation but does not depict the fact in the study area. In general, good to moderate groundwater potential zones were encountered at Yaw Wusukrom, Akantansu, Kofi Manukrom, and Kenyasi DA Girls School, whereas fair to poor groundwater potential zones were observed in Yakuba Village, Panaba (L1, L2 & L3), Nfahu-Nfaka and Kokofu. Furthermore, a strong positive linear correlation was observed between the observed and the 2D ERI predicted depth to bedrock as shown in Fig. 15. Thus, the 2D ERI survey technique effectively delineated the depth to bedrock in the study area.

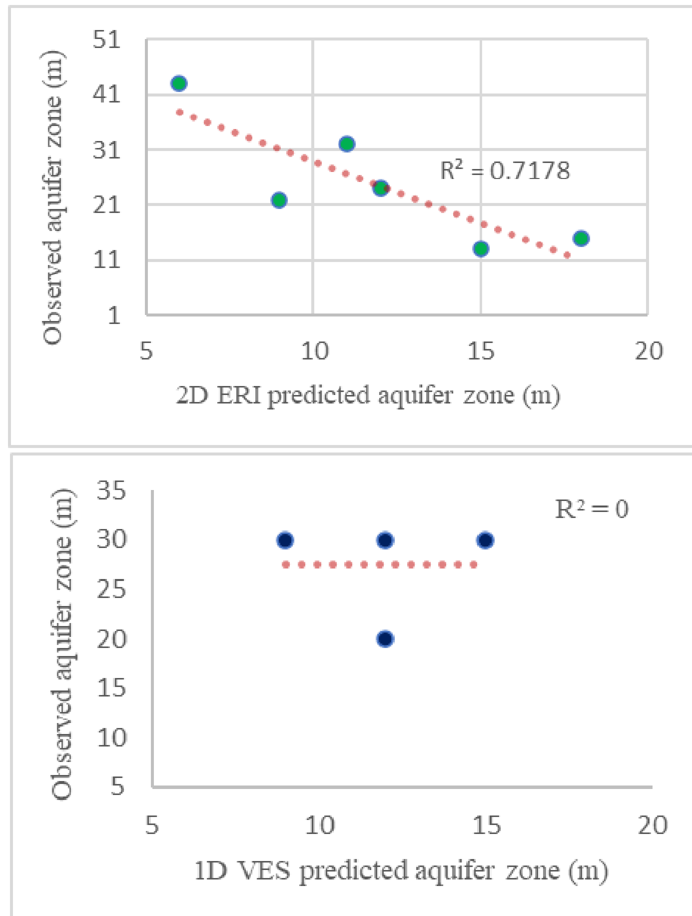

Figure 14 Correlation between observed and predicted aquifer zones from (a) 2D ERI and (b) 1D VES surveys

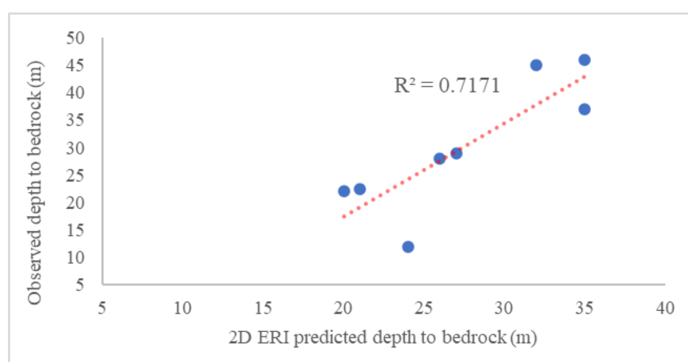

Figure 15 Relationship between the observed and 2D ERI predicted regolith thickness

Table 2 Comparison between the drilling and geophysical results

Town (BH Refer)	Borehole data (m)		Predicted aquifer zone from geophysical technique data	
	Depth	Aquifer zone	1D VES	2D ERI
Akantansu	42	32 - 41	20 – 50	7.4 – 46.3
Kenyasi By -Pass	55	39 – 45 & 48 - 54	20 – 40	No obvious aquifer zone detected
Obenkrom	52	31 – 37 & 43 - 49	20 – 50	No obvious aquifer zone detected
Yakuba Village	61	33 – 42 & 45 - 48	20 - 50	16.7 – 30
Manukrom	40	27 – 39	Not applicable	22.4 – 46.3
Kokofu	41	34 - 40	Not applicable	29.5 – 73.6
Panaba (L2)	48	32 – 48	Not applicable	22.4 – 37
Wusukrom	49	33 – 42 & 45 - 48	Not applicable	14.7 – 46.3

Conclusions

The study was focused on identifying the best ER technique for siting suitable groundwater points for drilling successful boreholes through a comparison of 2D ERI, 1D VES, and borehole logging data in the Asutifi North District of Ghana. The 2D ERI technique was able to effectively map the depth to bedrock with no significant difference between it and the observed depth from the logs, unlike the 1D VES. On the other hand, the 2D ERI delineated potential groundwater zones ranging from depths of 14.7 to 58.9 m (with resistivity values ranging from 2.08 to 156 Ωm) compared well with the 1D VES delineated potential groundwater zones ranging from 20 to 60 m (but had resistivity values between 67.10 to 545.28 Ωm).

A comparison of the observed aquifers zones from the boreholes in the study area with the delineated groundwater potential groundwater zones from the 2D pseudo-sections showed a positive linear correlation with R^2 value of 0.72 while there was no correlation between the observed aquifer zones the potential groundwater zones from the 1D VES data. Also, the 2D pseudo-sections of the 2D ERI showed varying zones (i.e., very good, good, moderate, fair and poor) of groundwater potential. The very good to moderate groundwater potential zones were mainly encountered at Yaw Wusukrom, Akantansu, Kofi Manukrom, and Kenyasi DA Girls School whereas the fair to poor groundwater potential zones were observed in Yakuba Village, Panaba, Nfahu-Nfaka and Kokofu communities.

Thus, the 2D ERI technique provided more detailed information of the subsurface in the area than the 1D VES approach. The 2D ERI technique is, therefore, recommended as a more viable technique for subsequent groundwater exploration projects in the study area and other areas with similar geology.

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Conflict of Interest Declarations

The authors declare no conflict of interest.

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