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Locating Aquifers in Crystalline Granitic Rock Using Electrical Resistivity Technique in the Sissala East District of Ghana

Reginald Mensah Noye* Festus Baafi Fofie Samuel Tetteh Nartey Edmund Kofi Mensah
Department of Physics, PMB-UPO, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi-Ghana

Abstract
Groundwater prospecting in the Sissala East District has been conducted using the electrical resistivity method. This has been done with the objective of locating suitable sites for borehole drilling and to determine groundwater potential of the district. The dipole-dipole technique of the electrical resistivity method was conducted using the McOhm 2119 resistivity meter in the horizontal profiling (HP) and vertical electrical sounding (VES) modes simultaneously. Geophysical data taken in both the HP and VES modes were presented in two dimensional (2-D) coloured vertical cross sections, from which VES curves were also plotted for selected station points and interpreted qualitatively. Results of the 2-D vertical cross sections and VES curves predicted an average depth range of groundwater or moisture interception of 10 to 15 m. The apparent resistivity of the wet boreholes was in the range of 15 Ωm and 300 Ωm. These were quantitatively confirmed with drill logs of the wet boreholes. The drill logs further showed that main aquifers and fractures were encountered between 20 m and 50 m depth range. The results yielded a success rate of about 89 %, thereby indicating that the district has a great potential for groundwater to meet their domestic and irrigation needs. Therefore, the dipole-dipole technique is effective in locating aquifers for groundwater in crystalline granitic rocks.
Keywords: Groundwater, Crystalline granitic rock, Aquifers, Apparent Resistivity

1. Introduction

In Ghana there is a high variation in the availability of water within the year due to climatic changes especially in the dry season, resulting in the drying up of water bodies (rivers, lagoons, lakes, streams etc). In this period of scarce hygienic water, people resort to unsafe sources of water which makes them prone to waterborne diseases such as guinea worm, cholera, bilharzia and typhoid fever. In order to remedy this situation there has been increased application of scientific techniques such as electromagnetic (EM) and electrical resistivity methods in locating groundwater resources or aquifers. These geophysical techniques have been applied extensively in locating aquifers connected with crystalline granitic rocks and in layered sedimentary basins, such as the Voltaian Sedimentary Basin in Ghana. However, location of groundwater accumulated zones (aquifers) and water table cannot be fixed beneath the surface, since their location with respect to depth beneath the surface vary seasonally with climate change with regard to rain fall pattern and extent of groundwater recharge. In the rainy or soon after the rainy season the water table tend to be relatively shallow and comparably deeper in the dry seasons.

The most effective aquifers of well-sorted and well-rounded sand and gravel, limestone in which fractures and bedding planes have been enlarged by solution are also good aquifers. Also, clay stones, igneous and metamorphic rocks can be good aquifers in many cases in which they contain fissures between layers, and other openings such as joints that permit free circulation of groundwater (Wicander *et al.*, 1995). Application of geophysical techniques in crystalline granitic terrain depends primarily on lithology, weathered or erosional background and tectonic record of the region under investigation (Hazell *et al.*, 1988). These geological properties and processes have the potential to change the local geology of the rock units to decrease resistivity, increase conductivity and result in increased porosity and permeability of such formations for groundwater flow and accumulation in aquifers (Mohammed *et al.,* 2012). Thus, porosity and permeability enhance the flow of groundwater from all parts of an aquifer through permeable channels into the drilled borehole or well for recovery. Essentially, without permeability groundwater can remain trapped in porous formations and thus cannot flow into the drilled borehole for pumping or recovery. Therefore, porosity and permeability are very important for groundwater recharge, accumulation and recovery.

Generally, electrical resistivity survey is aimed at delineating both horizontal and vertical resistivity boundaries in a non-homogeneous earth material (Sharma, 1986). However, survey design depends on the specific characteristics of the site and the objective of the survey. The three most common modes of electrical resistivity surveying are profiling, sounding, and profiling-sounding. Each of these techniques has its own specific purpose. If the purpose of the survey is to map the depths and thickness of stratigraphic units, then the electrical resistivity data should be collected in the sounding mode. Lateral electrical resistivity contrasts, such as lithologic contacts, can best be mapped in the profiling mode. In cases where the electrical resistivity is expected to vary both vertically and horizontally such as in contaminant plume mapping and 2D groundwater prospecting, the preferred mode is profile-sounding (Bodmar and Ward, 1968).

2. The Study Area

The Sissala East District is located in the North- Eastern part of the Upper West region of Ghana. It falls between Longitudes. 1.30° W and Latitude. 10.00° N and 11.00° N. The district has a total land size of 4,744 sq km - representing 26% of the total landmass of the region. It shares boundary on the North with Burkina Faso, on the East with Kassena Nankana and Builsa Districts, to the South East with West Mamprusi District, South West with Wa East and Nadowli Districts and to the West by Sissala West District. The district, due to its position, has an advantage for trade and other cross border activities. This locational advantage is a potential for the development of the local economy (Ametsife *et al*, 2008).

3. Geology and Hydrogeology

In general, interpretation of hydrogeophysical or geophysical data normally requires a good knowledge and understanding of the geology, hydrogeology and practical field experience in the study area (Chegbeleh *et al.*, 2009). Thus, there is the need to have a geological overview of the area under investigation. Geologically, the district is underlain by Dixcove Granite and Granodiorites as in Fig 1, which are apparently well consolidated with little or no inherent permeability. With a gently undulating topography, the district is bound with fresh granitic and bramine rock outcrops which give the district a whale-back landscape appearance. The granitic and bramine rocks weather fast as a result of low rainfall, high evaporation and sparse vegetative cover to form soils of lesser depths rich in minerals for potential farming.

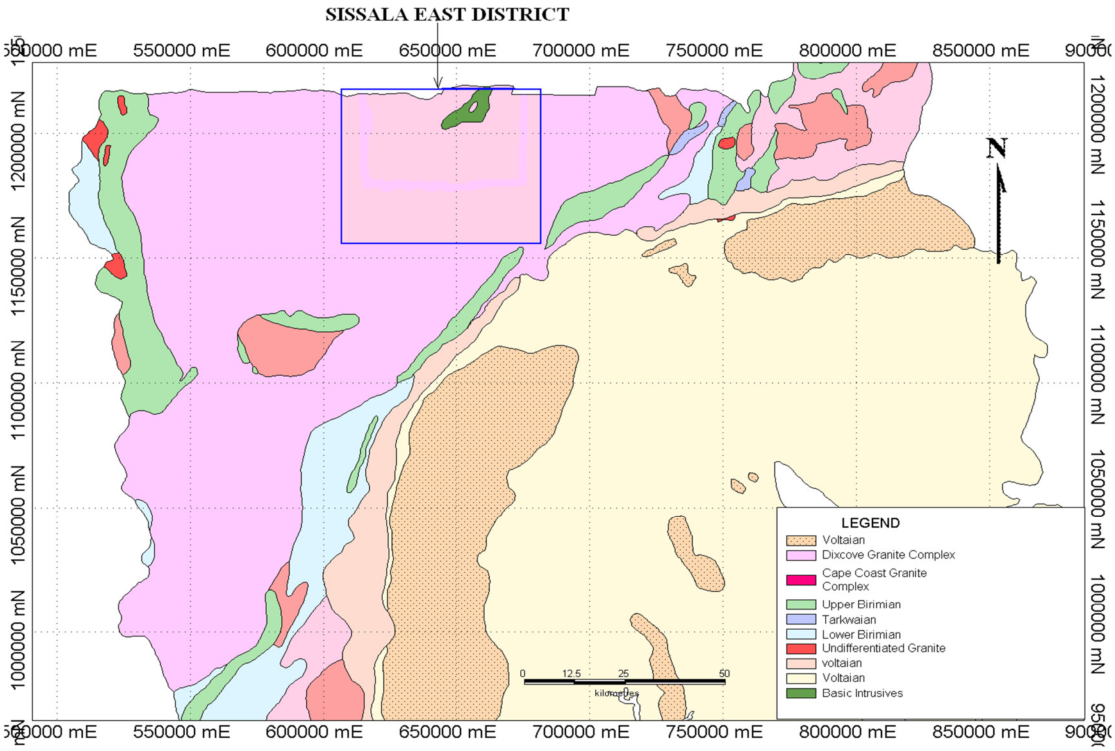

Fig 1 Geological Map of Northern Region of Ghana (Modified after Leube *et al.*, 1990).

The bramine and granitic geological formations in the district are characterised by meta-sediments and meta-volcanic rock formation. The bramine formation has a 65% of yielding underground water, while the granite has 55% chances of yielding water. Though the success rate of the granitic formation is lower, a successful borehole drilling in this terrain could yield over 600 litres of water per minute.

Secondary permeability, however, exists through relatively shallow in-situ weathering and fractures, joints, fissures. For hydrogeological considerations, transmission and storage of groundwater is through secondary permeability in the rocks. The main factor that appears to control the occurrence of groundwater is the presence of fractures at depth. In a geological setting of the district groundwater can be found within the weathered zone overlying the crystalline granitic bedrock or fracture embedded in the bedrock (Beeson and Jones, 1988). Previous groundwater exploration projects indicate that the main water-producing zones in the district are at depths ranging from 20 m to 50 m. This has been used as a guide to drilling boreholes in the district. Thus the geology and hydrogeological conditions of the district provide a very good potential for underground water development to increase access to potable water for socio-economic development of the people (Ametsife *et al.*, 2008).

4. Materials and Methods

In this study the electrodes are connected using the four electrode arrangement to form the dipole-dipole configuration. The McOhm 2119 resistivity meter (or Abem SAS 300C terrameter as substitute) has been used in this study. The McOhm 2119 has an internally built ammeter and a voltmeter, which respectively measure the input current and the potential difference between the potential electrodes. The equipment then automatically computes the resistance with which we calculate the apparent resistivities.

4.1 Dipole-Dipole Array

This array has been, and is still, widely used in resistivity and I.P. surveys because of the low electromagnetic coupling between the current and potential circuits. The arrangement of the current and potential electrodes is shown in figure 2.

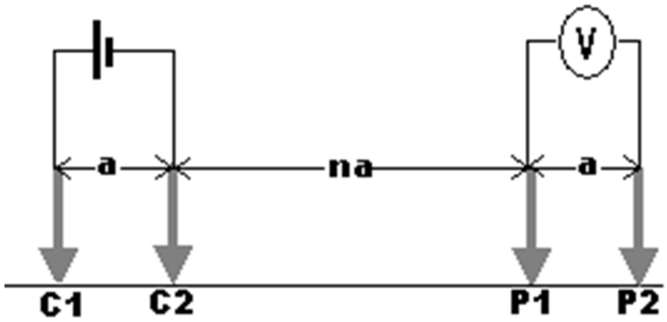

Fig 2 Dipole-Dipole electrode configuration

The spacing between the current electrodes pair, C1-C2, is given as "**a**" which is the same as the distance between the potential electrodes pair P1-P2. This array has another factor marked as "**n**". This is the ratio of the distance between the C1 and P1 electrodes to the C2-C1 (or P1-P2) dipole separation "**a**". For surveys with this array, the "**a**" spacing is initially kept fixed and the "**n**" factor is increased from 1 to 2 to 3 until up to about 6 in order to increase the depth of investigation. If the separation between each dipole pair is "**a**" and the distance between the centers of the respective pairs is **(n+1) a**, the apparent resistivity determined by this arrangement is

$$\rho_a = \pi an(n+1)(n+2)\left(\frac{\Delta V}{I}\right)$$

The geometric factor, k derived from this arrangement in given by

$$k = \frac{1}{2}an(n+1)(n+2)$$

Thus we have

$$\rho_a = \pi k\left(\frac{\Delta V}{I}\right) = 3.142\ k\left(\frac{\Delta V}{I}\right)$$

This array is most sensitive to resistivity changes between the electrodes in each dipole pair. The array is very sensitive to horizontal changes in resistivity, but relatively insensitive to vertical variations. This implies the array has a very high sensitivity to vertical subsurface geological structures. Thus, it is good in mapping vertical structures, such as dykes and cavities, but relatively poor in mapping horizontal structures such as sills or sedimentary layers. Therefore, the dipole-dipole configuration is particularly convenient for making vertical electrical sounding (VES), which measures variation of electrical properties with depth (Loke, 2000). Essentially, the dipole-dipole technique is widely used in geotechnical investigation for assessing the thickness of the overburden. It also finds application in hydrogeology to clearly define horizontal layers of porous formations (Kearey and Brooks, 1991).

4.2 Geophysical Measurements

The dipole-dipole array was operated in the profiling-sounding mode in order to obtain a two dimensional (2D) imaging. By using the 2D imaging survey a model of the subsurface indicating the resistivity variations in the horizontal as well as the vertical directions along the profile was obtained as shown in figure 3.0. To achieve this a number of electrodes were used at 5 m interval along the profile (Fig 3). Then with the dipole-dipole array the apparent resistivity is measured at different stations (the central point of symmetry of the entire configuration) along an entire profile at 5 m intervals for a number of movements or roll along, using the McOhm 2119 resistivity meter. This surface movement to probe a 20 m depth was repeated to probe depths at 30 m, 35 m, 40 m, 45 m, 50 m, and 60 m by increasing the electrode spacing.

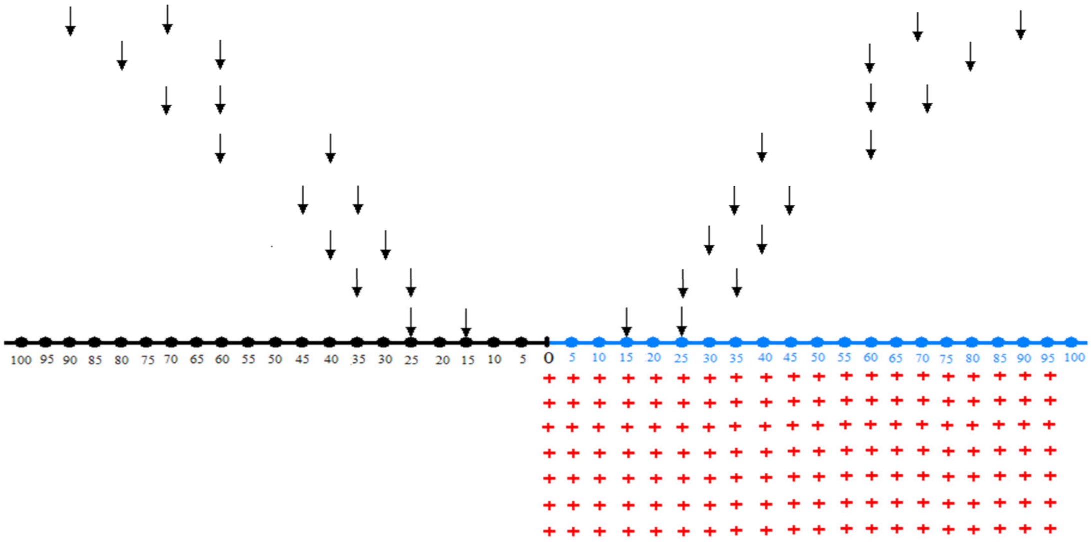

Fig 3 Schematic two-dimensional data pattern of Resistivity Survey

5. Results and Discussions

The results are presented in 2-D coloured vertical cross-sections to give a pictorial representation of the distribution of apparent resistivity within the subsurface. But the apparent resistivities from VES technique are presented as profile curves. Some selected 2-D vertical cross- sections, VES curves and drill logs have been presented for the analysis and discussion.

5.1 Results

The vertical cross sections show deep-blue and light-blue coloured portions as relatively lower and low resistivity zones respectively. These may be weathered zones depending on the orientation and distribution of the blue coloured regions. On the other hand, the deep-brown and light-brown coloured portions show relative higher and moderately high resistivity respectively. These may be either solid non-conducting rocks or overburden sediments. Below every 2D vertical cross section is a plot of the vertical electrical sounding (VES) curve of the selected drilling site.

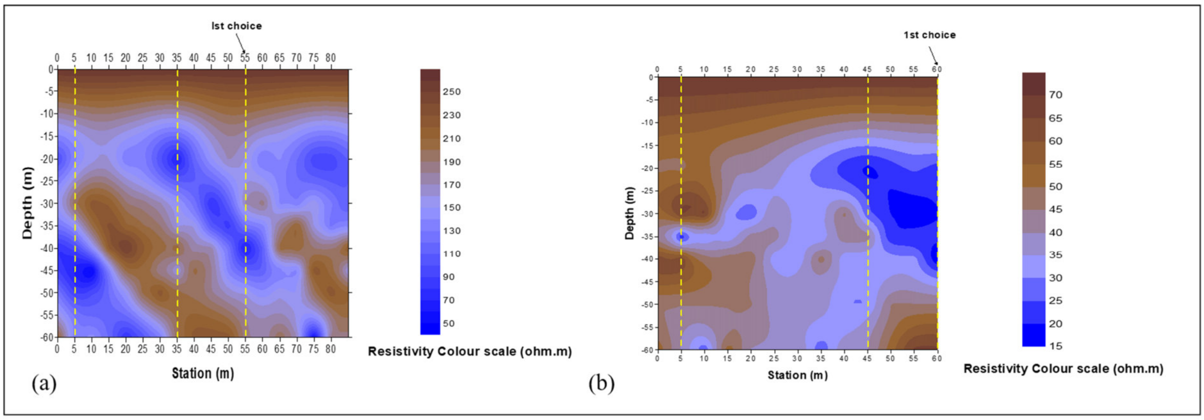

Fig. 4 Two-Dimensional Vertical cross section (a) at Kpunchorgu (b) at Kwapung

The apparent resistivity in the Kpunchorgu community is generally low, from the values obtained ranging from a minimum of 52.8 Ωm to a maximum of 253.4 Ωm as seen in the colour scale. The resistivity colour scale shows that the positive anomaly region (blue coloured areas) lies between 50.0 Ωm and 170.0 Ωm. On the other hand the negative anomaly region (brown coloured areas) falls between 170.0 Ωm and 260.0 Ωm. The overburden spans to about a 10 m depth from the ground surface, because the apparent resistivity values registered from the ground surface to 10 m depth, were relatively high. Also, one aquifer regime is anticipated in this area. This is because from the vertical cross section, the positive anomaly regions have the same contour spacing distribution and are also interconnected. There is a down-slope trend of fracture, which is evident in the pseudo section shown in figure 4(a). Interception of these fractures at reasonable depth is expected. Water strike is expected at about 12 m. The station point Chainage 55 m was selected as the first choice drilling point. The apparent resistivity in the Kwapung community is relatively low, ranging from a minimum of 15.8 Ωm to a maximum of 66.0 Ωm as seen in the resistivity colour scale in figure 4(b). The overburden sediment is about 14 m thick and the apparent resistivity values registered up to 14 m depth were relatively higher compared to other values registered in the area. The aquifer zone seems to be more developed towards the end of the profile at a mean depth of about 30 m in the interval of 40 to 60 m along the profile. he main aquifer is likely to be in the interval of 20 to 50 m depth beneath the surface. Thus, water strike is expected at 15 m deep beneath the surface.

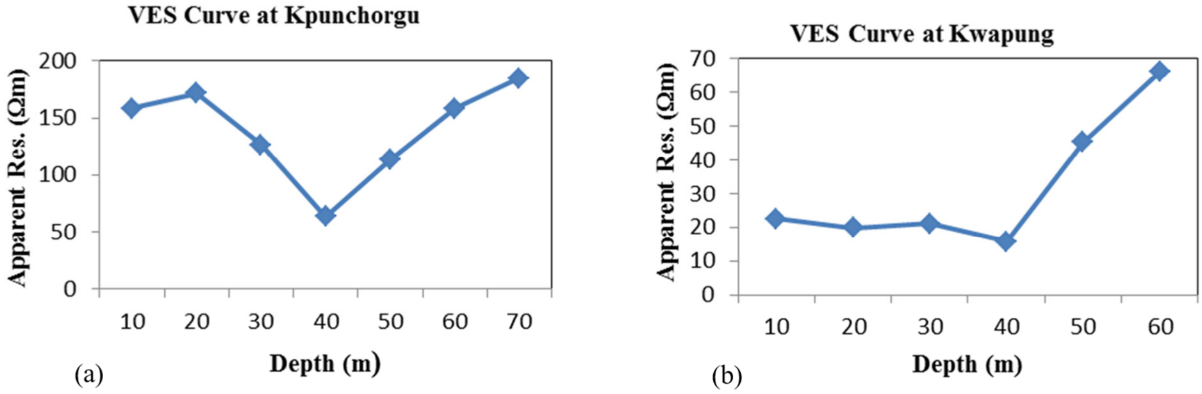

Fig. 5 VES curves for selected chainage points (a) 55 m at Kpunchorgu (b) 60 m at Kwapung

For the VES curve for Kpunchorgu for the station at 55 m in figure 5 (a), the curve drops abruptly from 171.6 Ωm at the 20 m depth to 63.3 Ωm at the 40 m depth and increases sharply throughout to 184.7 Ωm at the 70 m depth. This sharp fall and rise in apparent resistivity about the 40 m depth may be due to an interception of a highly conducting material within a non-conducting medium and this material may be a fracture or an aquifer. Thus, main aquifer zone may be between 20 m and 40 m. Station points at chainage 5 m and 35 m were also selected as alternative drill points because they registered some very low resistivity values at depth. For Kwapung, the station point at chainage 60 m was selected as the first choice drilling point because the VES curve shows a relatively low apparent resistivity of 22.6 Ωm at the 20 m depth and gradually drops to 15.8 Ωm at the 40 m depth and then increases sharply throughout to 66.0 Ωm at the 60 m depth as shown in figure 5(b). This sharp rise in apparent resistivity from the 40 m depth through to the 60 m depth is evident of a hard non-conducting formation intercepting a highly conducting material. This feature beneath the chainage 60 m point is evident of an anomalous zone between the 20 m and the 40 m depths. However, chainage 45 m and chainage 5 m were selected as alternative points because they registered some relatively very low resistivity values at depth.

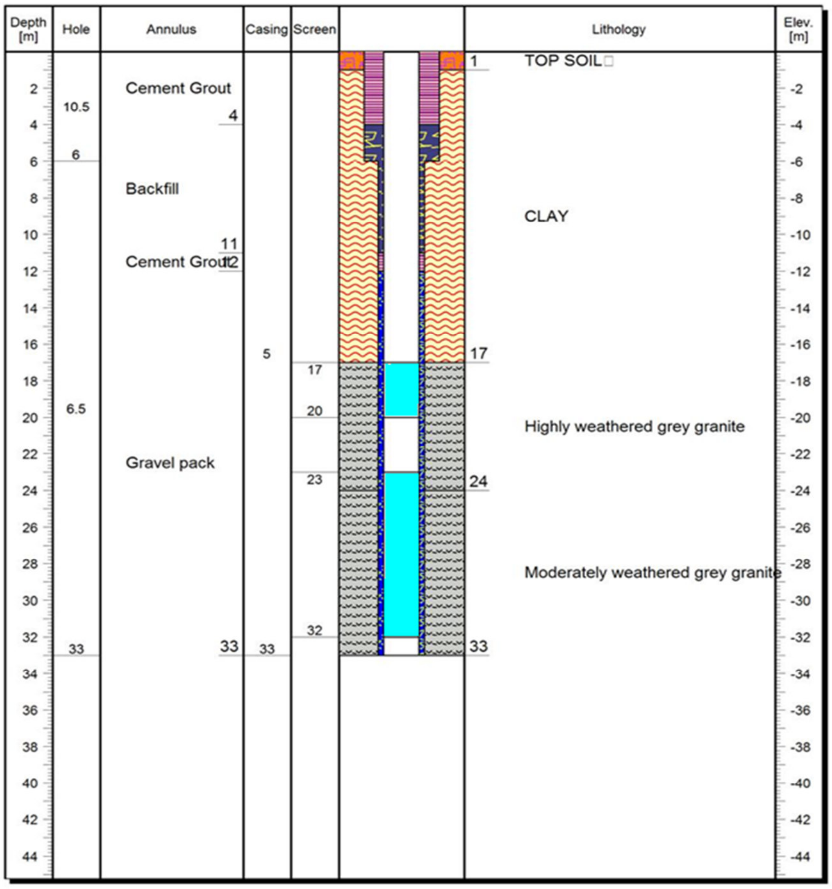

Fig 6 Drill log at **c**hainage 55 m at Kpunchorgu

Analysis of the drill log at Kpunchorgu as shown in figure 6 shows that the borehole was drilled to a depth of about 33.0 m. The log indicates that up to a depth 1.0 m below the surface is top soil. From 1.0 to 17.0 m is made up of clayey soil, 17.0 to 24.0 m is within a highly weathered grey granite, and 24.0 to 33.0 m traverse through a moderately weathered grey granite in the crystalline bedrock. Two aquifer zones were encountered at the intervals 17.0 – 20.0 m and 23.0 – 32.0 m. Thus, the well was screened from 17.0 to 20.0 m and 23.0 to 32.0 m. The yield from the aquifer was 18 litres per minute when developed with an airlift pump for 3 hours.

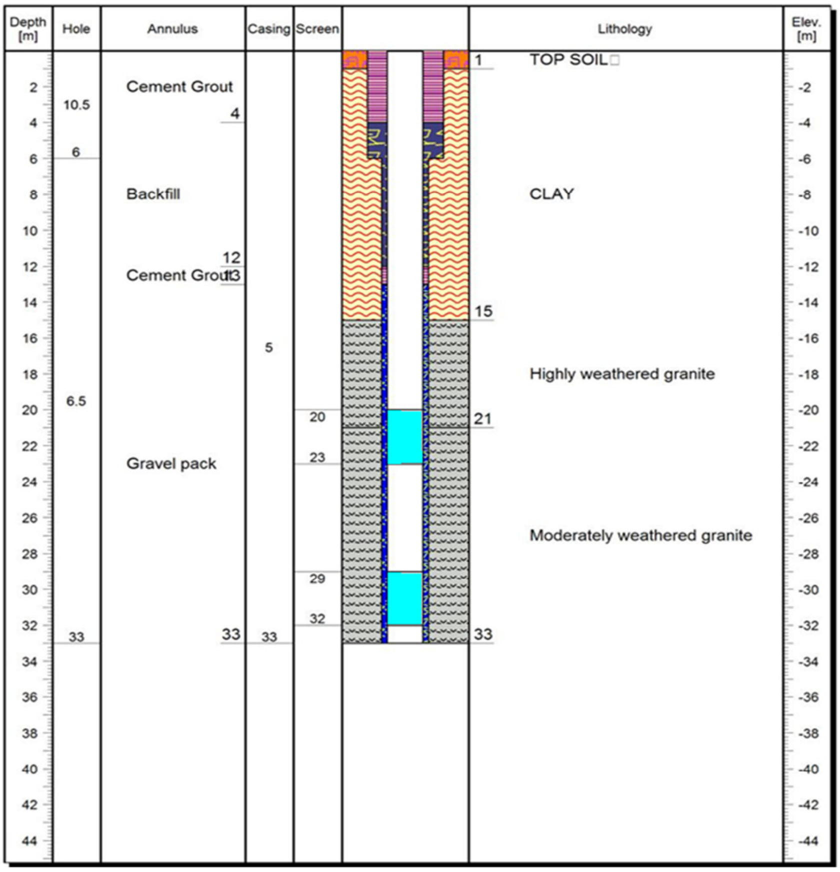

Fig 7 Drill log for chainage 60 m at Kwapung

Figure 7 shows the driller's log for chainage 60 m at Kwapung. The log shows that the borehole was drilled to a depth of about 33.0 m. It indicates that up to a depth 1.0 m below the surface is top soil. From 1.0 to 15.0 m is made up of clayey soil, 15.0 to 21.0 m is within a highly weathered granite, and 21.0 to 33.0 m traverse through a moderately weathered granite in the crystalline bedrock. Two aquifer zones were encountered at the intervals 20.0 – 23.0 m and 29.0 – 32.0 m. Thus, the well was screened from 20.0 to 23.0 m and 29.0 to 32.0 m. After 3 hours development and airlift pumping the aquifer yielded 48 litres per minute of water.

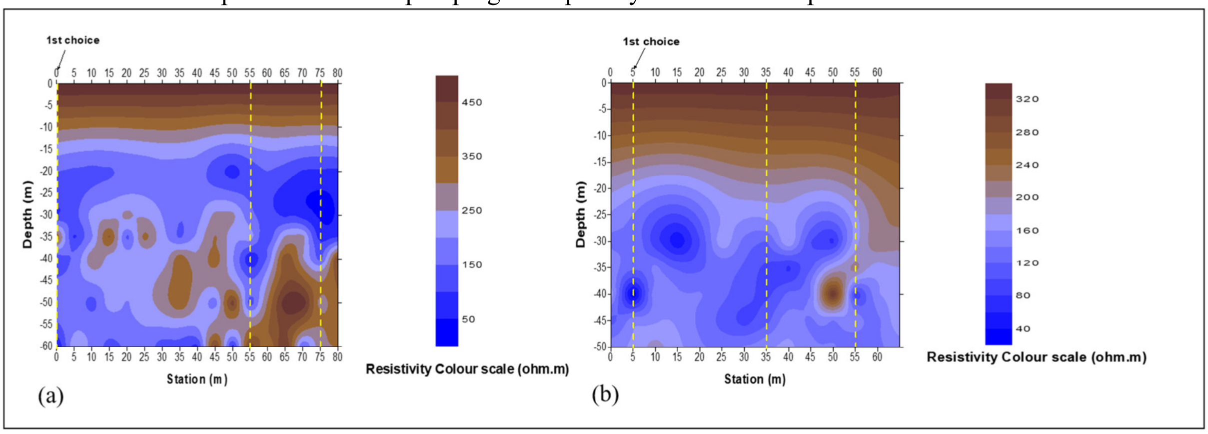

Fig. 8 Two-Dimensional vertical cross section at (a) Wuru (b) Nabiajan

In the Wuru community the apparent resistivity ranges from a minimum of 39.6 Ωm to a maximum of 490.3 Ωm. The resistivity colour scale shows that relatively higher apparent resistivity ranges from a minimum of 250.0 Ωm to about 450.0 Ωm as shown in figure 8(a). However, lower apparent resistivity zones range from a minimum of 50.0 Ωm to about 250 Ωm. The overburden sediment is about 14 m thick, with the aquifer system predicted to be more developed in extent beneath the profile towards the end of it. Thus water strike is expected at 15 m and main aquifer is likely to be in the interval 20 to 50 m depth. In the Nabiajan community the apparent resistivity ranges from a minimum of 36.9 Ωm to a maximum of 217.8 Ωm. The apparent resistivity colour scale shown in figure 8(b) shows relatively higher values ranging from a minimum apparent resistivity of 200.0 Ωm to 320 .0 Ωm. However, the relatively lower apparent resistivity values are in the range of about 40.0

to 180.0 Ωm. The overburden sediment is about a 14 m thick from the surface. One fracture system is anticipated in this region and the fracture system seems to be more developed from the beginning of profile towards the end. Water strike is expected at 15 m and main aquifer is likely to be from a depth of 25 m to 50 m depth.

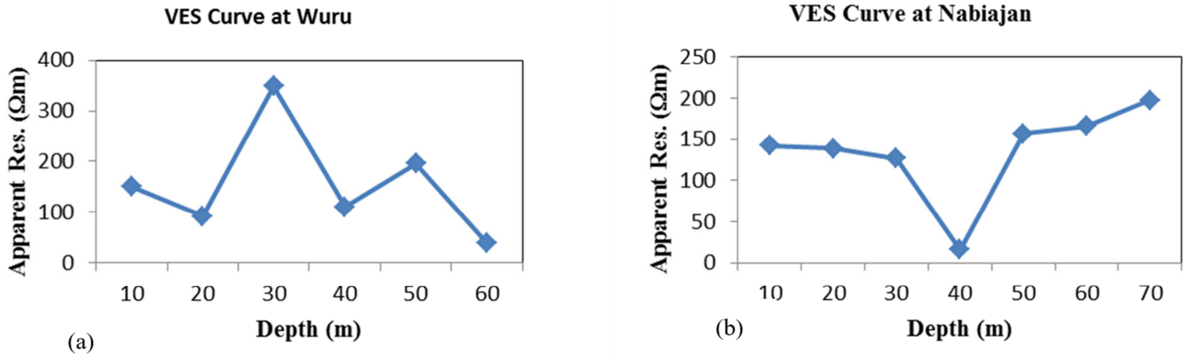

Fig. 9 VES curves for selected points at chainage (a) 0 m at Wuru (b) 5 m at Nabiajan

The station point at the beginning of profile at chainage 0 m was selected as the first choice drilling point because VES curve at the station shows a zigzag variation as shown in figure 9(a). It shows that there is alternate interception of relatively conducting and non-conducting media at depth, thereby depicting highly fractured formation beneath. The point of interest is in the sharp increase in apparent resistivity from 92.4 Ωm at the 30 m depth to 348.4 Ωm at the 35 m depth and an immediate decrease to 110.8 Ωm at the 40 m depth. This distinct variation shows a non-conducting material intruding a conducting material. The other points at chainage 55 m and 75 m were selected as alternative points because they registered relatively low resistivity points at depth. The VES plot as shown in figure 9(b), shows that the curve drops abruptly from 127 Ωm at the 35 m depth to 15.8 Ωm at the 40 m depth and increases sharply to 157 Ωm at the 45 m depth. This sharp fall and rise in apparent resistivity at the 45 m depth may be due to an interception of a highly conducting material within a non-conducting medium, which may be a weathered zone or fracture in the bedrock. The station points at 35 m and 55 m were selected as alternative drill sites as they show some relatively low apparent resistivity values at depth.

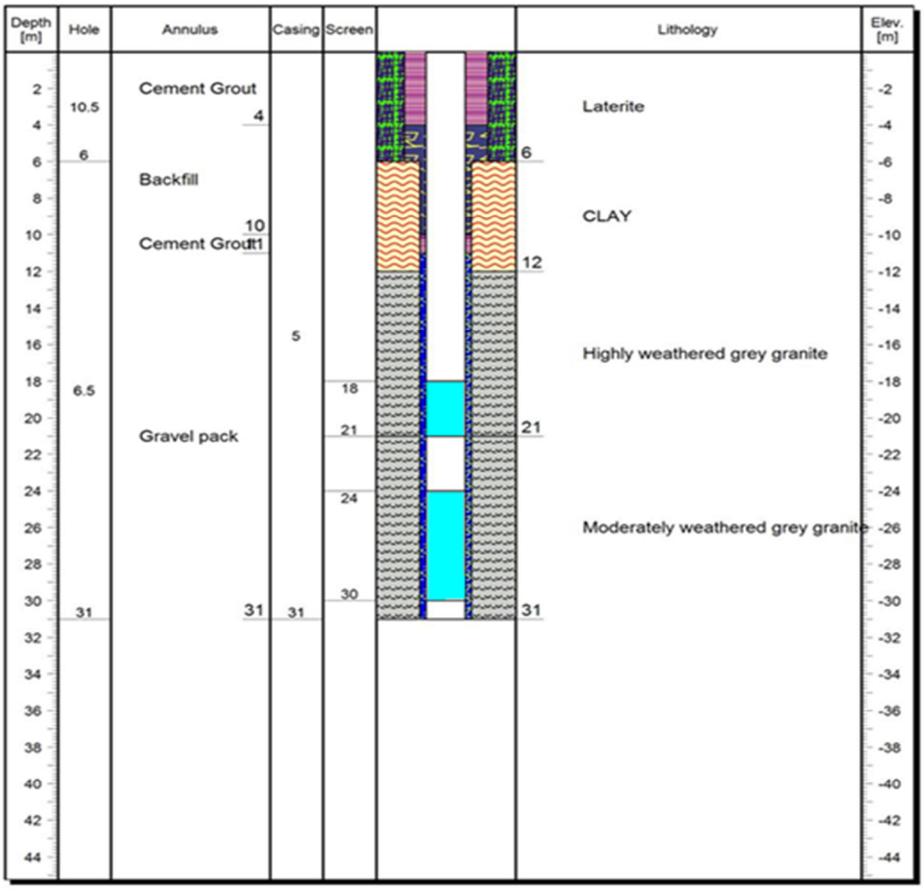

Fig 10 Drill log for chainage 0 m at Wuru

Figure 10 shows the driller's log for chainage 0 m at Wuru. The log shows that the borehole was drilled to a depth of about 31.0 m. It shows laterite up to a depth 6.0 m beneath the surface.. From 6.0 to 12.0 m is made up of clayey soil, 12.0 to 21.0 m is within a highly weathered grey granite, and 21.0 to 31.0 m is a moderately weathered grey granite in the crystalline bedrock. Two aquifer zones were encountered at the intervals 18.0 – 21.0 m and 24.0 – 30.0 m. Thus, the well was screened from 28.0 to 21.0 m and 24.0 to 30.0 m. The aquifer yield was 18 litres per minute after development and airlift pumping test for 3 hours.

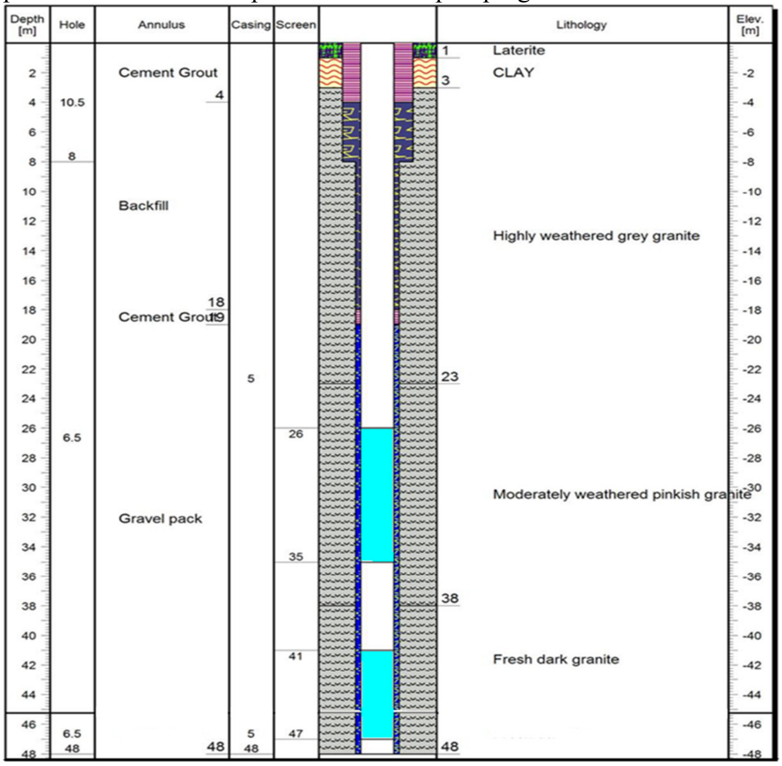

Fig 11 Drill log for a station point 5 m at Nabiajan

Figure 11 shows the driller's log for chainage 5 m at Nabiajan community. The log shows that the borehole was drilled up to a depth of 48 m. The lithology shows laterite up to a depth 1 m beneath the surface. From 1.0 to 3.0 m is made up of clayey soil, 3.0 to 23.0 m is within a highly weathered grey granite, and 23.0 to 38.0 m is a moderately weathered pinkish granite in the crystalline bedrock. The lithology continues from 38.0 to 48.0 m consisting of fresh dark granite. Two aquifer zones were encountered at the intervals 26.0 – 35.0 m and 41.0 – 47.0 m. Aquifer yield was 60 litres per minute when developed with an airlift pump for 3 hours.

Table 1 Summary of Borehole Depths and Yields

Community	Max. Drill Depth (m)	Aquifer Depth(s) Range (m)	Yield(l/min)
Kpunchorgu	33	17-20, 23-32	18
Kwapung	33	20-23, 29-32	48
Wuru	31	18-21, 24-30	18
Nabiajan	48	26-35, 41-47	60
Pieng Nanyour	27	14-26	15
Bombieboi	53	22-28, 34-40, 46-52	80
Forkiebieboi	70	No aquifer located	0 – Dry
Bichemboi	53	28-40, 46-52	200
Bawieboi	53	22-28, 34-40, 46-52	25

5.2 Discussions

From the interpretation of the 2-D (profiling and sounding) data, the following deductions can be made. For Kpunchorgu, station Chainage 55 m was selected as the first choice drilling point while stations Chainage 35 m and Chainage 5 m were selected as alternative drilling points. From the pseudo sections and VES curves for the selected stations, it was established that the overburden is about 10 m deep and also water strike was expected at 12 m. The interpretations further predicted that the main fracture or aquifer zone falls between 20 m and 50 m depth. From the drill-log it was seen that the first water strike was at 12 m and a water bearing fracture was encountered between 20 m and 25 m at a maximum drilling depth of 33 m and an appreciable flow rate of 18 lit/min was acquired, which lies within the range predicted in the pseudo section and VES interpretations.

For Kwapung, station Chainage 60 m was selected as the first choice drilling point while stations Chainage

45 m and Chainage 5 m were selected as alternative drilling points. From the interpretations provided by the pseudo section and VES curve for the selected stations, it was established that the overburden is about 14 m deep and also water strike was expected at 15 m. The interpretations further predicted that the main fracture or aquifer zone falls between 20 m and 50 m depth. From the drill-log it was seen that the first water strike was at 15 m and a water bearing fracture was encountered between 19 m and 21 m. Also, at a maximum drilling depth of 33 m an appreciable flow rate of 48 lit/min was acquired, which lies within the range predicted in the pseudo section and VES interpretations.

For Wuru, station Chainage 0 m was selected as the first choice drilling point while stations Chainage 75 m and Chainage 55 m were selected as alternative drilling points. From the interpretations provided, it was established that the overburden is about 14 m deep and also water strike was expected at 15 m. The interpretations further predicted that the main fracture or aquifer zone falls between 20 m and 40 m depth. From the drill-log it was seen that the formation was moist at 16 m and the first water strike was at 17 m and a water bearing fracture was encountered at 21 m. Also, at a maximum drilling depth of 31 m an appreciable flow rate of 18 lit/min was acquired, which lies within the range predicted in the pseudo section and VES interpretations.

For Nabiajan, station Chainage 5 m was the first choice drilling point while stations Chainage 35 m and Chainage 55 m were selected as alternative drilling points. From the interpretations made, it was established that the overburden is about 10 m deep and also water strike was expected at 15 m. The interpretations further predict that the main fracture or aquifer zone falls between 20 m and 60 m depth. From the drill-log it was seen that the first water strike was at 15 m and water was encountered at 20 m and 38 m. Also, at a maximum drilling depth of 48 m an appreciable flow rate of 60 lit/min was acquired, which lies within the range predicted in the pseudo-section and VES interpretations.

6. Conclusions

The Sissala East district is underlain by Dixcove granite complex formation which is well consolidated with little or no inherent permeability. This therefore makes infiltration of groundwater through the wet plastic surface layer of this geology almost impossible. Groundwater recharge therefore is very poor in this district. Interpretations of the pseudo sections, VES curves and drill-logs reveal that the district is predominantly underlain by granites with an average overburden thickness of about 10 m. The study further revealed that the average groundwater (moisture) interception (first water strike) was about 15 m at depth and also main aquifers and fractures were encountered between 20 m and 53 m depth range. Beyond this depth range, there exists a very low possibility of finding groundwater. Quantitatively, the drill-logs revealed that out of nine communities there was one dry hole and stations which were wet yielded groundwater from moderate to highly weathered and fractured granite formations. The implication is that in the crystalline granitic formation aquifers were located within the weathered (saprolite) and fractured zones. This gives a relatively high success rate of about 89 % in the district, with apparent resistivity of the wet wells between 15 Ωm and 300 Ωm. The maximum drilling depth for all the communities did not exceed 60 m. Thus the Sissala East district has a great potential for groundwater. Hence, groundwater sources can be relied upon as an alternative source of water for domestic and irrigation purposes for inhabitants of the district.

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