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Improving Access to Potable Water Supply using Integrated Geophysical Approach in a Rural Setting of Eastern Ghana

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ABSTRACT

Hydro-geophysical investigations were conducted on a 16-acre piece of land at Kaedabi-Ahwerease in the Akuapem-South Municipality in the Eastern Region of Ghana. The purpose of the study was to determine the groundwater potential at the site and the possibility of drilling a borehole that could yield considerable quantity of groundwater for sustainable potable water for a proposed bottled and sachet water factory. The survey was carried out using the Geonics EM-34 conductivity meter and ABEM Terrameter (model SAS 1000 C) equipment. Electromagnetic (EM) profiling and Vertical electrical sounding (VES) surveys were conducted to determine the vertical variation of the resistivity/conductivity of the sub-surface rock formation with depth with the view to detecting fractures, joints, shear zones and faults, which could serve as conduits for water traps within the underlying bedrock at the project site. The EM profiling data were obtained along three (3) evenly-spaced parallel traverses each of length 300 m with the 20 m inter-coil separation cable. Measurements were taken at 10 m station intervals in the northwest-southeast directions as a means of selecting suitable points for depth-probing (VES investigations). From the EM profiling results, 12 conductivity anomaly points were selected for further investigation using VES methodology. The Schlumberger array was used for the VES survey. The combined interpretation of the EM and VES results indicated the presence of possible aquifer units comprising the weathered, fractured and fresh bedrock within the subsurface of the study area. The results revealed the presence of three geo-electric layers. The resistivity of the top lateritic layer ranged from 78 to 1,895 Ωm with thickness between 0.8 and 1.7 m. The resistivity of the regolith (second layer) ranged from 10 to 135 Ωm with thickness of 2.1 to 6.4 m; while the bedrock had resistivity values between 303 and 1068 Ωm. The combined output from topographic interpretation, paleo-river channel location and resistivity modeling results clearly zoned out areas of high and low groundwater potential in the study area. The estimated groundwater yield for the three test wells drilled within the detected high groundwater potential zone ranged between 50 and 160 litres per minute (lpm), indicating that, the study area has adequate groundwater for the proposed project.

1.0 Introduction

The most obvious source of water to mankind (Mussett and Aftab, 2000) is that of the surface water in rivers, ponds, lakes, streams etc. but these are directly dependent on groundwater, which is concealed within the subsurface geologic rocks. One of the major concerns to hydrogeologist is how this hidden treasure can be explored and tapped with less cost. Over the years, hydrogeologists require the services of geophysicists to delineate possible aquifers, their depths, lateral extent and geological structures such as fractures, faults, joints, shear zones as well as groundwater flow direction. It must be pointed out that, the granite underlying the study area is massive with micro fractures to enhance groundwater development. Several attempts have been made by both government and private drilling companies such as Water Research Institute (WRI), Community Water and Sanitation (CWSA) with minimal successes. Although, the study area and it's environ has been touted as a 'no go' area, yet with the aid of geophysics the success rate of drilling a borehole has improved tremendously. Many geophysical methods find application in locating and mapping out the subsurface geology and groundwater resources. The geophysical exploration method provides easy way of collecting data on the geological structures and lithological units (Mussett and Aftab, 2000) to minimize the degree of possible unsuccessful attempt of borehole drilling. The most widely used methods for groundwater exploration are the electrical resistivity and electromagnetic methods. The electrical resistivity method measures the resistivity of the subsurface to determine the extent of anomalies that may exist within the geological strata. The electrical resistivity method is highly used because of the high electrical conductivity contrast that exists between the host rock and the pore water.

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The application of the electrical resistivity method over the years is highly documented in several scientific papers. It has been used successfully for groundwater exploration in hard rock terrain (Anechana et al. 2015; Nwankwo, 2011; MacDonald et al., 2001; Mohammed et al., 2012; Sharma and Branwal, 2005; Okrah et al., 2012; Darko and Krasny, 2000; McNeill, 1990) and also in sedimentary formations (Al-Bassam, 2005; and Claudia et al., 2003). It has to be underscored that, it is high cost and time-consuming to conduct vertical electrical sounding in a given location without having prior knowledge of a potential anomaly point. In the light of this, the electromagnetic method has been used over the years to serve as the reconnaissance tool to map out the conductivity contrast between the target and the host rock. It has also been used extensively for hydrogeologic studies including estimation of groundwater volume (Barry et al., 2010), mapping groundwater contaminant (Benson et al., 1997), groundwater exploration in fissured media (Bernard and Vella, 1991) and also in hydro-geophysical studies (Denielsen et al., 2003; Cook et al., 1992). The combined application of both geophysical methods in delineating potential groundwater drilling points for sustainable water supply will give detailed information about the geological and hydrogeological characteristics of the aquifer in terms of their overburden and aquifer thickness, bedrock resistivity, and vertical resistivity variation of the underlying geo-electric layers. This study seeks to delineate possible high groundwater potential points that could yield considerable amount of water supply for the intended bottled water production.

2.0 Local Setting

2.1 Location and Physical setting

The study area (Figure 1) is located at Kaedabi-Ahwerease within the Akim-South Municipal of the Eastern Region of Ghana. The geospatial coordinate of the study area is 0.38468W and 5.81822 N, which lies within the Wet-semi-equatorial climatic zone. The site experiences bi-modal rainy season with substantial amount of precipitation. This is characterized by a bi-modal rainy season with rainfall amount of between 1,238 mm and 1,660 mm, which is high enough to support all year round agriculture. The elevation of the site measures about 81 m above sea level. The average temperature ranges between 25.2 °C and 27.9 °C. Relative humidity ranges from 80 - 95% in the rainy season and 55-80% during the dry season (Dickson and Benneh, 2004). The vegetation is mainly characterized by tall trees with evergreen undergrowth and contains valuable economic trees.

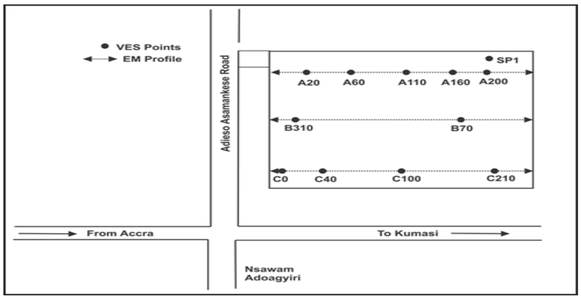

Figure 1. Schematic layout of the study area showing the EM profiles and the VES points location

2.2 Geology and Hydrogeology

Hydrogeologically, Ghana is underlain by two major and a minor hydrogeological provinces. The Basement Complex, which is made up of Precambrian crystalline igneous and metamorphic rocks as well as the Palaeozoic sedimentary rock formation constitutes the major province; whilst the Cenozoic, Mesozoic and Palaeozoic sedimentary strata occurs along the Coastal belts with some few occurrences of Quaternary alluvium along the major stream courses. The Basement Complex underlies about 54% of the entire rock mass of the country and consists mainly of gneiss, phyllite, schist, migmatite, granite and quartzite. The Palaeozoic sedimentary rocks also consist mainly of sandstone, mudstone, siltstone, shale, arkose, and limestone and constitute 45%. The remaining 1% is made up of the Coastal Block Fault and Coastal Plain provinces (Dapaah-Siakwan and Gyau-Boakye, 2000). The study area falls within the Basement complex, which is underlain by the Tamnean plutonic suite (Geological Survey, 2010), with granitoid-gneiss and biotite-gneiss as the main rock types (Figure 2). The granite associated with the formation is of considerable relevance to the water economy of the country (Dapaah-Siakwan and Gyau-Boakye, 2000). These rock types underlie extensive and highly-populated areas where water demand is high. Though the rocks are inherently impermeable due to little or no intrinsic porosity, secondary porosity has developed as a result of fracturing and weathering. Where precipitation is high, weathering processes increases thereby enhancing the development of groundwater in the overburden. On the contrary, where precipitation is low, there is less weathering, thereby causing the granite to occur in either massive or poorly-jointed units, which make it difficult to enhance groundwater development. In 1994, the Water Resources Research Institute (now CSIR Water Research Institute) completed a study on the borehole yield in the various provinces and sub-provinces and gave the borehole yield in the Basement Complex formation to range from 2.7 – 12.7 m^3/h, whiles that of the Palaeozoic sedimentary formation range from 6.2 – 8.5 m3/h. On the part of the Coastal Province, the yield range between 3.9 and15.6 m^3/h whilst that of the alluvium is from 1 - 15 m^3/h.

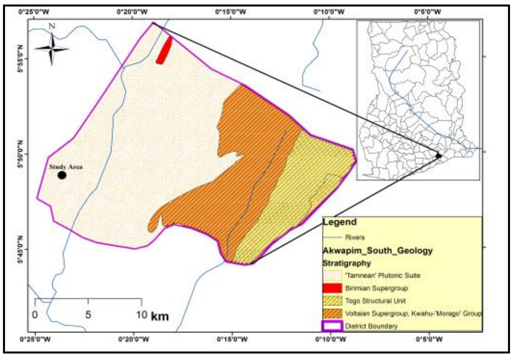

Figure 2. Geological map of Akim-South Municipal showing the study location.

3.0 Materials and Methods

Groundwater search started way back in the 15th century. In that era it was termed as water witching or water dowsing, where all sort of devices were used without any scientific basis. In recent times, a lot of scientific methods have been devoted to indirectly map out fractures within the sub-surface through geophysical methods. These methods rely upon the physical properties of the earth materials to predict the presence of anomalies within a geologic stratum. Two most widely used geophysical methods for groundwater exploration are; the Electromagnetic (EM) and the Resistivity methods. In this present study, the two aforementioned methods were used to delineate possible drilling points that could yield a sustainable amount of water for commercial purposes. The EM was used as a reconnaissance tool to narrow the search to few promising points where conductivity is expected to be high at depth for further resistivity probing.

3.1 Electromagnetic Field Measurements

The EM equipment used for this survey is the Geonics EM 34-3 with a 20 m coil separation. The maximum depth that the EM can probe with the 20 m separation is 15 m for the horizontal dipole (HD) response and 30 m for the vertical dipole (VD) response. To start measurements the receiver meter was connected to the transmitter coil in order to null the equipment to remove any offsets in the output (DC) circuitry (Geonics, 1991). The conventional way of laying out measuring tapes was applied and steps calibrated at walking pace with the equipment mounted on the operators. This was to fasten the survey operations and also to cover larger areas within the shortest possible time. During the survey, the transmitter operator was made to lead the process and stopped at designated spacing for readings to be taken by the receiver operator. The receiver operator recorded the apparent conductivity values after moving the coil forward and backwards until a stable reading was possible. Two readings were taken in the Horizontal Dipole (HD) and Vertical Dipole (VD) modes at each measurement station. The measuring station points for each spacing was taken at the midpoint thus between the receiver and the transmitter. Stations where both the HD and VD showed high conductivity values or where the VD readings outstripped their corresponding HD values were pegged for further investigations with the vertical electrical sounding (VES) methodology.

3.2 Resistivity Measurement

In this study, the vertical electrical sounding was employed to investigate the variations of electrical resistivity with depth. A highly-sensitive ABEM SAS 1000C Terrameter was used for the data collection. The conventional four-electrode array (Figure 3) in the Schlumberger protocol (Telford et al.1990) was used in the data acquisition. To start with, the two outer electrodes were made the current electrodes *(C1C2)* whilst the two inner electrodes were labelled as the potential electrodes *(P1P2)*, (Figure 2). In the Schlumberger array, only the current electrodes were moved to specific separation distances. The potential electrodes were only moved when the current separation became so high that the current was finding it difficult to penetrate. At every current and potential electrode spacing stations, current (I) was made to pass through the two current electrodes into the ground and the resulting potential difference (ΔV) measured using the potential electrodes (Figure 3). The resistivity meter measured the ratio ΔV/I, which represents the resistance of that particular electrode spacing.

Geometric factors were calculated from Eq. 1, and thus multiplied by the measured resistance to get the apparent resistivity (ρ) values Eq. 2. The highest potential electrode spacing for this study was 10 m with the total current separation of 200 m. For quality assurance purposes, the measured VES data were plotted in the field using a log-log graph to enable repetition and deletion of data points that were seen as bad. In all, 12 VES points were surveyed and the resulting data set were analysed using the ZONDIP 1D software to give the number of geologic layers as well as the formation resistivity and their corresponding aquifer thickness and depth. The software has been tested and proven reliable for the processing and interpretation of VES sounding data (ZONDIP, 2012). The software produces both the theoretical and the observed plot for each of the sounding points on the same graph. The generated sounding curves are automatically sub-divided into a number of layers based upon the nature of the curve. The differences between the observed and theoretical curves were adjusted until an acceptable agreement of the fitting process was met. A measure of this difference is given by the root-mean-square error (RMS %). In view of this, reasonable values of RMS (5.5-7.9.5) were maintained for all the VES points.

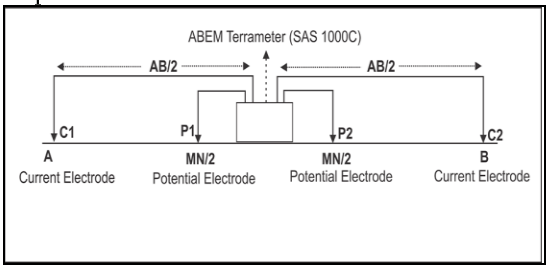

Figure 3. A typical VES survey setup using the Schlumberger array.

$$G = \pi \left\{ \left((C_1C_2)^2 - (P_1P_2)^2 \right) \Big/ 4P_1P_2 \right\} \quad (1)$$

Where C_1C_2 is the distance between the current electrodes, P_1P_2 is the distance between the potential electrodes; *G* is the geometric factor and π is a constant (*22/7)*

$$\rho = G\left(\Delta V / I \right) \quad (2)$$

3.3 Borehole drilling

Drilling through the overburden was done using 10-inch diameter roller bit to a depth of 10 m until the relatively harder rock was intercepted. This depth section was protected from caving by installing an 8-inch diameter working casing. Beyond this depth, the drilling bit was changed to 6½-inch diameter drilling hammer, and using air as the drilling fluid. Drilling continued with the hammer until it terminated at a final depth of 50 m. During the drilling process, logging and sampling of the drilling cuttings were made at every one metre intervals. This was to identify the precise fracture sections to allow placement of screens during construction. Measurements of the yields at the various aquifer sections were estimated and recorded as aquifer zones were intercepted.

4.0 Data Analysis and Interpretation

4.1 Electromagnetic profiling (EM)

Three EM profiles of traverse length 300 m in the North-East to South-West directions were demarcated for the continuous conductivity measurements. The results of the continuous conductivity measurements are shown in Figure 4. Figure 4A presents a possible conductivity anomalous points where conductivity was high at both shallow and deeper depth of reach of the signals. Five points were selected based upon the conductivity contrast between the HD response and the VD response for further investigation using the vertical electrical sounding methodology. At point A20, the HD and VD responses were 26 and 13 m mhos/m whilst the apparent conductivity measured in the HD and VD modes at point A60 were 17 and 16 m mhos/m respectively. VES points A110 and A160 along profile A (Figure 4) also recorded apparent conductivity values in the HD and VD modes as 17 and 18 m mhos/m for point A110 and 13 and 16 m mhos/m for A160 respectively. At point A200, the HD and VD responses of the subsurface were 16 and 18 m mhos/m. From the apparent conductivity plot along profile A, we could deduce that the conductivity of the subsurface is relatively low indicating a highly-consolidated subsurface. It was concluded that the bedrock contains micro-fractures with low porosity and permeability. The EM conductivity results along profiles B and profile C (Figure 3) were no different from that of profile A (Figure 4). Along profile B, two points were selected at B310 and B70 for further investigation. A remarkable conductivity contrast from the VD response of 32 m mho/m was recorded as against 9 m mho/m for the HD. This point is expected to have enough fractures at depth with a possible high groundwater accumulation. The results from point B70 was not encouraging, at shallower depth the HD measured the apparent conductivity at 4 m mho/m while the VD was 16 m mho/m at deeper depth. Along profile C, the HD and VD response values were generally in the range of 8-32 m mho/m for the four selected points. The apparent conductivity values indicate that, the subsurface is more compact with minimal fractures to enhance groundwater percolation and movement. Based upon the generally low trend of the conductivity values, it is therefore anticipated that the groundwater potential is expected to be low to medium. In view of this, the VES method was employed to investigate the potential drilling points marked by the EM survey in order to establish the vertical extent of the fractures with depth.

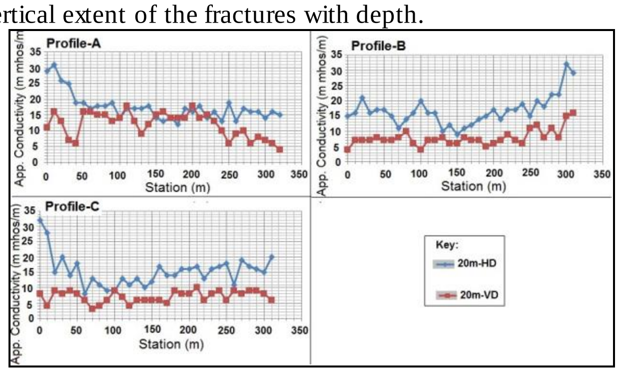

Figure4. EM Curves showing apparent conductivity profile and selected VES points at Kaedabi-Ahwerease

4.2 Vertical Electrical sounding (VES)

In all, twelve (12) VES points were investigated using the Schlumberger array up to a maximum probing depth of 55 m at half current spacing of 83 m. The selected points were A20, A60, A110, and A200. The rest were B70, B310, C0, C40, C100 and C200. Another point SP1 was strategically selected to be close to an existing hand dug well to serve as a control point. Generally, a thick regolith (overburden) with moderate resistivity values can produce an appreciable quantity of groundwater. Significant yield may also be obtained from the transitional zone between the regolith and fresh rock, a slightly weathered zone known as 'saprock'. Where the regolith is thin, deeper fracture zones may be able to yield groundwater to wells. Selection of VES points for borehole drilling was based on the thickness of the regolith and depth to bedrock, resistivity of the various layers within the regolith, bedrock and corresponding thickness. The drilling points were selected according to the likelihood of getting high-yielding boreholes, and they include; B310, C0, A20 and SP1. At VES point B310 (Figure 5), modelling results indicated three stratigraphic layers with relatively low resistivity values. The upper-most layer, which comprises lateritic sandy-clay, has a thickness of 1.6 m with apparent resistivity value of 184 Ω-m. The second layer, which is made up highly to moderately-weathered granite has apparent resistivity value of 19.5 Ω-m with thickness of 6.4 m. This is overlain by a formation with apparent resistivity value of 304Ω-m. The relatively low bedrock resistivity indicates that, the underlying granitic rock is less consolidated and hence has some fractures and inherent porosity to enhance groundwater development.

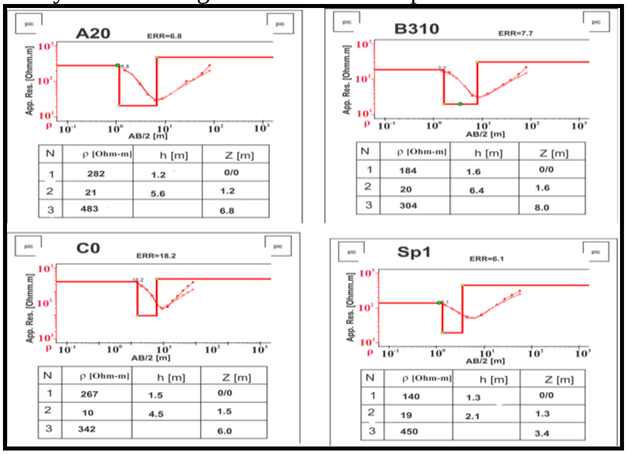

Figure 5. Curve fittings between the observed and computed data for A20, B330, C0 and SP1. Interpreted resistivities are shown numerically and thicknesses of various layers are shown on AB/2 axis for each sounding.

At point C0 (Figure 5), the bedrock was intercepted at 6 m with apparent resistivity value of 342 Ω-m, which is not far from the bedrock resistivity at point B310 . A thin layer of resistivity 9.6Ω-m sandwiched by a loose lateritic soil of resistivity 26.8 Ω-m had a thickness of 4.5 m. This thin layer can be inferred as a weathered layer lying on top of the fresh basement rock. The bedrock can be said to be moderately-fractured to facilitate the movement of groundwater and hence considered as a potential point for drilling. The 1D resistivity inverse model for the points A20 and SP1 were quite close. The bedrock apparent resistivity at A20 was 483 Ω-m whilst that of the point SP1 was 450 Ω-m. Though the thin layer sandwiched between the top layer and the bedrock had almost the same apparent resistivity values, yet, the thickness of the thin layer at point A20 was 5.6 m whilst that of SP1 was 2.1 m. This suggests that the degree of weathering at point A20 is thicker than that at SP1 and therefore can be concluded that the groundwater potential at point A20 would be higher than at SP1. It must be underscored that, the points A160, A200, B70, and C210 (Figure 6) recorded relatively high bedrock apparent resistivity in the range of 576 – 1068 Ω-m. High bedrock resistivity indicates very hard, compact and highly-consolidated material with little or no inherent porosity and permeability. Consequently, the groundwater potential at these points is expected to be low.

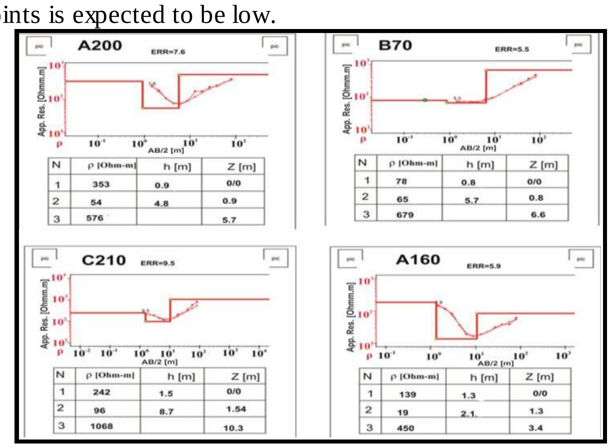

Figure 1. Curve-fittings between the observed and computed data for A200, B70, C210 and A160. Interpreted resistivities are shown numerically and thicknesses of various layers are shown on AB/2 axis for each sounding.

4.3 Potential Groundwater Flow Direction and Recommended Drilling Points

To ascertain the general sub-surface geo-electrical and hydrogeological conditions at the study area and to establish potential groundwater flow direction, geospatial analysis was carried out on the bedrock apparent resistivity. Using GEOSOFT minimum curvature gridding approach, the data was gridded and a 2D apparent resistivity spatial distribution map generated (Figure 6). It is envisaged that 2D sections would provide some level of information of the saprock underlying the study area. Most promising zones were delineated as potentially-high groundwater zones based on in-depth understanding of the prevailing geological setting.

Figure 6A, reveals that, areas around A110, A160, C40, C200 and B70 show possible groundwater divergent zones. These points could serve as possible discharge points to the points B310, A20, C0 and SP1, which are expected to have high groundwater potential.

The topographic map (Figure 6B) indicates higher elevations in the entire northern part and lowering in the southern parts of the study area.

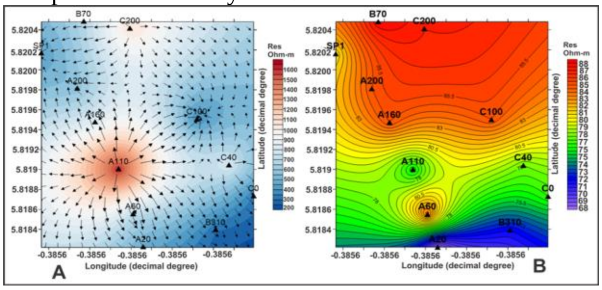

Figure 2A. Bedrock resistivity map (B) Topographic map of the study area.

In homogeneous geological environments, groundwater tends to flow in the general direction of the topography and therefore suggests that groundwater flows down the southern directions of the study area. From the geological map (Figure 2), there exist traces of paleo-river channels emanating from the northern part towards the southern direction of VES point SP1 vertically down and follows an easterly direction towards points A20 and B310. This suggests that in the area of the paleo-river channel, the subsurface is expected to be less consolidated with higher groundwater levels. This is confirmed when looking at the apparent resistivity of the underlying bedrock at points A20, B310, C0 and SP1. These points showed relatively high conductivity and therefore are classified as high groundwater potential points. By using the topographic map, the paleo-river channel location and the apparent resistivity model, it is possible to establish relative zoning of areas of high and low groundwater potential. In view of this the areas with low elevation and low bedrock apparent resistivity values (A20, B310, C0 and SP1) are classified as high groundwater potential points; while those on higher elevations and higher bedrock apparent resistivity values (B70, A160, A200 and C100) are classified as low groundwater potential points.

4.4 Borehole Drilling Results

Three (3) points (A20, B310 and SP1) were test-drilled to confirm the findings from the geophysical interpretation. The results from the drilling were to establish the correlation between the geophysical and the drilling results. In a hard rock geologic environment such as granite, the groundwater potential is influenced by the thickness of the weathered layer as well as the degree of fractures and their interconnectedness. However, the weathered layer is the most favourable place for groundwater development since the bedrock is highly consolidated with little or no inherent porosity. This is quite evident from the thicknesses of the weathered layer from the well logs (Figure 7) for B310, A20 and SP1. At B310, the weathered layer has a thickness of about 28 m and that of A20 and SP1 were 20 m and 10 m respectively.

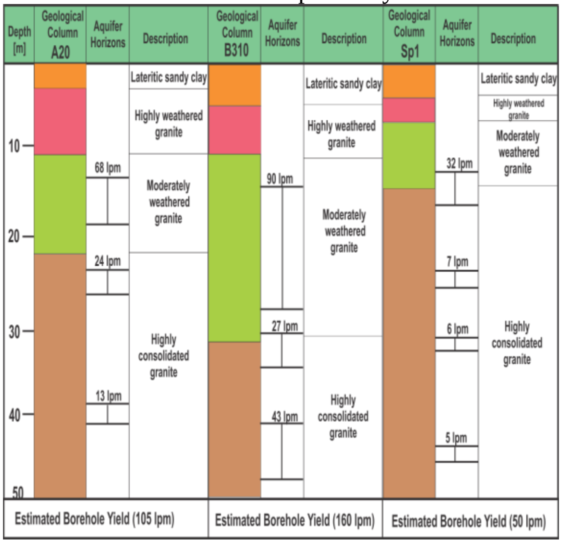

Figure 3. Borehole drilling log at drilling points A20, B310 and SP1.

The estimated borehole yield at B310 was 160 litres per minute (lpm); whilst that at A20 and SP1 was estimated at 105 and 50 lpm respectively, with the overburden yielding relatively higher groundwater than the bedrock. Comparing the drilling results with the geophysical results, it is revealed that four lithological sequence are present after drilling to a depth of 50m as against the three layer predicted by the resistivity model. This deviation could be due to the highly-weathered and moderately-weathered granite that were seen as one layer with close apparent resistivity and was difficult to be detected by the VES. This may be due to the problem of resistivity equivalence, which is a short-coming in resistivity data interpretation. Another remarkable revelation from the drilling logs is that, the yield from each aquifer section decreases at increasing depth and this is in conformity with the 1 D VES model results, which showed continuous increase in apparent resistivity with depth. It could therefore be said that, the formation becomes more compact and highly-consolidated at depth with little or no fractures and inherent porosity.

5.0 Conclusion and Recommendation

The application of surface electromagnetic and electrical resistivity measurements for groundwater exploration in a hard rock granitic environment has been successfully carried out. The study sought to delineate possible high groundwater potential zones that could yield considerable amount of water supply for the intended bottled and sachet water production. Analysis and interpretation of the results from the EM, VES and supporting drilling results revealed a four layer geologic formation with varying degrees of weathering and groundwater levels. The four geologic layers intercepted comprise; lateritic-sandy-clay within thickness of 3 and 5 m. This is followed by highly-weathered granite with thickness in the range of 2-8 m constituting the second layer. The other two layers, which were the water-bearing zones, composed of moderately-weathered granite with thickness between 5 and 22 m; whilst the fourth layer was the fresh consolidated granite. The geophysical results successfully predicted three zones of groundwater potential with the most southern part representing high groundwater potential zones whilst the northern and middle portions indicated low and moderate groundwater potential zones respectively. This was confirmed by test drill, which measured relatively high yield at B310 and A20 (Southern Zone) at estimated yields of160 lpm and 105 lpm, whilst that of SP1 (Northern Zone) recorded 50 lpm.

The results of this study have indicated that obtaining marginal to dry wells in hard rock geologic environment underlain by granite is not always the case. This study has revealed that, integrating a number of geophysical methods improves the success rate of borehole drilling in hard rock geologic terrains. The findings will sustain the water supply system for the intended bottle water production in the area. It is highly recommended that, more improved methodologies including 2-D electrical Resistivity Imaging, which has the ability to measure both the lateral and vertical cross-section of the earth should be used together with the Vertical Electrical Sounding (VES) to improve upon the yield and success rate in similar environments.

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