# Geo-Electrical Investigation Of Groundwater Resources And Aquifer Characteristics In Some Small Communities In The Gushiegu And Karaga Districts Of Northern Ghana

Van-Dycke Sarpong Asare, Aboagye Menyeh

**Abstract**: - The geo-electrical resistivity profiling and vertical electrical sounding data were acquired from some small communities and their outlying areas within the Gushiegu and Karaga Districts of Northern Ghana, in order to study the aquifer characteristics and recommend hydro-geologically suitable sites to construct water supply boreholes for the communities. The research covered four small communities, namely, Zantele, Kanshegu, Nyengbalo and Zei. The Schlumberger electrode configuration was first used in the line profiling. Qualitative interpretation of the geo-electrical resistivity profiling data resulted in the identification of weathered regions. Vertical electrical sounding using the dipole-dipole array were then conducted with at specific points within the weathered zones. The spread length ranged from minimum of 12 m to maximum of 204 m to provide depth information. Interprex 1X1D v3 software was used to compute layered earth model of the subsurface beneath the sounding points. Interpretation of the one-dimensional inversion of the VES resistivity data provided the overburden and aquifer layering resistivities and thicknesses. The geoelectric sequence revealed predominantly a three subsurface layer which is largely congruous to the weathering profile above the fresh bedrock - thick top soil, the weathered and the variably weathered and fractured bedrock respectively. The geoelectic sections provide no evidence of a descent into the fresh bedrock. The geophysical target is a reasonably thick and extensive zone of saturated weathered rock beneath the overburden. On the basis of the perceived aquifer properties, sites were recommended for drilling water supply boreholes for the communities.

**Keywords**: - Apparent resistivity, Aquifer, Dipole-Dipole array, Geo-electric layers, Groundwater, Schlumberger resistivity profiling, Vertical electrical Sounding (VES) and Weathering.

————————————————◆————————————————

## 1 INTRODUCTION

People who live in rural communities mostly rely on water from surface water schemes like rivers, streams, brooks and in some cases unprotected shallow dug wells. Apart from the fact that these sources of water sometimes run dry, there are numerous water borne diseases that attend the consumption of water from these sources. Economic implications are stark. Where planning and economic dictates rule out the provision of pipe borne water, construction of boreholes becomes the verity option. In many areas and instances the construction of wells has proceeded without any detailed insight into the hydrogeological and geophysical parameters which determine the existence of exploitable groundwater. In many of such constructions, only geological reconnaissance with emphasis on user convenience of distance to site is employed. Though such approaches have worked well in certain terrains, in some others it has achieved very limited successes. The expanding demand for water and the cost involved in sinking these boreholes therefore require the application and the proper use of groundwater investigation techniques in order to locate high yielding aquifers.


- Van-Dycke Sarpong Asare, Lecturer Department of Physics, Kwame Nkrumah University of Science and technology, Kumasi. E-mail: vandyckea@yahoo.co.uk
- Aboagye Menyeh, Professor, Department of Physics, Kwame Nkrumah University of Science and technology, Kumasi. E-mail: amenyeh@yahoo.com


Where only geological reconnaissance is used, it is likely that the information gathered may not be adequate to allow a proper understanding of the local hydrogeology. Geophysical investigations which supplement the initial geological assessment of the terrain afford wider understanding of the local hydrogeology. A number of these geophysical methods are applicable in delineating subsurface water resources. Generally, subsurface parameters relevant to groundwater exploration could be revealed by the application of various geophysical methods without recourse to expensive test drilling (Foster, 1984). Some of these subsurface features of interest include depth of contacts between layers of different aquifer properties, lateral changes in aquifer properties, thickness of aquifer and the presence of subsurface fractures among others. The paper explains how geo-electrical investigation was conducted to explore the groundwater potential in the Gushiegu-Karaga District of the Northern Region of Ghana. The study area lies in a sedimentary environment – the middle Voltain sedimentary basin. Sedimentary basement environments are characterized by basement aquifers which are very important source of groundwater supply. Basement aquifers are often developed within the weathered overburden and the fractured bedrock (Wright, 1990). The aquifer system consists of the regolith, the variably weathered bedrock and the fresh bedrock. The regolith is made up of the collapsed zone, sometimes called the overburden, and the saprolite, which is derived from the in situ weathering of the bedrock but disaggregated (Wright, 1990). The weathered bedrock also called the saprock, is made up of weathered and jointed rocks containing fractures with high transmissivity but limited storage. It grades into the fresh bedrock as the number of fractures diminish. The geo-electrical resistivity method is a widely used geophysical exploration technique for groundwater exploration in this part, and indeed other parts of the country. It affords insight to be rapidly obtained in the nature of the water bearing layers. The use of the technique in hydrogeological investigations is in relation to aquifer delineation, lithologic boundaries and geological structures to provide subsurface information (Bose et al., 1973). The geo-electrical resistivity method involves the injection of current into the ground and the measurement of the response of the earth to the current. The current enters the ground through a pair of current electrodes, and the response which consists of the record of the potential difference by another pair of potential electrodes, measures the impedance of the subsurface material. The material property measured is the resistivity. In the theory of the geo-electrical survey method, current flow in the subsurface is assumed to be predominantly electrolytic. Consequently, the presence of water within the pores, fractures and other such voids, and the connectivity of these voids, controls much of the resistivity changes in underground materials. Lithologic changes in subsurface materials also affect the resistivity. The determination of the response of materials at depths to current is accomplished by increasing the separation of the current electrodes, basically, in a survey. By increasing the current electrodes separation, resistivity variation with depth, called the vertical electrical sounding (VES) would be obtained in a survey. This theory of the geo-electrical resistivity methods are treated copiously and rigorously in standard texts such as in Telford (1976), Kearey and Brooks (1991), and Burger (1992). The interpretation of the VES needs to be related explicitly to the aquifer and its properties. In evaluating the aquifer, the geophysical target is a sufficiently thick and extensive zone of saturated weathered material within the subsurface structure (Hazel et at 1988). The geophysical signature of this target zone is an intermediate subsurface layer of low to moderately high resistivity, which is broadly associated with fresh groundwater. Extremely low formation resistivities in this environment may however, be due to the presence of clays and or brackish water (Terrahydro, 1997), (Danida, 1995).

## 2 METHODOLGY

### 2.1 Location, Geology and Hydrogeology

The study area is located in the North Eastern part of the Northern Region. The area lies approximately between the longitudes $0^o$ 45' W and the Greenwich, and the latitudes $9^o$ 45' N and $10^o$ 15', Fig. 1. It falls within the Middle Voltain Basin. The geology of the main Volta is dominated by the Voltaian system, which together with the basement complex dominate the hydrogeological systems. The Voltain system is partly underlain by aquifers of the crystalline basement and aquifers of the consolidated sedimentary rocks. The crystalline basement formation is composed of gneiss, phyllite, schist, granite-gneiss and quartzite and the major lithological units of the sedimentary formation are alternating grey, green and brown shales, siltstones, sandstones, conglomerates and limestone (Kessie, 1985). Details of the geology and hydrogeology are copiously contained in reports such as by (Junner and service 1936; Junner and Hist, 1964). In this formation, groundwater potential is low. This is due to the fact that rock decomposition and primary porosities are low. However, where secondary porosity imposed by fracturing and weathering of rocks occurs, the hydrogeological properties of these rocks are very much enhanced. Therefore, the hydrogeological parameters are based on secondary permeabilities in the form of fractures, joints, fissures, and other weak zones (Kessie, 1985).

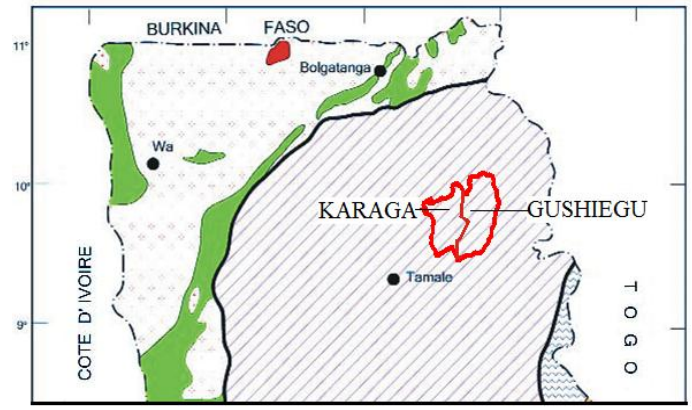
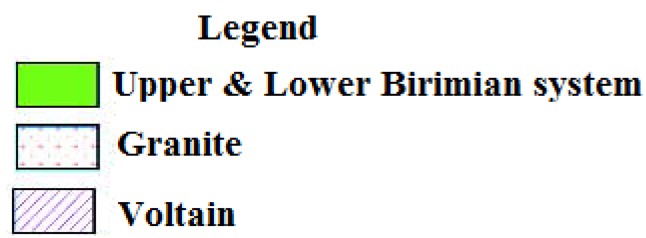



**Fig. 1. Geological map of Northern Ghana, showing the Gushiegu and Karaga Districts in the sedimentary formation of the Middle Voltain System (Adapted, Geological Survey of Ghana)**




### 2.2 Geo-Electrical Investigations and Data Acquisition

#### 2.2.1 Terrain evaluation

The terrain evaluation involved hydrogeological observations, a study of lithology, structure and topography to identify areas for geophysical survey. Information was also gathered on potential sources of pollution in and around the villages. Features considered were type and location of on-site sanitation, burial grounds, cattle pens etc.

#### 2.2.2 Procedure for geo-electrical profiling

Simple resistivity traversing methods have been used with some success to identify and trace localised anomalous zones, almost invariably those showing lower resistivities (Carruthers and Smith, 1983). The objective of the resistivity profiling is to map out any lateral variations in subsurface resistivity that might exist in the survey area along the traverses. After delineating targets areas, horizontal resistivity profiling was conducted along traverses in the demarcated zones. Traverses were cut through bushes and also through the settlements. Traverse lengths were between 200 m to 350 m, determined by the boundaries of the survey. For these reasons, traverses were not strictly linear or necessarily parallel and distances between them were also not regular. The symmetric Schlumberger array (Fig. 2) was used for the resistivity profiling in all the communities. The apparent resistivity $\rho_a$, referenced to the midpoint of the array, is given as

$$\rho_a = \pi \frac{L^2}{2l} \frac{\Delta V}{I} . \qquad (1)$$

Where the lengths *L* and *l* are defined as in Fig. 2 and the ratio

$\frac{\Delta V}{I}$ represents the impedance.

In this work, the ABEM Terrameter SAS 300C was used to acquire the apparent resistivity data along the traverses. Two different values of $L$ corresponding to half the current electrodes separation $\left(\frac{C_1C_2}{2}\right)$ and two respective half potential electrodes separation, $l=\left(\frac{P_1P_2}{2}\right)$ were selected. These data are shown in Table 1. The two different electrodes separations were chosen to reflect lateral apparent resistivity variations along two depths. The expected effective midrange depth for the Schlumberger array is $Z_E = 0.38L$ (Edwards, 1977).

**Table 1. Schlumberger electrodes separations and their respective multiplication factors**

| Half-Current Electrodes Separations $L$ (m) | Half-Potential Electrodes Separations $l$ (m) | Multiplication Factor |
|---|---|---|
| 40.0 | 5.0 | 502.0 |
| 19.0 | 0.5 | 1133.0 |

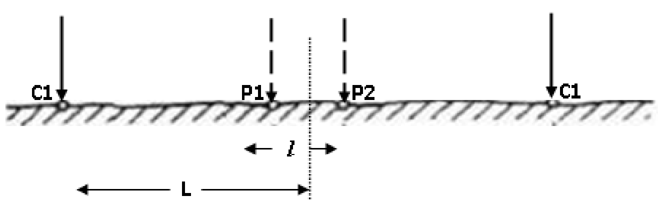



**Fig 2. The symmetrical Schlumberger array**

### 2.2.3 Vertical electrical sounding (VES)

After the preliminary analysis of the resistivity profiling, significant anomalous zones were identified. These were regions with a wide weathered base. Vertical electrical soundings were then conducted at selected points within these anomalous zones. Vertical Electrical Soundings (VES) are conducted to basically delineate the different sub-surface geo-electric layers (resistivity and thickness of sub-surface geological materials). Following from this delineation, the aquifer units and their characteristics could be established. In this study the dipole-dipole electrode configuration (Fig. 3) was used. The dipole of dipole was 2 m and the '*n*' spacing varied from 4 m in the shortest array length to 100 m in the longest array length. The apparent resistivity measured with this configuration is given as

$$\rho_a = \pi na(n+1)(n+2)\frac{\Delta V}{I}. \quad (2)$$

This was undertaken to provide depth information below selected groundwater potential zones.

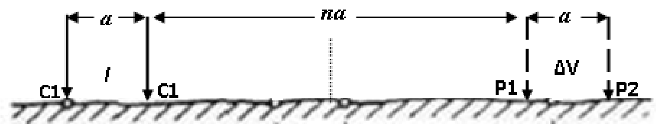



**Fig 3. The Dipole-Dipole array**

## 3 RESULTS

The results which evolved from the VES data are presented as VES curves. The curves consist of log-log plots of apparent resistivity as function of the '*n*' spacing of the dipole-dipole array. Quantitative interpretations of vertical electrical sounding data were facilitated by the use of IX1D software, proprietary software owned by Interpex (Interprex, 2007). Initially, model parameters estimated from the data are used for the iterative operations. Estimating these initial model parameters is inspired by the study of the shapes of the VES curves, for the shapes of the VES curves are related to the subsurface geological situation; that is, the shapes are influenced by the number of layers, their thicknesses and resistivities. With these initial model parameters the field data are compared with the data from a layer model obtained by curve matching. If the agreement between the two sets of data is unsatisfactory, then the parameters of the layer model are adjusted. The index of agreement is the RMS (Root Mean Square) fitting error. It is used as an indication of the fit between the synthetic data generated from the model and the actual data themselves (Interprex, 2007). This procedure is repeated until a sufficient agreement between the model data and the field data was obtained. In this work agreement is deemed sufficient if after 5 iterations the RMS is at most 10 %. The application generated geo-electric layering for the subsurface. The information from these geolectric layers were related to the geologic situation in the subsurface. This consequently enhanced the identification of subsurface geologic parameters which included possible aquifer depth, thickness, and resistivity. The overburden resistivity and thickness are also identified. In all, a total of 19 VES locations were occupied within the four communities in the study area. In the community of Nyengbalo, 4 VES stations were occupied, in Zei, 4, Zantele 6 and in Kanshegu 5. The VES processed data were subjected to detailed interpretation aimed at unraveling the subsurface groundwater potential, aquifer characteristics and the protective capacity of overburden units in the study area. The VES curves and their one–dimensional resistivity inversions have been shown in Figs. 4 to 21. Summaries of the geoelectric layering at the VES locations at the various communities are also detailed in Tables 3 – 6.

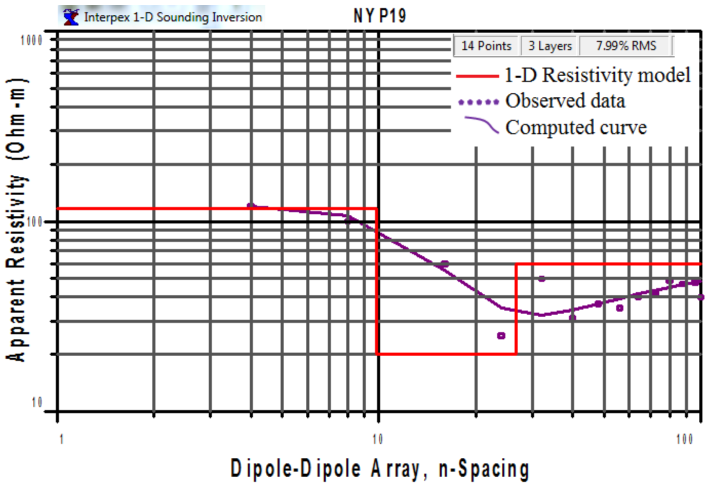



**Fig. 4 Iterated field curve and the apparent resistivity model of VES conducted at 90 m from the beginning of profile 1, Nyengbalo Community (NY P1 9)**

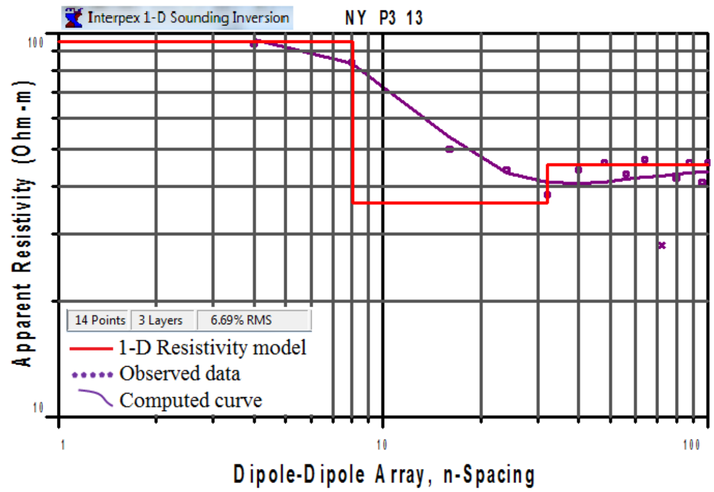



**Fig. 7 Iterated field curve and the apparent resistivity model of VES conducted at 130 m from the beginning of profile 3, Nyengbalo Community(NY P3 13).**

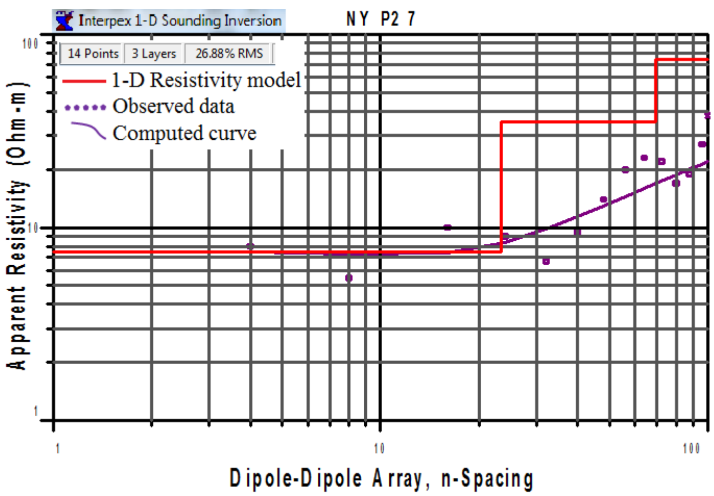



**Fig. 5 Iterated field curve and the apparent resistivity model of VES conducted at 70 m from the beginning of profile 2, Nyengbalo Community (NY P2 7)**

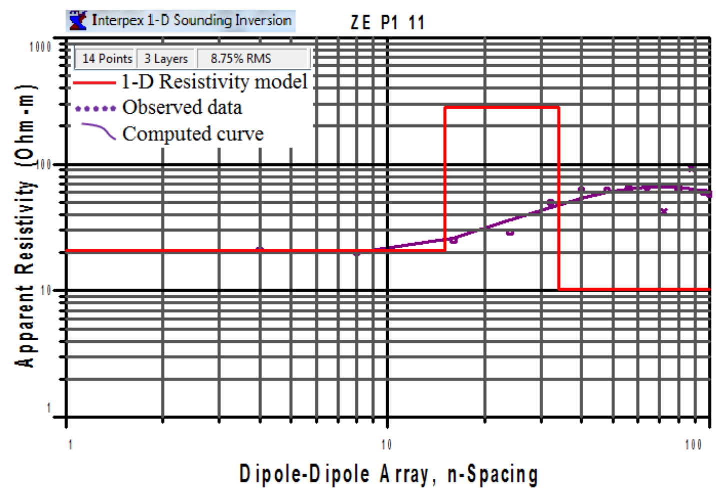



**Fig. 8 Iterated field curve and the apparent resistivity model of VES conducted at 110 m from the beginning of profile 1, Zei Community (ZE P1 11).**

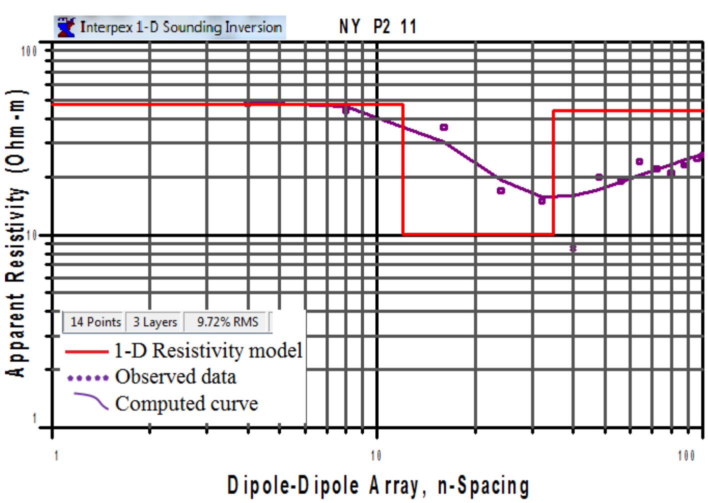



**Fig. 6 Iterated field curve and the apparent resistivity model of VES conducted at 110 m from the beginning of profile 2, Nyengbalo Community (NY P2 11).**

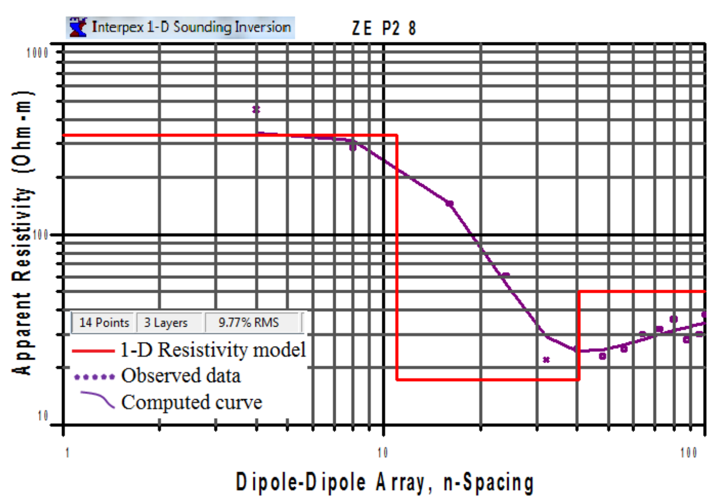



**Fig. 9 Iterated field curve and the apparent resistivity model of VES conducted at 80 m from the beginning of profile 2, Zei Community(ZE P2 8).**

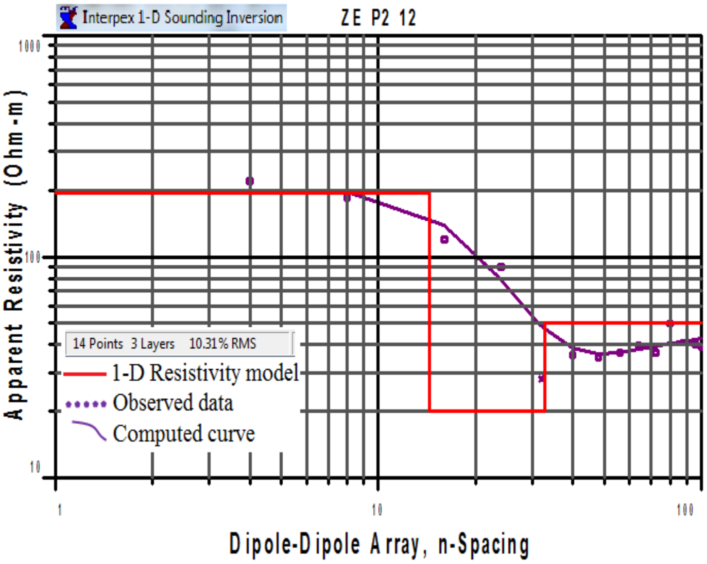



**Fig. 10 Iterated field curve and the apparent resistivity model of VES conducted at 120 m from the beginning of profile 2, Zei Community(ZE P2 12).**

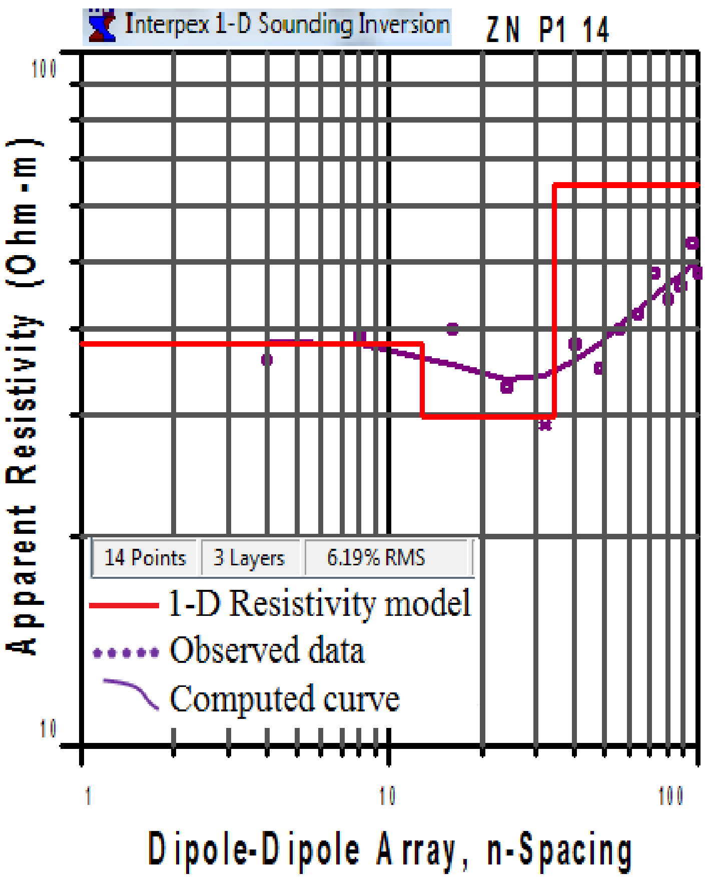



**Fig. 11 Iterated field curve and the apparent resistivity model of VES conducted at 140 m from the beginning of profile 1, Zantele Community(ZN P1 14).**

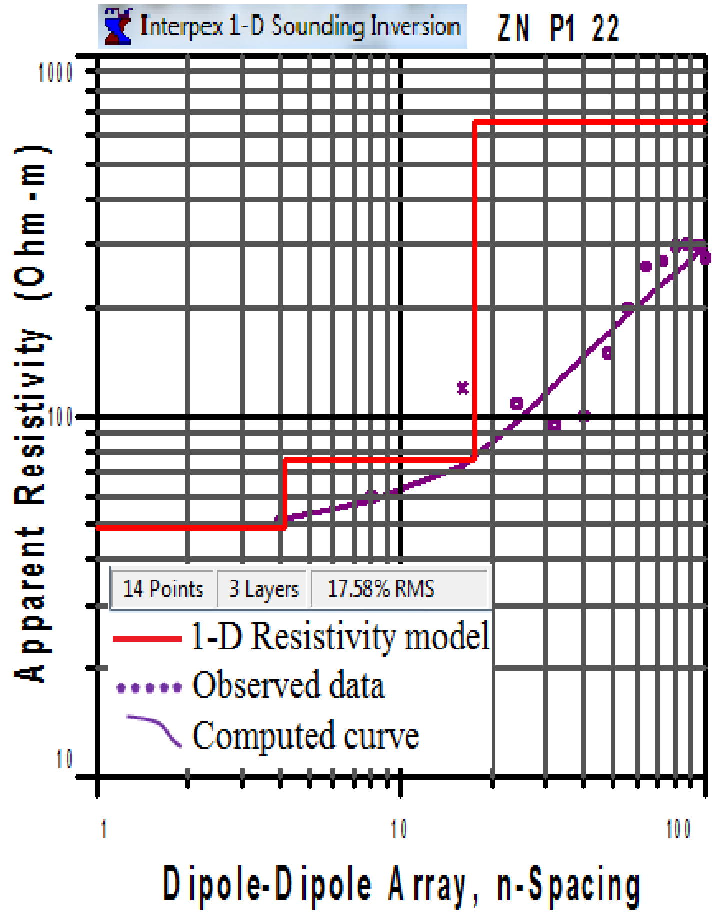



**Fig. 12 Iterated field curve and the apparent resistivity model of VES conducted at 220 m from the beginning of profile 1, Zantele Community(ZN P1 22). [3 layer modeling]**

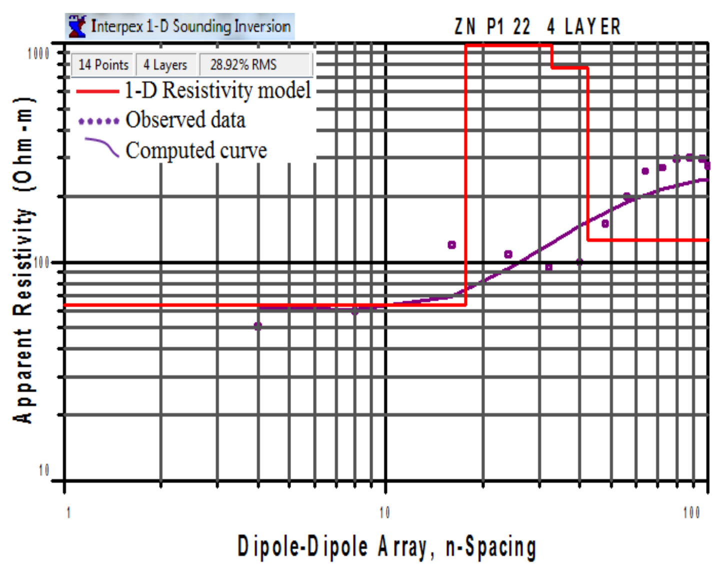



**Fig. 13 Iterated field curve and the apparent resistivity model of VES conducted at 220 m from the beginning of profile 1, Zantele Community (ZN P1 22). [4 layer modeling]**

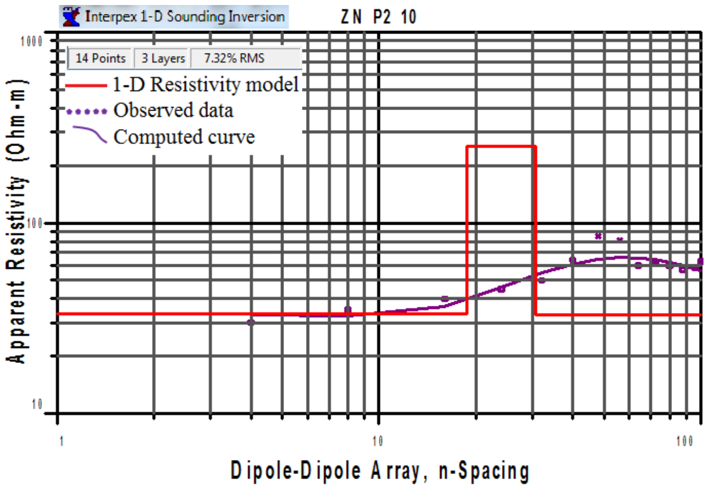



**Fig. 14 Iterated field curve and the apparent resistivity model of VES conducted at 100 m from the beginning of profile 2, Zantele Community(ZN P2 10).**

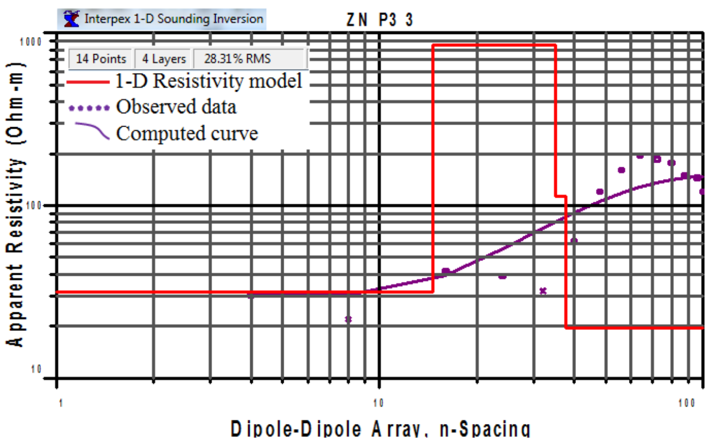



**Fig. 15 Iterated field curve and the apparent resistivity model of VES conducted at 30 m from the beginning of profile 3, Zantele Community (ZN P3 3) [4 Layer modeling].**

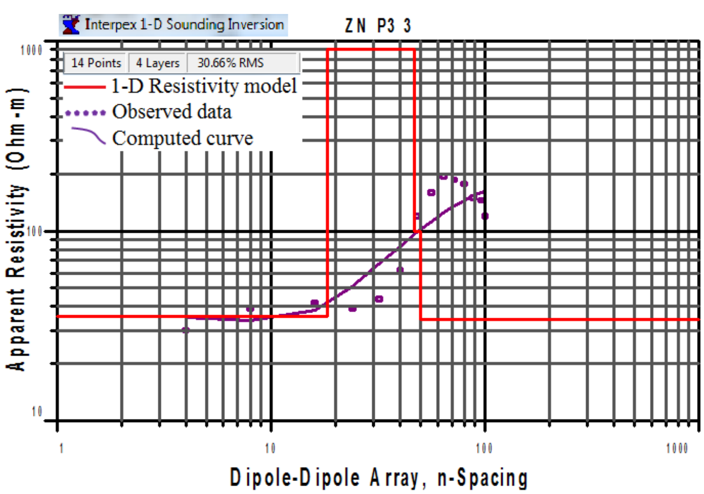



**Fig. 16 Iterated field curve and the apparent resistivity model of VES conducted at 30 m from the beginning of profile 3, Zantele Community (ZN P3 3). [3 Layer modeling].**

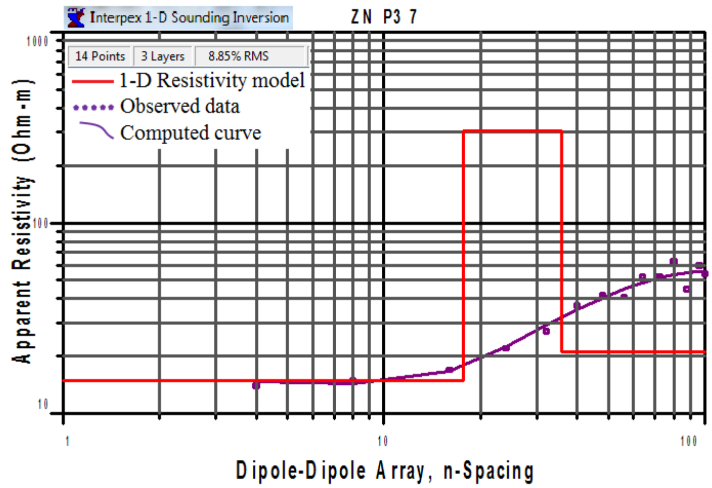



**Fig. 17 Iterated field curve and the apparent resistivity model of VES conducted at 70 m from the beginning of profile 3, Zantele Community (ZN P3 7).**

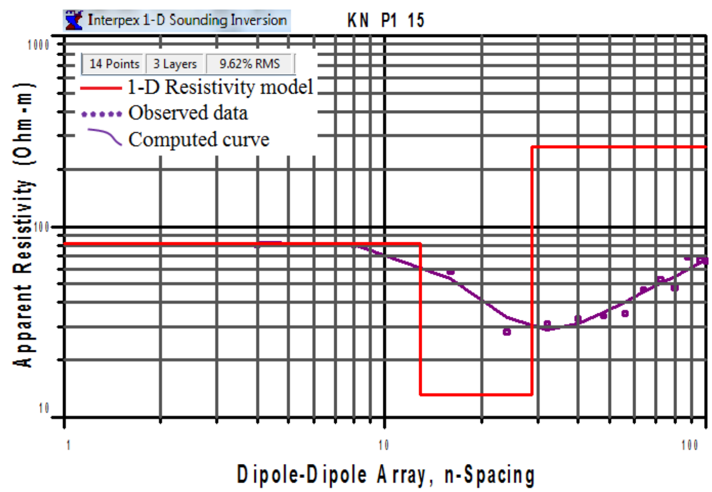



**Fig. 18 Iterated field curve and the apparent resistivity model of VES conducted at 150 m from the beginning of profile 1, Kanshegu Community (KN P1 15).**

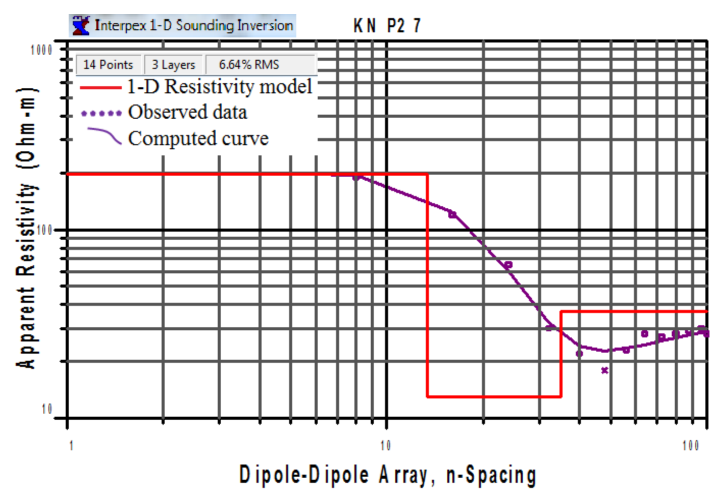



**Fig. 19 Iterated field curve and the apparent resistivity model of VES conducted at 70 m from the beginning of profile 2, Kanshegu Community (KN P2 7).**

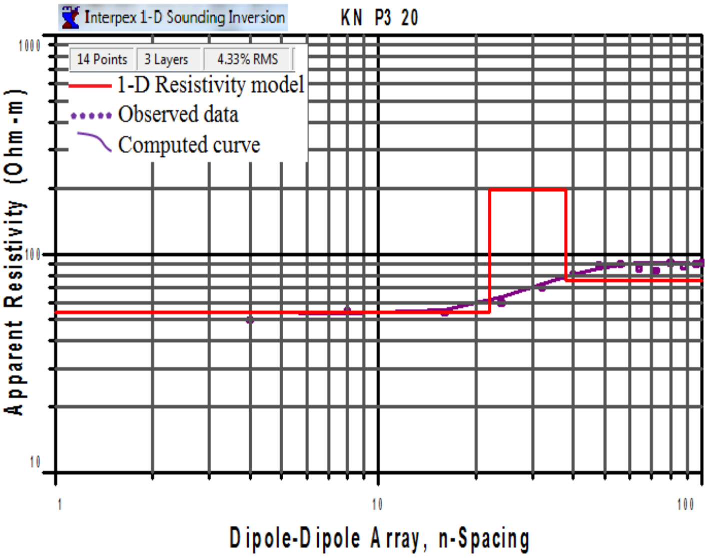



**Fig. 20 Iterated field curve and the apparent resistivity model of VES conducted at 200 m from the beginning of profile 3, Kanshegu Community(KN P3 20).**

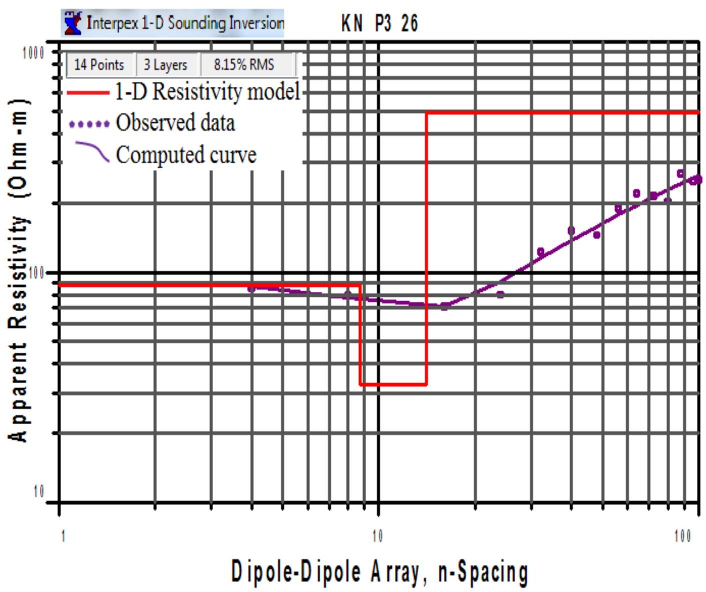



**Fig. 21 Iterated field curve and the apparent resistivity model of VES conducted at 260 m from the beginning of profile 3, Kanshegu Community (KN P3 26).**

**Table 3. Modeled Layer parameters for the VES conducted in the Nyengbalo community.**

| VES ID | # | Rho | Thick | Depth |
|---|---|---|---|---|
| NY P1 9 | 1 | 117.55 | 9.8604 | 9.8604 |
| | 2 | 20.082 | 16.787 | 26.647 |
| | 3 | 59.832 | | |
| NY P2 7 | 1 | 7.4798 | 23.445 | 23.445 |
| | 2 | 35.242 | 46.057 | 69.502 |
| | 3 | 73.824 | | |
| NY P2 11 | 1 | 47.645 | 11.960 | 11.960 |
| | 2 | 10.015 | 22.719 | 34.679 |
| | 3 | 44.069 | | |
| NY P3 13 | 1 | 95.338 | 8.0869 | 8.0869 |
| | 2 | 36.091 | 24.028 | 32.115 |
| | 3 | 45.478 | | |

**Table 4 . Modeled Layer parameters for the VES conducted in the Zei community.**

| VES ID | # | Rho | Thick | Depth |
|---|---|---|---|---|
| ZE P1 11 | 1 | 20.877 | 15.000 | 15.000 |
| | 2 | 279.70 | 18.960 | 33.960 |
| | 3 | 10.275 | | |
| ZE P2 8 | 1 | 332.10 | 10.965 | 10.965 |
| | 2 | 17.337 | 29.682 | 40.646 |
| | 3 | 50.204 | | |
| ZE P2 12 | 1 | 194.16 | 14.361 | 14.361 |
| | 2 | 20.058 | 18.392 | 32.753 |
| | 3 | 50.288 | | |

**Table 5. Modeled Layer parameters for the VES conducted in the Zantele community.**

| | Layer parameters | | | |
|---|---|---|---|---|
| | # | Rho | Thick | Depth |
| ZN P1 14 | 1 | 38.073 | 12.744 | 12.744 |
| | 2 | 29.876 | 21.546 | 34.290 |
| | 3 | 64.358 | | |
| ZN P1 22 | # | Rho | Thick | Depth |
| | 1 | 49.096 | 4.1601 | 4.1601 |
| | 2 | 76.111 | 13.322 | 17.482 |
| | 3 | 655.24 | | |
| ZN P1 22 | # | Rho | Thick | Depth |
| | 1 | 63.230 | 17.663 | 17.663 |
| | 2 | 975.48 | 15.054 | 32.717 |
| | 3 | 766.64 | 9.6185 | 42.336 |
| | 4 | 125.93 | | |
| ZN P2 10 | # | Rho | Thick | Depth |
| | 1 | 33.458 | 18.712 | 18.712 |
| | 2 | 252.37 | 11.847 | 30.558 |
| | 3 | 32.981 | | |
| ZN P3 3 | # | Rho | Thick | Depth |
| | 1 | 35.489 | 18.299 | 18.299 |
| | 2 | 900.00 | 28.361 | 46.660 |
| | 3 | 99.666 | 3.5035 | 50.163 |
| | 4 | 34.240 | | |
| ZN P3 3 | # | Rho | Thick | Depth |
| | 1 | 35.506 | 18.149 | 18.149 |
| | 2 | 950.00 | 30.487 | 48.637 |
| | 3 | 20.594 | | |
| ZN P3 7 | # | Rho | Thick | Depth |
| | 1 | 14.969 | 17.664 | 17.664 |
| | 2 | 302.25 | 18.078 | 35.742 |
| | 3 | 21.160 | | |

**Table 6. Modeled Layer parameters for the VES conducted in the Kanshegu community.**

| VES ID | Layer parameters | | | |
|---|---|---|---|---|
| | # | Rho | Thick | Depth |
| KN P1 15 | 1 | 81.290 | 12.850 | 12.850 |
| | 2 | 13.228 | 15.819 | 28.668 |
| | 3 | 261.82 | | |
| KN P2 7 | # | Rho | Thick | Depth |
| | 1 | 195.76 | 13.381 | 13.381 |
| | 2 | 12.999 | 21.550 | 34.931 |
| | 3 | 36.891 | | |
| KN P3 20 | # | Rho | Thick | Depth |
| | 1 | 54.167 | 22.009 | 22.009 |
| | 2 | 196.74 | 15.917 | 37.926 |
| | 3 | 75.648 | | |
| KN P3 26 | # | Rho | Thick | Depth |
| | 1 | 87.759 | 8.7418 | 8.7418 |
| | 2 | 32.410 | 5.2898 | 14.032 |
| | 3 | 492.80 | | |

## 4 Discussion

From the results of the VES in the Nyengbalo community, Figs. 4 – 7, and table 3, the resistivities of the third layers, in each of the VES is too low enough to suggest the presence of the substratum. The VES identified as NY P3 13 (Fig. 7) has the thickest middle layer and is therefore recommended for drilling. In the VES NY P2 7, the thicknesses of the layers resulting from the modeling appear to be overestimated. It can also be observed in this community that the tops layers more resistive than the underlying layers. The subsurface earth model generated for this community, Zei, in Figs. 8 –10 and Table 4 depict a three layer structure with the top surface layers being more resistive than those found at depths. The intermediate layer for the VES point ZE P2 8 has a thickness of about 30 m and will therefore have potential aquiferous properties. In Zantele, the VES on profiles 1 and 3, i.e ZN P1 14 and ZN P3 7 (Fig. 11 and Fig. 17) respectfully put the depth to the bottom of the middle layer as approximately 34.5 m (Table 5). ZN P3 7 however has very high resistive middle layer. Groundwater potential will therefore be higher at ZN P1 14 which has a low resistive middle layer. The errors associated with the inversion of the VES curves at locations ZN P1 22 (Figs. 12 and 13) and ZN P3 P3 (Figs 15 and 16) were too high. For this reason two different earth models were produced for each of the curves, but the RMS error did not improve. Finally, in Kanshegu, four VES were interpreted. Figs. 18 – 21 and Table 6. In this community the four interpreted VES all show good groundwater potential. Among the four interpreted VES, the one represented by KN P2 7 exhibits resistivity and thickness of middle layer that makes it the most conducive for groundwater abstraction. It has a middle layer resistivity of 13.0 ohm.m and a middle layer thickness of 21.5 m at the depth of 35 m. In general, the geoelectric sequence indicated relatively high resistivity for the top surface layer in most of the surveyed sites. The geophysical targets – possible location of underground aquifers – which were sufficiently thick and extensive weathered rock units were characterized on the sounding curves as depressions or troughs. Such signatures were located mostly beyond 20 m from the ground surface. This depth information is instructive because potable water abstracted from boreholes in these areas may not be found shallower than 20 m.

## 5 CONCLUSION

Groundwater developed by the siting of productive boreholes could be successfully accomplished by using the electrical resistivity method complemented with the results of geological and hydrological site investigations. The results of Schlumberger resistivity traversing and vertical electrical sounding (VES) conducted in these four small communities in the Gushiegu and Karaga Districts have allowed the identification of subsurface layers and weathered zones that are targets for borehole construction. The VES gave the variation of apparent resistivity with depth and they provided the geophysical signatures of the subsurface groundwater potential zones. The geoelectric sequence revealed a predominantly three subsurface structure which is largely congruous to the weathering profile above the fresh bedrock; - the thick top soil, the weathered and the variably weathered and fractured bedrock respectively. The geophysical signature was an intermediate layer of lower resistivity lying between a more resistivity cover and the bedrock. Another important conclusion that can be drawn is that the interpreted VES sections lead to the knowledge of the depths most likely to locate sustainable sources of groundwater.

## 5 REFERENCES


[1] Bose K.N., Chatterjee D, Sen A.K (1973). Electrical resistivity surveys for groundwater in the Aurangabad Sub-division, Gaya District, Bihar, Indian pp. 171-181

[2] Burger, H. R., 1992. Exploration Geophysics of the Shallow Subsurface: Prentice Hall, Inc.

[3] Carruthers, R.M. Smith, I.J., (1983) The use of ground electrical survey methods for siting boreholes in shallow crystalline basement terrains

[4] Danida (1995) Volta RWSS. Hydrogeological and Geophysical report. Foster, S.S.D. (1984). African groundwater development- the challenges for hydrogeological science, *in*: Challenges in African Hydrology and water Resources, *Proceedings of the Harare symposium*, July 1984, IAHS publication.

[5] Ghana Geological Survey, 2009. Geological Map of Ghana. Geological Survey Department, Ghana and BRG, Hanover.

[6] Hazel, J., Jones, C., and Thomas, D., 1988, “Application of EM transverse and D.C. resistivity for location of aquifers in Northern Nigeria,” Journal of Royal Geological Society, No.1: 159 – 175

[7] IX1D v3, 2007. Instruction Manual, Version 1.1. Interpex Limited Golden

[8] Junner N.R., Service H (1936). Geological notes on Volta River District and Togoland under British mandate. Annual Report on the Geological Survey by the Director, 1935–1936

[9] Junner N.R., Hirst, T (1946). The geology and hydrogeology of the Volta Basin. Gold Coast Geological Survey, Memoir

[10] Kearey, P., Brooks, M., 1991. An introduction to geophysical exploration. Blackwell Scientific Publications.

[11] Kessie G.O (1985) Minerals and rocks resources of Ghana.

[12] Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976. Applied geophysics: Cambridge University Press.

[13] Terrahydro Associates Ltd. (1997) NORRIP Rural Water Supply project; Hydrogeological and geophysical reports.

[14] Wright, E.P (1990) Groundwater occurrence and groundwater flow systems in basement aquifers. Groundwater Exploration and development in crystalline basement aquifers. The Commonwealth Science Council.


## 5 APPENDIX

**THE SCHLUMBERGER RESISTIVITY PROFILES IN ALL THE COMMUNITIES.**

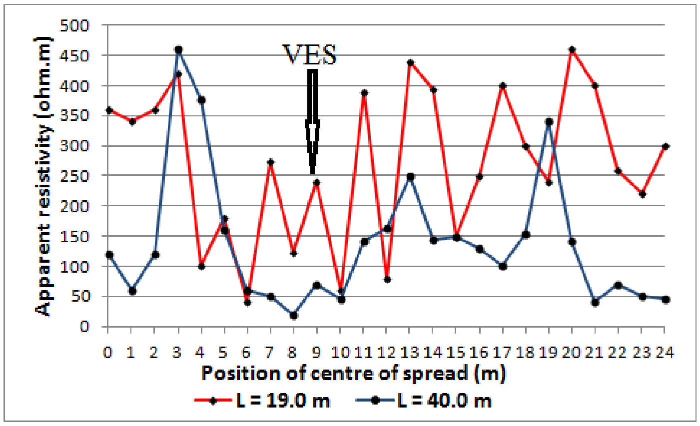



**Fig. A1 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Nyengbalo Community.**

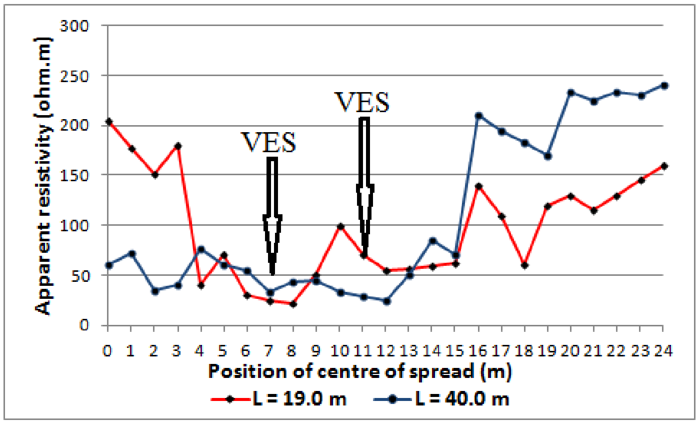



**Fig. A2 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Nyengbalo Community.**

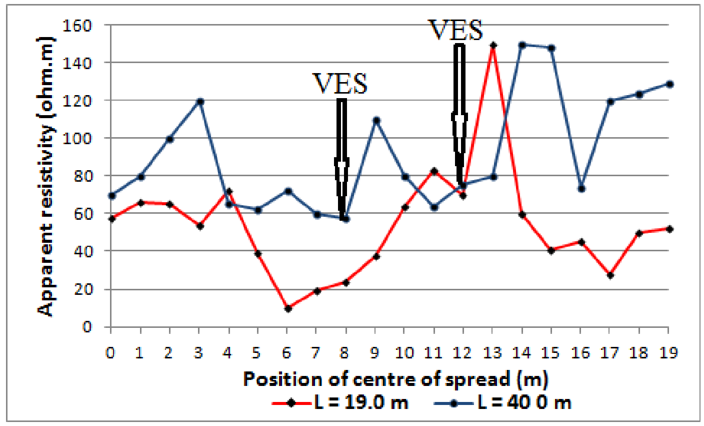



**Fig. A5 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Zei Community.**

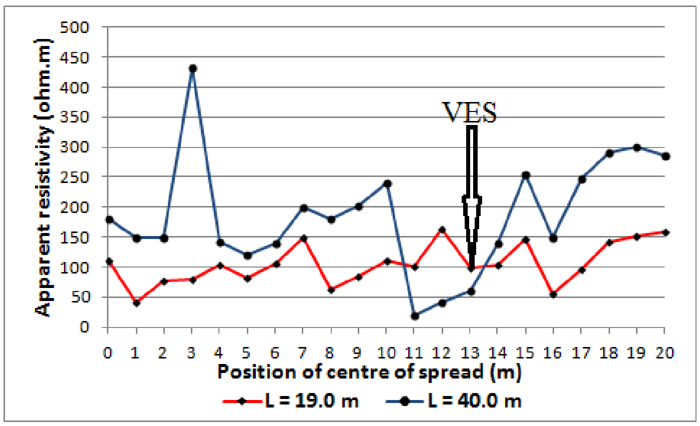



**Fig. A3 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Nyengbalo Community.**

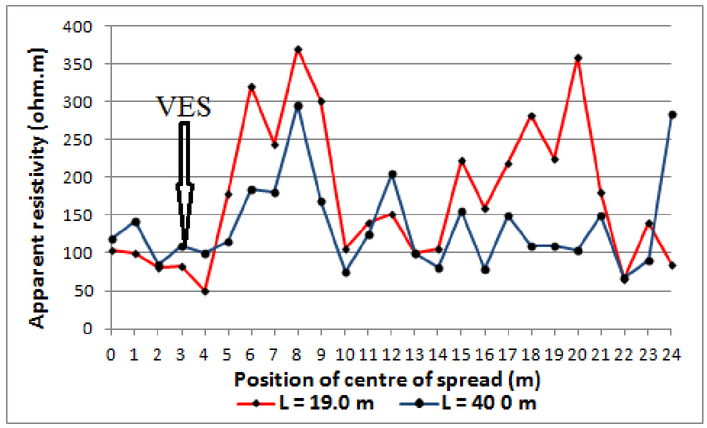



**Fig. A6 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Zei Community.**

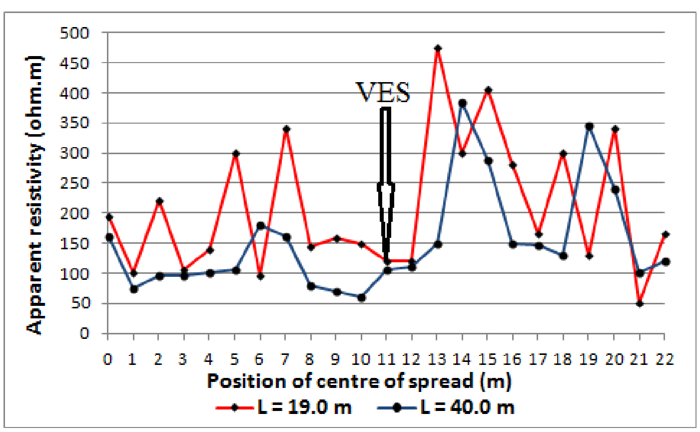



**Fig. A4 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Zei Community.**

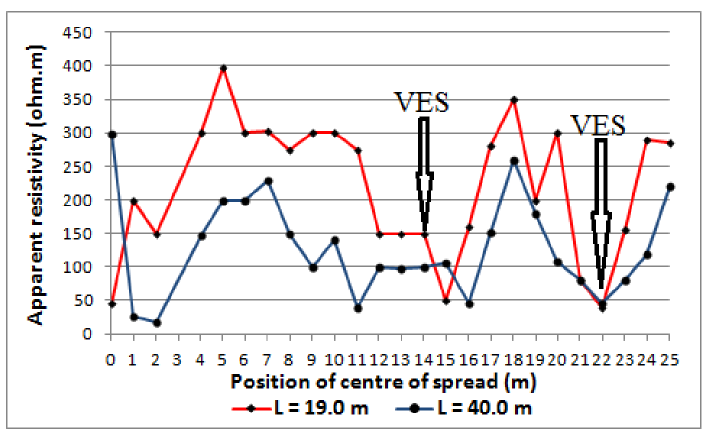



**Fig. A7 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Zantele Community.**

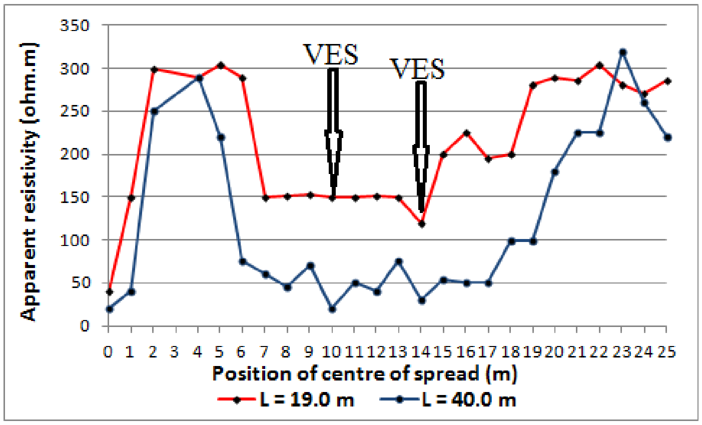



**Fig. A8 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Zantele Community.**

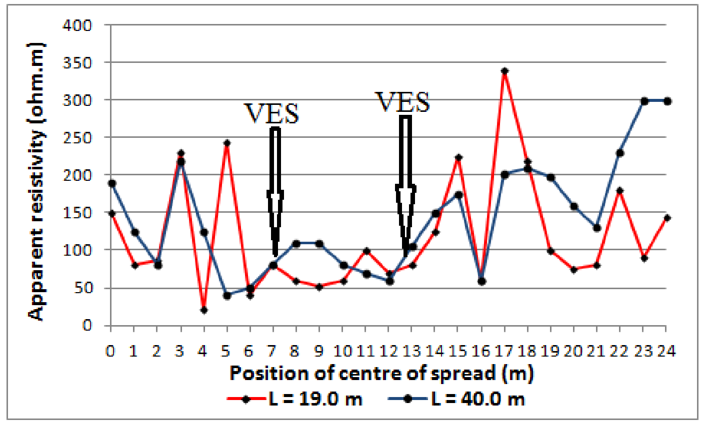



**Fig. A11 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Kanshegu Community.**

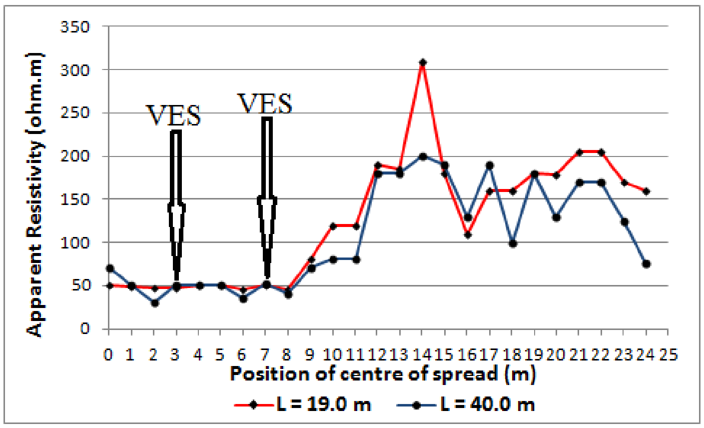



**Fig. A9 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Zantele Community.**

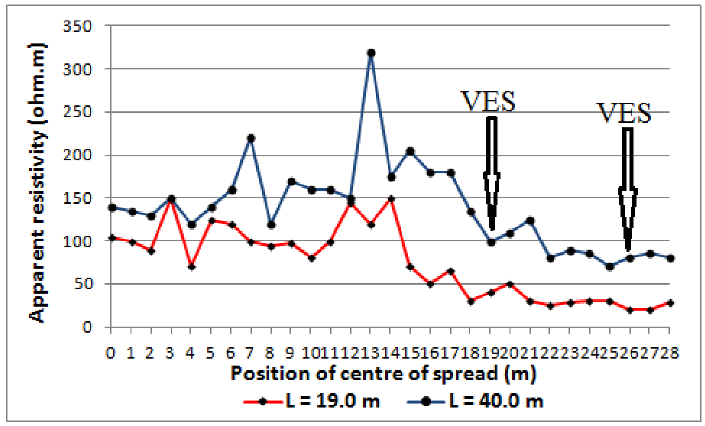



**Fig. A12 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Kanshegu Community.**

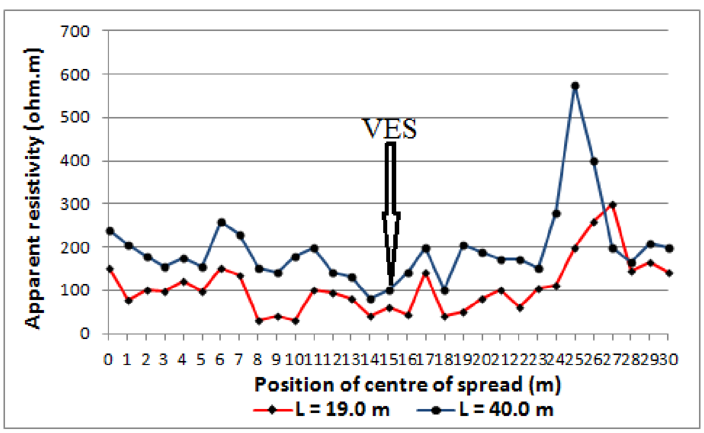



**Fig. A10 Schlumberger resistivity profiles, showing apparent resistivity as a function of position of centre of spread for two values of electrode separation, Kanshegu Community.**