

## PROSPECTING FOR GROUNDWATER USING THE ELECTROMAGNETIC METHOD IN THE VOLTAIAN SEDIMENTARY BASIN IN THE NORTHERN REGION OF GHANA – A CASE STUDY OF THE GUSHIEGU-KARAGA DISTRICT

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### ABSTRACT

*The Gushiegu-Karaga District is one of the most deprived areas in the Northern Region of Ghana in terms of water supply. Only about 15% of the population have access to potable water, and has a chronic water supply problem. In an attempt to improve the water supply situation the Ghana Rural Water Project (GRWP) of the World Vision initiated Conrad-Hilton Funded Borehole Water Project in Gushiegu-Karaga district, with the objective of drilling 100 wet boreholes. In this study a ground geophysical technique, the Electromagnetic (EM) method using the GEONICS EM 34-3 equipment has been used to delineate and locate water-bearing zones. The EM profiles of interest were analysed and interpreted qualitatively to locate suitable and potential sites to drill boreholes for groundwater abstraction. Drilling results and findings from drill logs show that the mean depths of productive and unproductive boreholes were 41.0 and 64.0 m respectively. The groundwater producing zones were found to be between 30.0 m and 60.0 m depths. A minimum yield of 10 litres per minute has been used as the basis for a borehole to be successful. However, 60% success rate was achieved out of 100 boreholes drilled. When compared with the success rate of drilling productive boreholes, the 60% success achieved was higher. It is recommended that the EM method, which is fast, efficient, less laborious and cost effective, be used to locate suitable borehole sites in programmes aimed at accelerated rural water supply to the rural communities in the district.*

**Keywords:** *Electromagnetic method, groundwater, weathered zone, fractured zone, profile.*

### INTRODUCTION

Seasonal shortages of water, especially potable water is a chronic problem in the Northern Region of Ghana, as a result, there is growing inter-

est in exploration and exploitation of groundwater resources to meet the demands of the region. Traditional methods of exploration for groundwater resources had not been effective due to the widespread distribution of impermeable rocks associated with the Voltaian System. This requires therefore, the use of appropriate and cost

effective methods to locate potential sources of groundwater, and improve accessibility to groundwater supplies in the region by 85% by the year 2008 (Kwei, 1997).

Groundwater occurs within geological formations such as weathered zone above the crystalline bedrock or in fractures within the bedrock itself (Beeson and Jones, 1988). In weathered sedimentary rocks, such as the Voltaian System, groundwater occurs in the pores between grains as well as in fractures within the rocks (Fetter, 1994). These underground conduits serve as targets of the EM method when locating groundwater.

Groundwater exploration often takes a hierarchical approach in which regional assessments are followed by more detailed ground investigations (Lloyd, 1995). Researchers have emphasized the importance and application of electromagnetic traversing (EMT) method in groundwater exploration. It is simple, quick and effective (Aked, 1995; Fitterman and Stewart, 1986; McNeil, 1995). The method is suitable for groundwater exploration because water collected or accumulated in pores or fractures of rocks contains dissolved salts, which act as electrolytes for good electrical conduction (Telford *et al.*, 1994; McNeil, 1995).

In this study the EM method of geophysical prospecting has been used to identify suitable groundwater potential sites for borehole locations in the Gushiegu-Karaga District. Groundwater supplied from a borehole is hygienic and free from surface pollution provided the general borehole design principles are followed and proper sanitation is ensured around the borehole. The use of potable groundwater resources could go a long way to solve the chronic water supply problem and increase the access to potable water beyond the estimated 15% coverage. This will help decrease guinea worm infections and bilharzia cases so prevalent in the district, and ultimately improve tremendously the socio economic life of the people.

### **The Gushiegu-Karaga District**

Gushiegu-Karaga District is the third largest of the thirteen districts in the Northern Region, with a population of about 127,501 (Population Census, 2000) and a total district land area of 5,657.89 square kilometres.

### **Location and Accessibility**

The district is located in the north-eastern part of the Northern Region of Ghana between latitude 9°30' N and 10°18' N of the equator; and between longitude 0°09' E and 0°48' W of the Greenwich Meridian. It shares boundaries with five other districts (Figure 1): East Mamprusi to the North, Yendi to the South, Saboba-Chereponi to the East, Savelugu-Nanton to the West and West Mamprusi to the Northwest. The district is accessible through three major feeder roads, in the South from Yendi, in the North from Nalerigu or Bawku, and in the East from Tamale through Nanton.

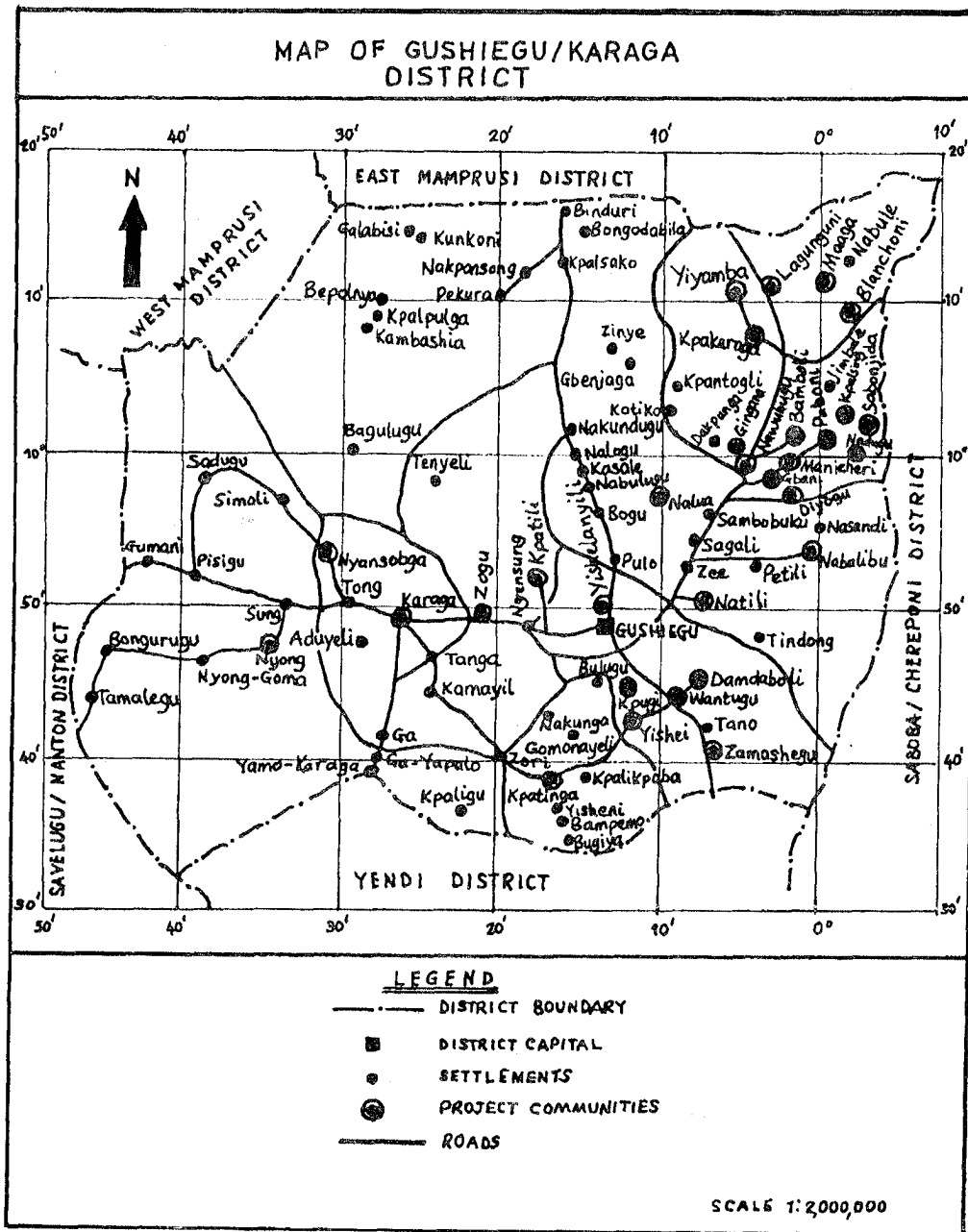
### **Topography**

The Voltaian Basin is made up of gently dipping or flat-bedded sandstones, shales, and mudstones, which are easily eroded (Dickson and Bennet, 1988). The result is an almost flat and extensive plain. The district under study is associated with low relief (almost plain) with few scattered hills, valleys and rock outcrops. Generally, elevations in the district range from 120 m to 180 m above mean sea level. Most of the rock outcrops can be found near Karaga, especially west of Karaga towards Tong.

### **Climate and Rainfall**

Climate and rainfall of Gushiegu-Karaga District are strongly influenced by the North-East Trade Winds (Harmattan) and the South-West Monsoon Winds. Like other parts of the Northern Region, the district is covered by the Tropical Continental (Interior Savannah) Climate. According to Harrison-Church (1980), all stations north of the latitude of Tamale have single rainfall maximum and a drought of four to six months. Hence, the district is characterized by wet and dry seasons.

Fig. 1: Map of the Gushiegu-Karaga District (Source: World Vision –GRWP)



The district has a single rainy season from May to October with the peak in September, followed by a prolonged dry season from November to March. The mean annual rainfall is about 1000 mm to 1150 mm. The mean monthly temperatures vary from about 36°C in March to about 27°C in August. In recent years, due to the Greenhouse Effect (Ozone Layer Depletion) the mean maximum monthly temperature may be higher. Thus, the area is characterised by high evaporation and evapotranspiration due to the long period of dry season and high temperatures. In effect, estimates of the proportion of rainfall that infiltrates into the ground are difficult to arrive at since the rainfall pattern in the district is irregular and not reliable (Wills, 1962).

### ***Vegetation and Soils***

The study area falls within the Interior Wooded Savannah Vegetation (Guinea Savannah) of the Northern Region of Ghana. According to Dickson and Benneh (1988), this vegetation constitutes the largest single vegetation zone in Ghana covering an area of about 170,000 square kilometres. Trees such as the baobab, acacia and shea nut have adapted to the environment. The vegetation or trees are generally few and widely scattered.

While the amount of rainfall must be taken into account, the nature of the surface, as well as of the rocks below are much more important (Wills, 1962). Geology, topography, drainage, climate and vegetation are physical factors, which affect the formation of soils as an important element of the physical environment. The study area is covered with the Interior Wooded Savannah soils (Dickson and Benneh, 1988) of which groundwater lateritic soil covers nearly three-quarters (or 75%). Generally, present at shallow depths of the soil is a cemented layer of laterite (ironstone), called iron pan or hardpan underlain by the shale. Rainwater does not easily penetrate the soil and there is practically no percolation below the hardpan. Therefore, in the wet season shallow floods cover large areas of the land.

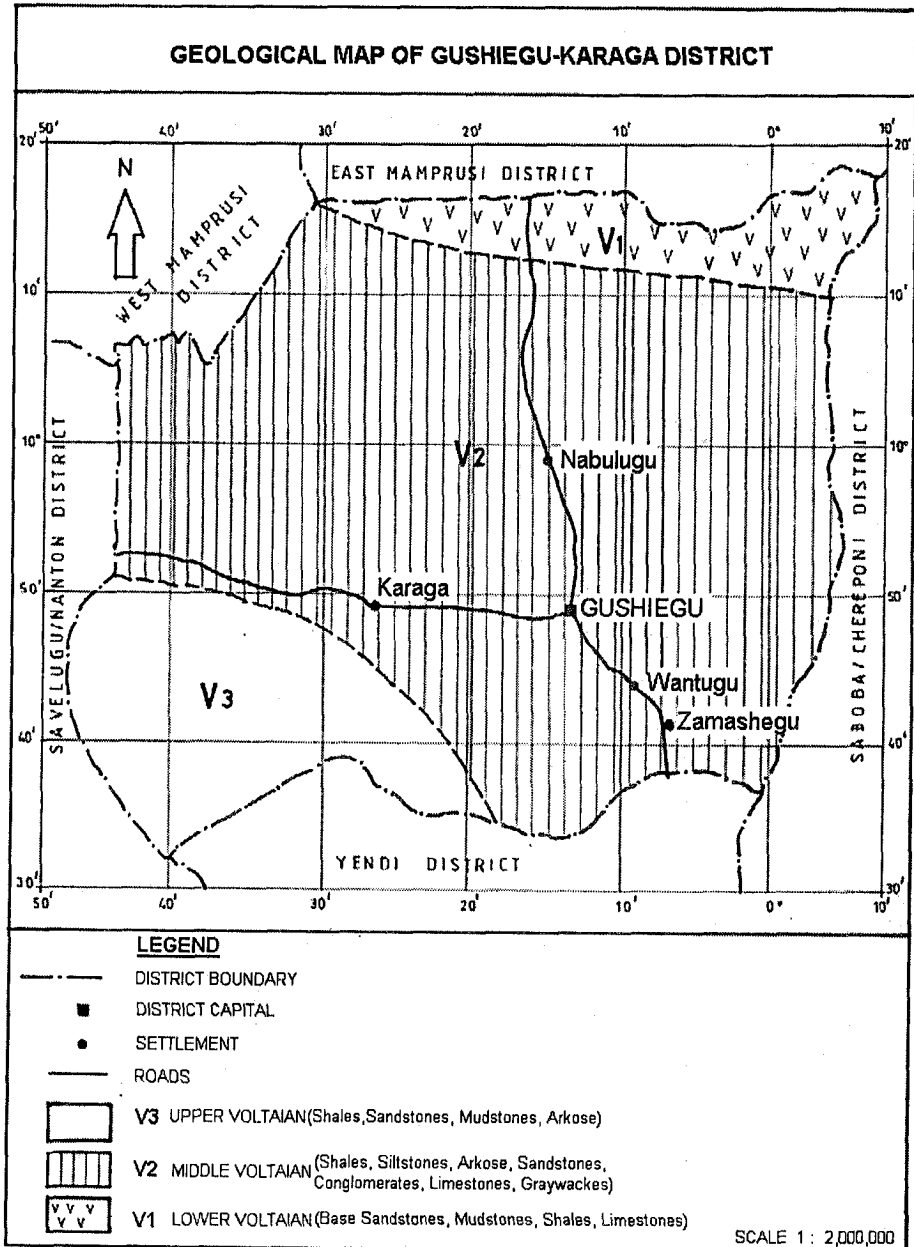
### ***Drainage Pattern***

The Northern Region of Ghana is drained by rivers such as the White Volta, Black Volta and Oti, but there are other smaller rivers and streams draining the region. The sources of water supply for these rivers are rainfall and springs. Rainfall in the region is highly seasonal. Rivers are intermittent: they flood their basins in the rainy season and dry up in the long dry season. Despite the highly seasonal rainfall, springs rarely dry up in the Northern Region because they are not fed by only rainwater but also by groundwater sources (Dickson and Benneh, 1988). The study area is drained by ephemeral streams, which eventually drain into the Volta River. These streams are partially controlled by underlying impervious and flat lying rocks, which enhance more runoff, and the streams flood their basins during the rainy season.

### ***Geology and Hydrogeology***

The Voltaian Basin is a large depression of the Earth's crust, which is drained by the Volta River and its tributaries. The Basin is an area that is underlain by a group of sedimentary rocks called the Voltaian System. A stratigraphic division of the Voltaian System, based on lithological differences makes up the Voltaian Formation. The Voltaian Formation consists of the Upper Voltaian (youngest), Middle Voltaian and the Lower Voltaian (oldest) in that succession (Kesse, 1985). Geologically, the district is underlain by the Lower, Middle and Upper Voltaian formations. The Middle Voltaian formation (V2, Fig. 2) forms about 85% of the underlying rocks. The Lower Voltaian formation (V1, Fig. 2) covers about 5% to the north-eastern part; while the remaining 10% is covered by the Upper Voltaian formation (V3) as in Figure 2. On the basis of lithology of the rocks, the Lower Voltaian consists of basal sandstone with overlying shale, which constitutes the base of the Voltaian. Overlying this is feldspathic and quartzitic sandstone alternating with beds of shale and siltstone. The Middle Voltaian is composed of alternating beds of greenish grey or brown shale,

Fig. 2: Geological Map of Gushiegu-Karaga District (Adapted from World Vision - Ghana Rural Water Project)



siltstone, arkose, conglomerates, greywackes, limestone and sandstone. For the Upper Voltaian, it consists of sandstone, shale, mudstone, arkose, and conglomerates.

Hydrogeologically, the Lower and Middle formations have their principal aquifers in the sandstones and siltstones. These rocks have low groundwater potential due to the absence of primary porosity. Nonetheless, appreciable secondary porosity has been developed through fracturing and jointing as the main water-bearing zones in the rocks.

## MATERIALS AND METHODS

### The GEONICS EM 34-3 Equipment

In this study the EM 34-3 equipment designed and manufactured by the GEONICS Limited in Ontario, Canada was used. The model used for this study is two-man portable. The equipment consists of insulated transmitter and receiver coils with respective internal diameters of 58 cm and 97 cm, and with different colours for easy identification in the field.

### Terrain Evaluation

A topographical study of the area was undertaken to identify drainage pattern, rock-outcrops, valleys and type of vegetation. The position and orientation of trees such as the fig tree (*Ficus species*), black berry tree (*Vitex doniana*), dawadawa tree (*Parkia-biglobosa*) the ebony tree (*Diospyros m espiliformis*) and trees of the spe-

cies *Danielia oliveri* were also studied. It has been found out that such trees are of great value as groundwater indicators in the Voltaian Sedimentary Basin and have been used extensively to site boreholes (Bannerman, 1989).

### Geophysical Measurements

Traverse lines were located away from identifiable fixed cultural features or landmarks. Station intervals of 10 m were also marked on the traverse. The equipment was set at 20 m interval spacing and used throughout the survey. Measurements were recorded in millisiemens per metre ( $mSm^{-1}$ ). At each station the horizontal dipole (HD) mode reading was taken first, followed by that of the vertical dipole (VD) mode, to probe depths of 15 m and 30 m respectively. For the HD mode the receiver ( $R_x$ ) and transmitter ( $T_x$ ) coils were placed on the ground in such a way that their axes were parallel, but their planes were vertical and coplanar (Fig. 3a). The receiver coil was moved back and forth until the meter indicated a null setting, and the terrain conductivity read from a second digital meter and recorded (McNeill, 1980). Similarly, for the VD mode the coils were placed on the ground with their axes parallel, and planes horizontal and coplanar (Fig. 3b).

The procedures at each station were repeated until the desired total length of each traverse line was covered. If the terrain conductivity value of the VD mode at a station was observed to be

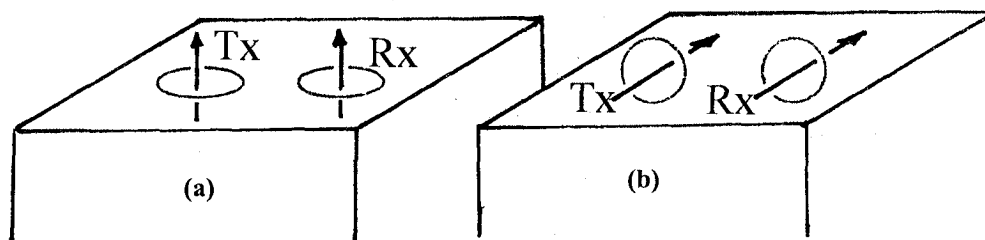


Fig. 3: (a) Vertical Dipole (VD) and (b) Horizontal Dipole (HD) Configurations (After McNeil, 1980)

greater than that for the HD mode, a conductor, fractured or weathered zone could be present within the subsurface. Such readings were cross-checked to ascertain the extent of the fractured or weathered zone. This cross-checking was done by taking readings along a short traverse line perpendicular (offset) to the main traverse line.

**The Electromagnetic Method in Groundwater Prospecting**

It can be shown (McNeill, 1981) that the ratio of the field ratios for horizontal and vertical dipole configurations as shown in Figure 5 is given by:

$$\frac{H_s}{H_p} = \frac{i\omega\mu_0\sigma s^2}{4} \dots\dots\dots (1)$$

where  $H_s$  = secondary magnetic field at the receiver coil,

$H_p$  = primary magnetic field at the receiver coil,

$$i = \sqrt{-1}$$

$$\omega = 2\pi f$$

$f$  = frequency (Hz),

$\mu_0$  = permeability of free space,

$\sigma$  = ground conductivity (mhm<sup>-1</sup>),

$s$  = intercoil spacing (m).

Equation 1 is incorporated in the design of the GEONICS EM 34-3 equipment. This makes it possible to construct linear terrain conductivity meter to give a direct reading by simply measuring this ratio.

Further, the ratio  $H_s/H_p$ , and the apparent conductivity,  $\sigma_a$  indicated by the instrument are related by the equation

$$\sigma_a = \frac{4}{\omega\mu_0 s^2} \left( \frac{H_s}{H_p} \right) \dots\dots\dots (2)$$

where  $\sigma_a$  is in mho (siemen) per metre or milimho per metre.

Thus, 
$$\sigma_a = \frac{2}{\pi f \mu_0 s^2} \left( \frac{H_s}{H_p} \right) \dots\dots\dots (3)$$

This gives the apparent conductivity,  $\sigma_a$  in terms of the frequency,  $f$  and intercoil spacing,  $s$ . Therefore, the ratio of the secondary magnetic field to the primary magnetic field is linearly proportional to the apparent terrain conductivity. Hence, measurements taken under the condition of low induction numbers provide an apparent terrain conductivity,  $\sigma_a$ , which the EM34-3 equipment reads directly, and it is defined by

$$\sigma_a = \frac{4}{\omega\mu_0 s^2} \left( \frac{H_s}{H_p} \right) \text{quadrature component}$$

**RESULTS**

Figures 4–6 show the results of the EM field data plotted as apparent conductivity versus station profiles. Presentation and analysis of data in profile form have some specific advantages. Firstly, interpretation is theoretically valid if the anomaly sources strike perpendicular to the traverse and are two-dimensional (McNeill, 1980), and secondly suitable points could be selected as target drilling sites relative to the rest of the profiles.

Figure 4a shows the EM profile along traverse A at Maaga over a distance of about 400 m. The apparent sinusoidal nature of the VD curve shows more rapid changes of the apparent conductivity at 30 m depth than that at 15 m depth (HD curve). However, the apparent conductivity values at 15 m depth probed in the HD mode are higher than the values at 30 m depth probed in the VD mode. This indicates that the overlying rocks at shallower depth are more conductive than the underlying rocks at deeper depth. At the station 350 m along the traverse, the deeper EM response shows a rather sharp increase in apparent conductivity, producing a sharp peak of a very significant anomaly with a narrow width.

Fig. 4a: EM Profile along traverse A at Maaga over a distance of about 400m

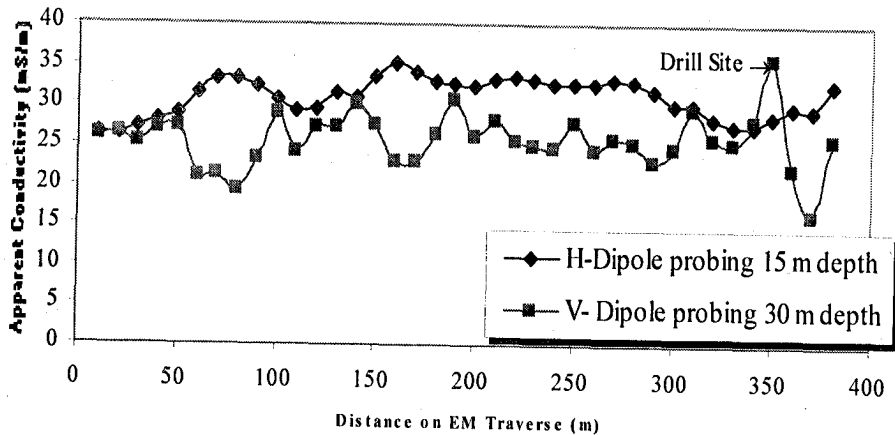
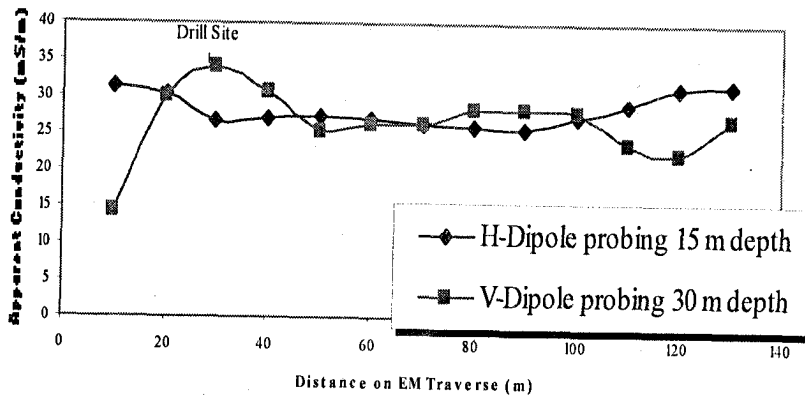


Fig. 4b: EM Profile for Traverse B at Maaga



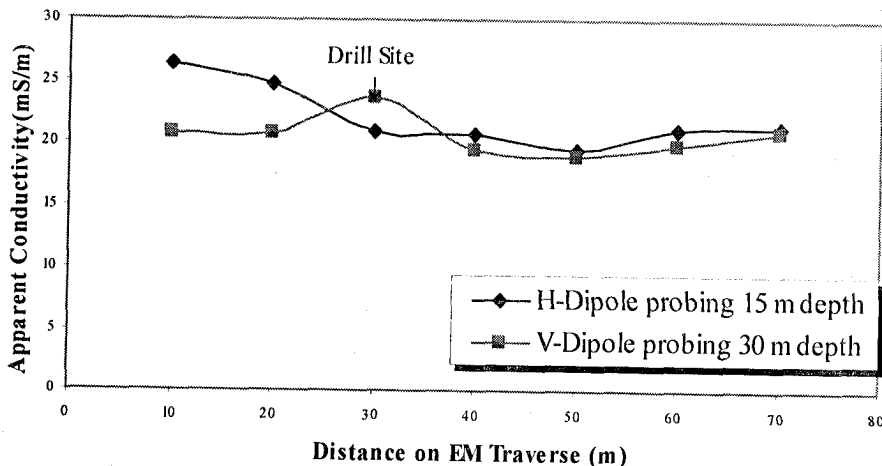
This may be an indication of a deep fractured zone with potential groundwater storage. Thus, the point was selected as possible drilling site on traverse A. appears to be more pronounced than that on Profile A. Nonetheless, the wide width and symmetrical shape indicate that the anomaly was completely traversed. This, correspond to the same deep fractured zone identified on profile A as a potential drilling site. The proximity of the site to a big evergreen fig tree of the *ficus*

*species*, stated earlier under Terrain Evaluation supported the choice as a potential site for groundwater occurrence.

Figure 5 shows the EM profile along a traverse over a distance of about 80 m, at Zamashegu town. The deeper EM response curve at 30 m depth (VD mode) crosses over the shallower EM response curve at 15 m depth (HD mode), resulting in a peak close to the 30 m station on the



Fig. 5: EM Profile for a Traverse at Zamashegu

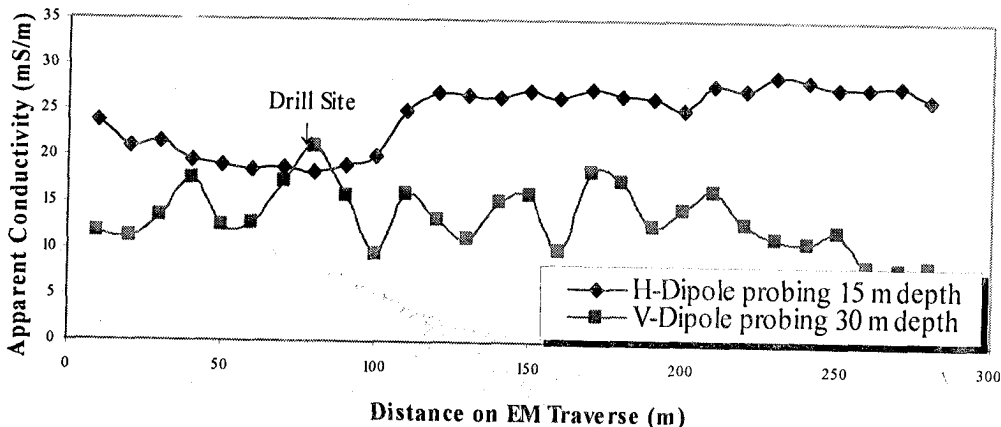


traverse. The anomaly, with a wide width suggests a deep weathered zone. The symmetrical shape and wide width also suggest a complete traverse over the anomaly. Thus, the site could possibly be underlain by a deep fractured zone and as a result, was selected as a potential drilling site. The choice was reinforced by its proximity to a natured ebony tree (*Diospyros me-*

*spiliformis*), whose presence often indicates the presence of groundwater.

Figure 6 shows the EM profile along a traverse over a distance of about 300 m at Wantugu town. For the HD mode, apparent conductivity decreases along the traverse to the 80 m station and increases again up to the 120 m point. The interval between 120 m and 280 m shows approximately a uniform apparent conductivity.

Fig.6: EM Profile for a Traverse at Wantugu



**Table 1: Driller's log at selected site on the EM Traverses A and B at Maaga**

Depth (m)	Rock type within interval
0 – 3.0	Dark red duricrust; completely weathered shale.
6 – 12.0	Hard greenish grey shally siltstone; fresh fractured shally siltstone.
12 – 30.7	Siltstone with chocolate brown shally intercalations.

However, the apparent conductivity values for the VD mode, at 15 m depth are higher compared to the values at 30 m depth. This may suggest that sub-surface rocks at 15 m depth are more conductive than rocks at the 30 m depth due to weathering at shallower depths. At the 80 m station along the traverse, a sharp peak in apparent conductivity is recorded, with the deeper EM response (VD curve) crossing over the shallower EM response (HD curve). The anomaly may probably be due to a deep fractured zone, and therefore could be a possible site for groundwater occurrence, which could be drilled.

The lithology is predominantly shally (clay filled) siltstone. Two aquifer zones were encountered at the intervals 12.5 – 18.5 m and 24.0 – 28.0 m. The well was screened from 11.2 to 20.2 m and from 23.2 to 29.2 m. The yield from the aquifer was 107 litres per minute when developed with an airlift pump for 3 hours.

Table 2 shows the driller's log of the borehole drilled to a depth of about 27.7 m at a site on the EM Traverse at Zamashegu

The geological logs indicate a shally siltstone lithology. Groundwater was struck at 15.5 m depth and aquifer zone at 15.5 – 18.0 m. Thus, the resulting wet well was screened from the depth of 14.3 to 26.3 m. Pump test for 3 hours and 15 minutes produced water at 102 litres per minute. Table 3 shows the driller's log of the borehole drilled to a depth of about 42.0 m at a site on the EM Traverse C at Wantugu.

The log reveals that the sub-surface geology is predominantly siltstone with mudstone intercalations from 12.0 m to 18.0 m. Groundwater was struck at 38.0 m within a deep fractured aquifer zone at 36.0 – 39.0 m. The resulting wet well was screened from 31.5 to 40.5 m. It was pumped for 3 hours and 15 minutes. The final water flow rate after pumping test was 288 litres per minute.

#### DISCUSSION

The three selected examples of drill logs indicate that the local geology of the boreholes drilled is generally siltstone, with few cases of shally-siltstones. The soil profile is predominantly

**Table 2: Driller's log at selected site on the EM Traverse at Zamashegu**

Depth (m)	Rock type within interval
0 – 3.0	Light brown laterite soil; hard moderately weathered yellow shale.
3 – 6.0	Greenish grey shally siltstone; fractured hard brown shally siltstone.
6 – 9.0	Hard brown shally siltstone.
9 – 27.7	Greenish grey shally siltstone; hard chocolate brown freshly fractured shally siltstone.

**Table 3: Driller's Log at a site on the EM Traverse at Wantugu**

Depth (m)	Rock types within interval
0–2.0	Dark brown partially deformed hardpan laterite (duricrust).
2–6.0	Dark brown hard-pan laterite; clayey soil
6–9.0	Yellowish green moderately weathered siltstone; hard siltstone.
9–42.0	Greenish grey hard siltstone; fresh fractured siltstone with mudstone intercalation at 12–18 m.

characterised by lateritic topsoil overlying weathered and fractured siltstones with isolated cases of shale intercalations. Most of the boreholes drilled revealed a general lithology of greenish-grey or brown shale, siltstone, sandstone, mudstone and greywackes. This means the Middle Voltaian underlies a greater part of the Gushiegu-Karaga District. Greater number (90), of the 100 boreholes drilled were located in this rock formation. Areas with high apparent terrain conductivity produced high yielding wells compared to regions with relatively low apparent terrain conductivity. Most of the wet wells have their apparent terrain conductivity in the range of 20 – 35  $mSm^{-1}$ . However, there were few wet wells with apparent conductivities below 20  $mSm^{-1}$  or above 35  $mSm^{-1}$ .

The drilling results also indicate that the mean depth of successful wet wells is 41.0 m, while that for unsuccessful dry boreholes is a 64.0 m. Aquifers were found to lie between 30.0 m and 60.0 m. The high yielding wet wells were located in fractures within a local geology of shale-siltstones, whereas the low yielding wells were in pure siltstones. Three highest yielding wet wells were drilled at Wantugu, Maaga and Zamashegu with respective flow rate of 288, 107 and 102 litres per minute. Using 10 litres per minute threshold as the basis for a wet well to be acceptable and developed, 100 boreholes were drilled. Out of the hundred wells, 60 of the boreholes produced wet wells (successful) and 40 were declared dry (unsuccessful), i.e., these wells produced less than 10 litres per minute.

Thus, 60% success rate was achieved in the project and compared with 50% success rate of existing boreholes.

### CONCLUSION

The electromagnetic technique has been used successfully to locate and delineate aquifers (water-bearing zones) in the Gushiegu-Karaga District within the Voltaian Sedimentary Basin of Ghana. The following conclusions were drawn from the study:

- i) The study area has a good groundwater potential.
- ii) The water-bearing zones were between 30.0 m and 60.0 m depths and could be located in the greenish-grey or brown shale and siltstones.
- iii) The mean depths of successful and unsuccessful wells were respectively 41.0 m and 64.0 m.
- iv) The success rate of 60% if compared to 50% success rate of the existing boreholes is 20% higher.

Therefore, the EM technique, which is fast, efficient and effective in the location of water-bearing zones, can be used to site boreholes for groundwater within the district. Above all, the wet boreholes drilled have greatly improved the socio-economic life of the people in the sense that, they no longer walk long distances to fetch or buy water. In addition, their new source of water is free from water-borne diseases like bilharzias and guinea worm. However, a problem that has been encountered in using the GEON-

ICS EM 34-3 equipment for profiling is that some areas with high apparent terrain conductivities, were found after the drilling to have very little or no water whilst some with low apparent conductivities had water. In view of these findings, further investigation of the groundwater potential of the area is suggested. The study may include the use of photo images and topographic maps in addition to the ground geophysical investigation. Also, electromagnetic sounding technique at the selected points on the traverse lines can be carried out to probe and delineate deeper structures within the subsurface. Due to the high cost of drilling, identified wet wells with rather insufficient water could be hydrofractured to force open up tight joints, and small fractures obstructing the flow of water into the borehole. This would improve the yield and increase successful drilling results and potable water supply to the communities. These selected examples and their driller's logs allude to the fact that the electromagnetic method can be used to site productive wells/boreholes. Therefore, the technique is dependable in locating groundwater resources in the Voltaian Sedimentary Basin.

#### ACKNOWLEDGEMENT

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