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USING LOW COST GEOPHYSICAL METHODS TO LOCATE HIGH YIELDING GROUNDWATER AQUIFERS IN THE GRANITE ROCK REGION OF MATABELELAND SOUTH PROVINCE OF ZIMBABWE - A CASE OF GWATEMBA AREA

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ABSTRACT

This study involves the use of two basic geophysical methods in groundwater exploration in the granite rock formation of Gwatemba area in southern Zimbabwe. The aim was to identify high groundwater potential zones. The Slingram e-m survey method was first used in line profiling. This provided information of fractured, weathered, fissured and contact zones to a depth of approximately 30 m along the profile lines. The vertical electrical sounding using Schlumberger depth sounding technique were measured with electrode spacing ranging from AB = 10 m to AB = 1000 m, where AB is the distance the current electrodes. This was undertaken to provide depth information below selected groundwater potential zones. These measurements were only done in an area with a wide weathered base identified during profiling. The results of profiling and vertical electrical sounding were interpreted using excel and a computer vertical electrical sounding (VES) freeware respectively. This was used to compute a layered earth model using the least square technique to match the theoretical apparent resistivity curve as close as possible to the field curve. Finally, the joint evaluation of the results provided both the lateral thickness and the depth of weathered part at a given point, which is the aquiferous zone.

Keywords: Aquifer, Apparent resistivity, Profiling, Regolith, Groundwater and Weathering.

INTRODUCTION

The availability of sufficient, safe and affordable water is vital for human development (Jayyousi, 2007). This is fundamental as it is one way of eliminating poverty in a given community since time is freed up to focus on income generating activities rather than fetching for clean and safe water. According to the (UN, 2003; WHO, 2003; Howard & Bartram, 2003), there are more than 1.2 billion people who lack access to adequate supply of safe and clean water.

The adoption of the Human Right approach to water was to put the peoples' need first regarding water use and to promote human-centred water resource development based on a coherent framework of binding legal norms and accountability. The term 'human rights' refers to those rights that have been recognized by the global community in the Universal Declaration of human rights, adopted by the United Nations (UN) member states in 1948, and in subsequent international legal instruments binding on states. The human rights approach is especially used to challenge the economic and social injustice. The consensus on human rights reflects a global moral conscience (Water Aid, 2003).

The adoption of the Millennium Development Goals (MDGs) sets water as one of its specific targets to achieve. The 1992 Dublin Water Conference, Principle 4 states that, "water has an economic value in all its completing uses and should be recognized as an economic good" (Cosgrove & Rijsberman, 2000). The rational for the emergence of water as a human right stems from the need to secure water for the poor and marginalized people and to urge governments to address the water agenda as a national priority as outlined in the MDGs (Jayyousi, 2007).

Groundwater (GW) is one natural source of clean and safe drinking water. It can be found in most underground environments and generally requires no prior treatment since it is naturally protected from contamination. Generally GW does not vary significantly seasonally and is often drought resistant (Macdonald, Davies, Calow and Chilton, 2005). It is available in large quantities and has an almost constant quality and temperature (Foster, 1994).

In Zimbabwe GW forms the main source of safe drinking water in rural areas where about 70% of the population lives. The total annual abstraction of GW in these areas, from approximately 40,000 boreholes, is estimated at 35 x 10^6 m^3 and the total GW abstraction for the agricultural sector is estimated at 350 x 10^6 m^3. GW is also abstracted for emerging Growth Points (e.g. Gokwe), Urban Centres (e.g. Bulawayo) and Rural Institutions (e.g. schools, health and business centres) (Sunguro, Beekman and Erbel, 2000). Overall, GW presently contributes more than 10 % to the total water used in Zimbabwe. This means that proper GW exploration is needed to locate high GW potential zones in urban areas, Growth Points, farming areas, schools clinics, etc. These high GW potentials zones could be abstracted during shortages from other sources like rivers and dams during the dry season. Furthermore, in Zimbabwe the demand of GW has increased due the near collapse of water and sewerage treatment plants in urban areas during the 2008 to 2009. The principal cause of the outbreak was lack of access to safe and clean water.

It should be noted that the proper siting of a borehole using multiple geophysical methods can significantly increase the success rate of locating a drilling site and reduces the total cost of the whole project (Lissa, Maanen and Odera., 1987). In Zimbabwe hardly any attention is given to the use of more than one geophysical method of GW exploration. The use of multiple methods to explore for GW triangulates data and overcome the venerability to errors linked to a single survey method (Patton, 1990).

Thus the main purpose of this study was to determine the effectiveness of using two low-cost basic survey methods in identifying areas with high GW potential. The two methods employed in this research are the Slingram electromagnetic method using the geonics EM34-3 for line profiling and the geo-electrical method using the Schlumberger array for vertical electrical sounding (VES). Geophysical resistivity and conductivity techniques are based on the response of the earth to the flow of electrical current. In this method, an electrical current is passed through the ground and two potential electrodes are used to record the resultant potential difference between them, giving a direct measure of the electrical impendence or conductance of the subsurface. In the shallow subsurface, the presence of water controls much of the conductivity / resistivity variations. Thus the measurement of conductivity / resistivity in general, is the measure of the amount of water saturation and connectivity of pore space (Cardimona, 2002).

The new crafted method involves using the geonics EM34-3 for line profiling. This was to identify fractured, weathered, fissured and contact zones to a depth of approximately 30 m along the profile lines. The anomalous points identified along the profiles are the target areas for further investigations. At these anomalous points VES were performed to find the thickness of the possible aquifers. The method is based on the assumption that exploitable aquifers in hard rock usually occur in fractured, faults or contact zones. In choosing the combining of surveying methods i took into account the fact that it has been used cost effectively in a number of countries yielding successful results. For example, in Kenya, the Lake Basin Development Authority in the initiation of the rural domestic water supply and sanitation programme in Nyanza province (Lissa et al, 1987) used a combination of electromagnetic, Wenner profiling and Schlumberger methods. A success rate of around 80% of the boreholes drilled was obtained. Additionally, the average depth was only half that of existing boreholes with abnormal yields about 140 % higher.

GEOLOGY OF THE AREA

The research was done around the Gwatemba Rural Community, in Matabeleland south province of Zimbabwe. The area lies between the lines of latitude and longitude 20°15'S to 20°30'S and 29°30'E to 29°45'E. The area is shown on the map of Zimbabwe on Figure 1 below.

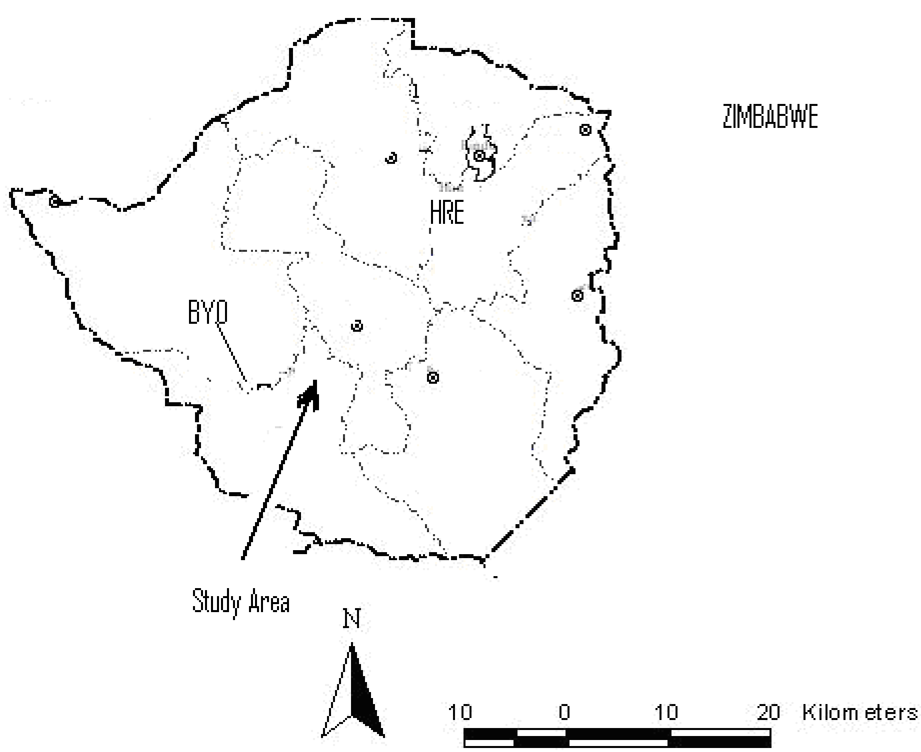

Figure 1: The map of Zimbabwe showing the study Area.

The area shown on the map forms part of the post – African erosion cycle (Lister, 1987). The region is dominated by the archaean granitic and gneisse rocks, which comprise proterozoic intrusive granites, granodiorite, adamellite and tonalite of the younger granites, paragneisses (Asteir, 1971). Younger granites produce a less regular terrain than the older granite and gneisses, with the development of exfoliated bornhardts as well as rectangularly jointed castle kopjes. Significant petrographic variations are exhibited with several ages of intrusions present (Wilson, Jones, and Kramers, 1985). The youngest dolerite dykes characterized by subophitic and intergranular textures, are commonly olivine bearing and their mid protozoic emplacement probably marks the last igneous event in the area. These narrow dykes (around 5 m to 10 m) give rise to masses of boulders atop red soils. These soils support a denser vegetative cover than the pale granitic country rock (Baglow, 1998). The geological map showing the distribution of granite units in the area of study is shown on Figure 2.

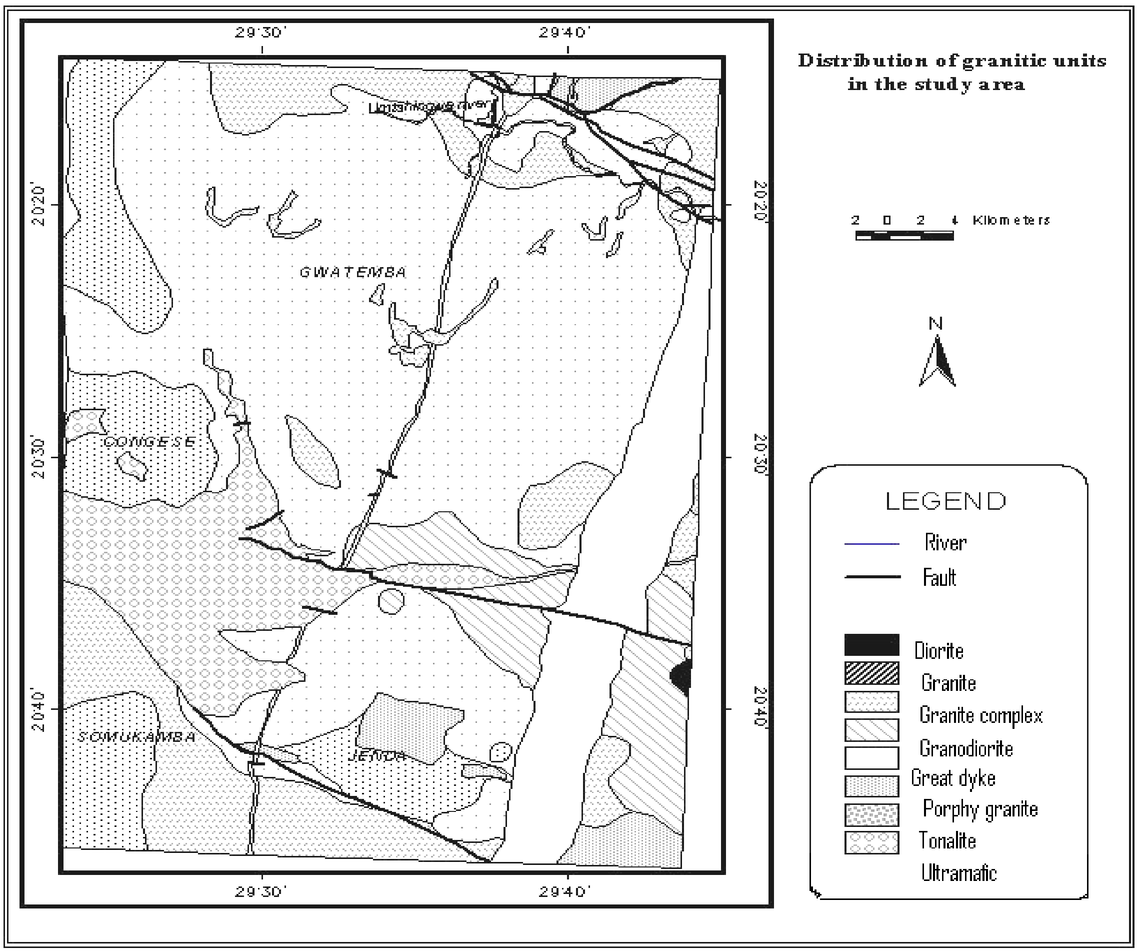

Figure 2: Distribution of granitic units in the Gwatemba area (adopted from 'The geology of the Filabusi greenstone and the surrounding granitic terrain by N. Baglow').

The area is drained mainly by the Umtshingwe river. Small streams feeding into the river only run during heavy rains and rarely hold any water longer than a few weeks after the termination of the rainy season. The streams are in sequent throughout the area and typically display a dendritic drainage pattern. The lack of perennial surface water has made boreholes necessary over much of the area. Depths of at least 40 m are required to get below the water table and GW has been tapped along fractures through all lithologies (Baglow, 1998). In areas where granite outcrops extensively on the surface, GW development potential ranges from marginal to nil. All geomorphological factors being equal, the highest GW development potential is found in those areas possessing the deepest and most spatially extensive weathering. This means that the thickness of water bearing formations or regolith correlates almost linearly with the quantity of water in an aquifer.

There is a known relation between resistivity range and GW occurrence in most lithologies and this relationship is of particular importance in hard rock aquifers (Bolognini and Mouton, 1966: Biscaldi, 1968). The resistivity in granite aquifers can be classified as shown on table 1.

Table 1: Resistivity ranges and their significance in terms of potential GW occurrence

(adopted from Martinelli and Hubert, 1985)

RESISTIVITY (Ωm)	Classification	Groundwater potential
≤ 20	Very low	Advanced clay weathering, with limited groundwater potential
20 -100	Low	Optimum weathering conditions, with optimum groundwater potential
100 - 150	Medium	Favourable weathering conditions with associated moderate groundwater potential.
150 - 250	High	Limited weathering with some fracturing in bedrock, and poor groundwater development potential
≥ 250	Very high	Insignificant weathering, with minor fractures in bedrock, poor to no groundwater potential.

As a result resistivity values of between 20 Ωm to 150 Ωm constitute the target area for borehole siting provided sufficient dimensions of the regolith both lateral and vertical are available.

METHODOLGY

Satellite images of the area between latitudes 20^0 South and 21^0 South and longitudes 29^0 East and 30^0 East were used to highlight regional structures such as major faults. A desk stereoscope was then later used to analyze aerial photographs of the area. This exercise served the purpose of identifying features indicative of the presence of GW. Due to increased soil moisture and vegetation density, fault systems were easily identified as they appeared as dark lineation on aerial photographs.

The desk study resulted in the area being divided into three GW potential availability zones. The north-east part of the area was rated as having high GW availability, whilst the western and the southern parts were rated as having low water availability potential. This was due to overwhelming presence of granite outcrops all over the area.

A fieldwork reconnaissance of the area was then carried out using the desk study results as a guiding tool. This was to determine where the geophysical measurements were to be done. Soil types in the area were identified. These included sandy loam soils, sandy clay soils and red clays. The general drainage patterns of the area and possible recharge water areas were also identified. Existing boreholes were also visited, where the average borehole yields were verified.

The main fieldwork involved geophysical measurements. Here the geonics EM34-3 instrument operating at a frequency of 1,6 kHz was used for line profiling. A low frequency signal was used to maintain a low induction number, in which case the penetration depth depended only on the antenna separation (McNeill, 1980). The instrument was carried by two individuals. It consists of a transmitter console, a receiver console, transmitter coil, and receiver coil and accessory cables. It measured apparent conductivity of the ground in mill-Siemens per meter (mS/m). The instrument noise level is less than 0.2 mS/m, with accuracy at 5 %. The operating frequencies are: 6.4 kHz at 10 m spacing, 1,6 kHz at 20 m spacing and 0,4 kHz at 40 m spacing. The operating temperature range of between -40 degrees and 50 degree Celsius.

Some of the limitations of the geonics EM34-3 system are that at low values of terrain conductivity, it becomes difficult to magnetically induce sufficient current into the ground to produce a detectable magnetic field at the receiver coil. The system also has limited vertical sounding capability such that it cannot exceed a depth of 60 m.

To measure terrain conductivity the transmitter operator was to stop at the measurement station with a transmitter console and coil. The receiver operator carrying the receiver console and coil then moved forward until the meter indicated correct inter-coil spacing. The transmitter operator then took readings of the terrain conductivity. The readings where done with the coils in vertical dipole mode. This allowed surveying at greater depth. The only problem was that more care was to be taken to ensure inter-coil alignment. All profiles used a 20 m point spacing allowing the researcher to explore a depth of up to 30m. The profile lines were 1000 m long and cutting across the fault systems observed using aerial photographs.

A total of 200 measurement points were performed along four profiles which were 50 m apart. These measurements stations were selected carefully to avoid cultural magnetic sources such as fences, buried pipes, etc. Cases where it was impossible to eliminate the influence of cultural magnetic sources, such data was eliminated during preprocessing. Areas of anomalous conductivity of the range 15mS/m to 30mS/m along the line profile were assumed to be points of high GW potential. These were also the points selected for further investigation using VES. The results of profile line 2 were not plotted on the graph due to the fact that it was along the fence, as a result, data obtained was not reliable.

The electrical resistivity equipment comprising of Abem terrameter SAS 3000C transmitter/receiver system was used to undertake VES on this survey project. SAS stands for Signal Averaging System, a method whereby consecutive readings are taken and the results averaged continuously. In resistivity mode the terrameter comprises a battery powered deep penetrating resistivity meter with an output sufficient for a current electrode separation of 2000m under good surveying conditions. The transmitter system sends out well-defined and regulated currents signal. The receiver system discriminates noise and measures voltages correlated with the transmitted signal current. The microprocessor runs a check on circuits and switch positions, also checking battery conditions and usability of selected parameters. If something is wrong warning information comprising a beeper signal and error codes warns the operator. If everything is right, the microprocessor starts the measurement cycle, and after all readings have been taken it puts the instrument into standby mode with the final result displayed. The overall accuracy of the terrameter SAS 300C is reported to be + 2%.

Stainless steel electrodes were used in the survey. These are strong and resistant to corrosion (Telford, 1990). One concern was the consistency of electrical contact between the electrodes and the ground. For this reason, according to (Herman, 2001) a small amount of slightly salty water was poured on the base of the electrodes where they came into contact with the ground. This was to ensure good contact between the electrodes and the ground. The amount of water used was supposed to be small enough so as not to saturate the ground more than a couple of centimeters away from the electrode. Thus it did not interfere with the resistivity data.

In the Schlumberger array that we used, potential electrodes were much closer together and placed symmetrically about the centre of the array. The current electrodes were moved progressively and symmetrically apart after every reading. Moving the current electrodes had two advantages: there were fewer electrodes to move, and with the potential electrodes fixed the readings were less affected by any lateral variations that may have existed (Musset and Khan, 2000). However, at some point the expansion of the current electrodes caused the value of the potential difference to be too small to be measured precisely. The potential electrodes were moved much further apart to overcome the above stated problem. This was done while the current electrodes were fixed. Further readings were then taken by expanding the current electrodes using the new potential electrodes positions. This also allowed the increase in depth of investigation. A total of nine VES were measured in this research work.

RESULTS AND DISCUSSIONS

Slingram electromagnetic method profiling results:

The apparent conductivity data obtained from the line profile measurements was plotted against the length of each profile line. The results are shown on Figure 3.

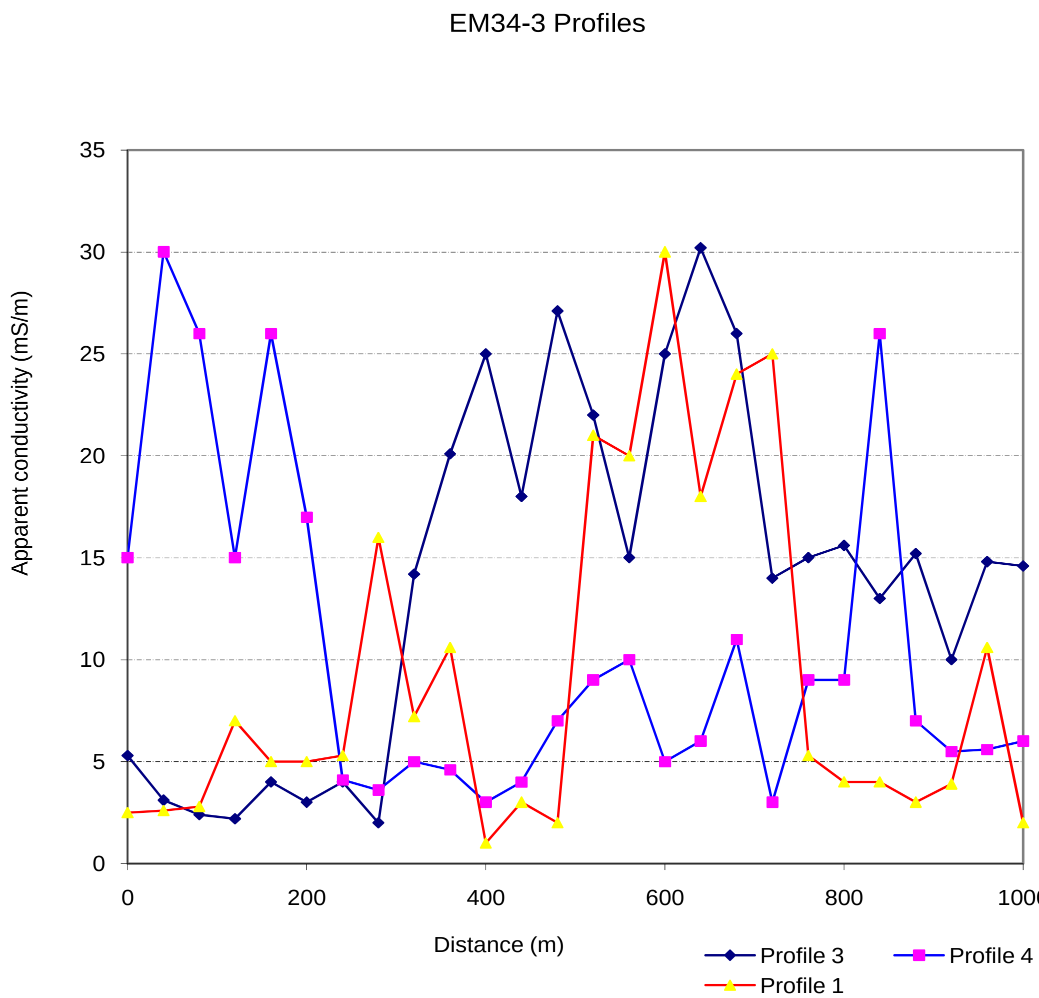

Figure 3: Plot of Apparent conductivity data against length of profile line 1, 3 and 4

An assumption for interpreting such measurements is that the subsurface is approximately horizontally layered. The apparent conductivity of the area along the profile line 3 is on average 3 mS/m between the starting point and the 300 m mark. It then rises sharply to values of 25 mS/m between the 300 m and 700 m mark, and thereafter goes down to around 14 mS/m. The area between 300 m and 700 m is considered as a high potential area of GW. This is presumed to be a contact zone which may act as a suitable site for a high yielding borehole. For profile 1, there is an area of high conductivity between the 500 m to 750 m mark. The position exactly rest on a fault zone observed from satellite images and aerial photographs of the area. Although the area has a high probability of GW the position was not chosen for a VES, since it not accessible with heavy drilling equipment and might be vulnerable to flooding. The apparent conductivity of the area along the line profile 4 is continuously changing. The area with lower conductivity of the range 2 mS/m is clearly noted between 250 m and 400 m.

This may be interpreted as the granite rock basement reaching closer to the surface. This is evidenced by granite rock outcrops in the nearby surrounding areas. At the 600 m mark the apparent conductivity is high, indicative of a weathered layer below but the lateral dimension in terms of distance is too narrow for a potential high yield aquifer. A site to undertake a VES was chosen at the 500 m mark of profile 3 from the origin. This was due to high conductivity associated with a lateral distance of approximately 250 m of a weathered layer. It was presumed that the weathered zone is highly saturated with GW since thickness correlates almost linearly with the quantity of the GW stored in an aquifer.

Vertical electrical soundings results:

The apparent resistivity data obtained from VES sites where plotted against half the current electrode spacing (AB/2) using a VES 130 freeware (Cooper, 2000). The method of interpreting sounding curves uses curve matching techniques. This involves matching small segments of a field curve with an approximate theoretical curve, which enables one to determine both the thickness and apparent resistivity of particular layers in a half space. From the interpretation of the resistivity curves three major layers of the subsurface were observed. These layers consist of the topsoil, regolith and bedrock. Depth and thickness of subsurface layers were also identified.

The results shown on Figure 4 were obtained from VES 1 measured at the 500 m mark along profile line 3.

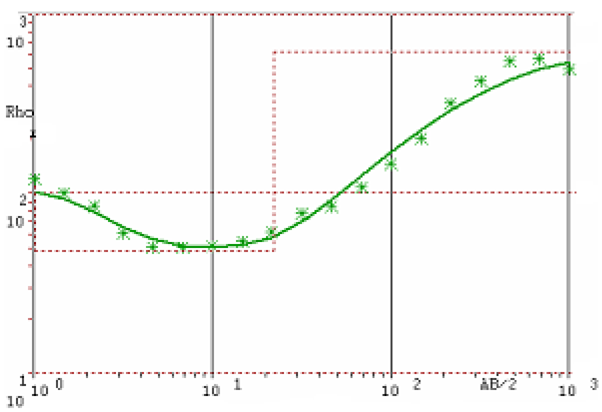

Figure 4: Observed and computed VES 1 sounding curve at 500 m point of profile 1.

A resistivity model, whose calculated apparent resistivity fit the measurement well, the resistivity of the top layer of the soil is 130Ωm, a value characteristic of wet soil. The second layer is approximately 45 m thick, with apparent resistivity of 59.0 Ωm. This is interpreted as the weathered layer saturated with pore water. Then the apparent resistivity begins to rise steadily with depth, revealing the presence of the third layer which we presumed to be the bedrock.

VES 7 was conducted 640 m from the beginning of profile 1. The resistivity values as indicated by the VES curve shown on Figure 5 below dropped from high resistivity values of 274 Ωm in the overburden to a minimum value of about 53 Ωm which is presumed to be the second layer. This assumed that the weathered zone is highly saturated with GW. Its thickness is about 40m, enough to store an adequate quantity of GW. The depth to bedrock is about 45m, which is deep enough for areas were water is expected to come from the weathered zone. The bed rock has a higher resistivity value. But it is probably fractured, hence saturated with water.

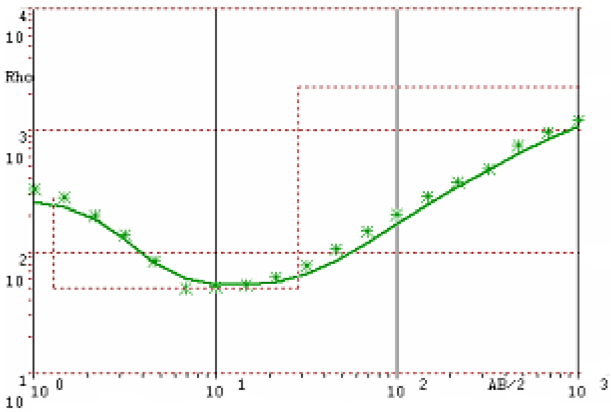

Figure 5: Observed and computed VES 7 curve at 640m point of profile 1.

The site is located at a pronounced fractured zone along the granite-dolerite contact zone. Since the site is also accessible with heavy drilling machinery, it was selected as a possible drilling site. Other VES results were not consider due to the fact that they provided thicknesses of the regolith less than 20m, and these could not be consider for high yielding aquifers.

CONCLUSION

From the analysis of the fieldwork results, it can be seen that geonics EM34-3 method can be used for lateral conductivity mapping when exploring for GW. It provides vital information on the lateral changes in the subsurface rock types and structures, without much emphasis on the vertical thickness or depth to bedrock. The VES then provided quantitative depth information below the selected site stations. Typical information obtained from the combined methods includes lateral thickness of the weathered layers and the depth to the bedrock. The results jointly model the weathered layer in a two dimensional manner. The study justified the usage of the two methods jointly in GW exploration. In short the line profiles provides lateral thickness at particular depth whilst the VES giving the vertical thickness at a chosen point. The two methods compliment each other, to pin point a high GW potential area with a high degree of accuracy. It has to be noted that points with thin lateral distance along the line profile, even if they have the right vertical depth were not considered since they were presumed to be points of low GW potential. The resulting geophysical models are an excellent basis for guiding the drilling activities. This will result in the provision of adequate clean and safe water for the Zimbabwe community in general. Also the MDGs can be achieved this way.

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