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Electrical resistivity survey for groundwater investigations and shallow subsurface evaluation of the basaltic-greenstone formation of the urban Bulawayo aquifer

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ABSTRACT

Electrical resistivity surveying methods have been widely used to determine the thickness and resistivity of layered media for the purpose of assessing groundwater potential and siting boreholes in fractured unconfined aquifers. Traditionally, this has been done using one-dimensional (1D) vertical electrical sounding (VES) surveys. However, 1D VES surveys only model layered structures of the subsurface and do not provide comprehensive information for interpreting the structure and extent of subsurface hydro-geological features. As such the incorporation of two-dimensional (2D) geophysical techniques for groundwater prospecting has often been used to provide a more detailed interpretation of the subsurface hydro-geological features from which potential sites for successful borehole location are identified. In this study, 2D electrical resistivity tomography was combined with 1D VES to produce a subsurface resistivity model for assessing the availability of groundwater in the basaltic-greenstone formation of the Matsheumhlope well field in Bulawayo, Zimbabwe. Low resistivity readings (<50 Ωm) towards the central region of the study area suggest a high groundwater potential, while high resistivities (>500 Ωm) around the western margin of the study area suggests a low groundwater potential. 2D electrical resistivity surveys provide a more detailed subsurface structure and may assist in identifying the configuration of possible fractures which could conduct groundwater into the shallow subsurface of study area. It is concluded that 2D electrical resistivity methods is an effective tool for assessing the availability of groundwater in the highly weathered and fractured basaltic greenstone rocks. The methods provided a more precise hydro-geophysical model for the study area compared to the traditional VES. Results from this study are useful for technical groundwater management as they clearly identified suitable borehole locations for long term groundwater prospecting.

1. Introduction

Availability of groundwater in unconfined aquifers underlain by impermeable crystalline igneous and/or metamorphic rocks is often controlled by the development of secondary porosity and permeability from weathering and fracturing. To ensure maximum and perennial yields, a borehole should be sited where it can penetrate the maximum possible thickness of the regolith. In the basement areas of western Zimbabwe, Wright (1990) and Ndlovu et al. (2010) noted that a minimum overburden of 20–25 m is needed for siting a borehole. Here, a thick regolith of about 40 m developed under wet, tropical conditions and serves as the shallow water table aquifer with hydraulic properties largely controlled by faults and shear zones (Mangore and Taigbenu, 2004).

Hydrogeological and geophysical investigations are often conducted to assess the groundwater potential of a particular area. Geophysical investigations, although sometimes plagued with ambiguities and uncertainties in interpretation, provide a rapid and cost-effective means of deriving distributed information on subsurface hydrogeology (Kearey and Brooks, 1991). The use of geophysical methods for both groundwater resource mapping and water quality evaluation has increased dramatically over the last decade due to rapid advances in electronic technology and the development of numerical modeling solutions (e.g. in Olayinka (1991), Ndlovu et al. (2010), and Metwaly et al. (2009)). Although various hydro-geophysical techniques are available, electrical resistivity is a popular method because of its low cost, simple operation, and efficiency in areas with high contrasting resistivity, such

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as between the weathered overburden and the bedrock (Telford et al., 1990). Electrical methods are particularly suitable for groundwater studies because hydrogeologic properties, such as porosity and permeability, can be correlated to electrical resistivity values. Geo-electrical techniques are essentially concerned with the measurement of electrical resistivities of subsurface materials, which preferentially provides information on the different geological layers, structures and the associated occurrence of groundwater (e.g. in Van Overmeeren (1989), Stewart (1982), Dahlin et al. (1999), Nowroozi et al. (1999), and Meju (2005)). Resistivity is related to various geological parameters such as the mineral and fluid content, porosity, and degree of water saturation. Occurrence of groundwater in rocks and soil materials is summarized by Archie's Law;

$$\rho = a\rho_w\phi^{-m} \tag{1}$$

where ρ is the bulk resistivity, ρ_w is fluid resistivity, ϕ is porosity, and a and m are empirical parameters (Keller and Frischknecht, 1966).

Traditionally, one-dimensional (1D) vertical electrical soundings (VES) have been used to obtain a layered model of the subsurface and the depth to bed rock (e.g., in Ako et al. (1986), McDowell (1979), Martinelli (1978), and Olorunfemi and Olorunnlwo (1985)). In many cases, however, the subsurface cannot sensibly be resolved into horizontal homogeneous layers or into simple zones with lateral conductivity variations as required for profile interpretation. In this study, two-dimensional (2D) electrical resistivity tomography (ERT) surveys were combined with VES surveys to assess groundwater potential and evaluate the shallow subsurface of the basaltic greenstone formation of the Matsheumhlope well field aquifer in Bulawayo, Zimbabwe.

The specific objectives of the study are to (a) determine the depth, thickness, and extent of potential water bearing formations, (b) generate a 2D resistivity model of the shallow subsurface showing the thickness of weathered and fractured zones, and (c) develop a model of the structural and stratigraphic conditions controlling the groundwater occurrence in the shallow subsurface of the study area.

2. The study area

The survey was conducted in the Barham Green medium-density residential suburb in the city of Bulawayo, Zimbabwe (Fig. 1), a major part of which lies in the 52-km^2 Matsheumhlope well field (Weaver et al., 1992; Rusinga, 2002). The area lies in the semi-arid region of Zimbabwe which often receives erratic below normal average annual rainfall. The average annual rainfall is about 600 mm with a range of vales from 199.3 mm to 1 258.8 mm, with a standard deviation of 202.3 mm (Mangore and Taigbenu, 2004).

Movement of groundwater follows the surface topography with seasonal variations in water levels characterized by rising water levels during the wet months, from November to March, and declining water levels during the dry months, from May to September. The study area is underlain by the Archean Bulawayan Group sequence (Garson, 1995). The main direction of faulting and joining is NNW to N with several faults oriented NNE (i.e., parallel to the Great Dyke). Many of the fractures are in-filled by dolerite dykes while others, to the west and northwest of the study area, are filled by massive quartz veins. Shearing is mainly oriented NW, with more WNW trends in the western side of the study area. Below the regolith is the basement aquifer consisting of fractured crystalline rocks of intrusive and metamorphic origin. The metabasaltic formation of the study site is generally water yielding (Martinelli, 1978).

Weathering of the fractured basaltic green stones controls the occurrence of groundwater in the area. Since weathering is most effective in the vadose zone and in the region where the water

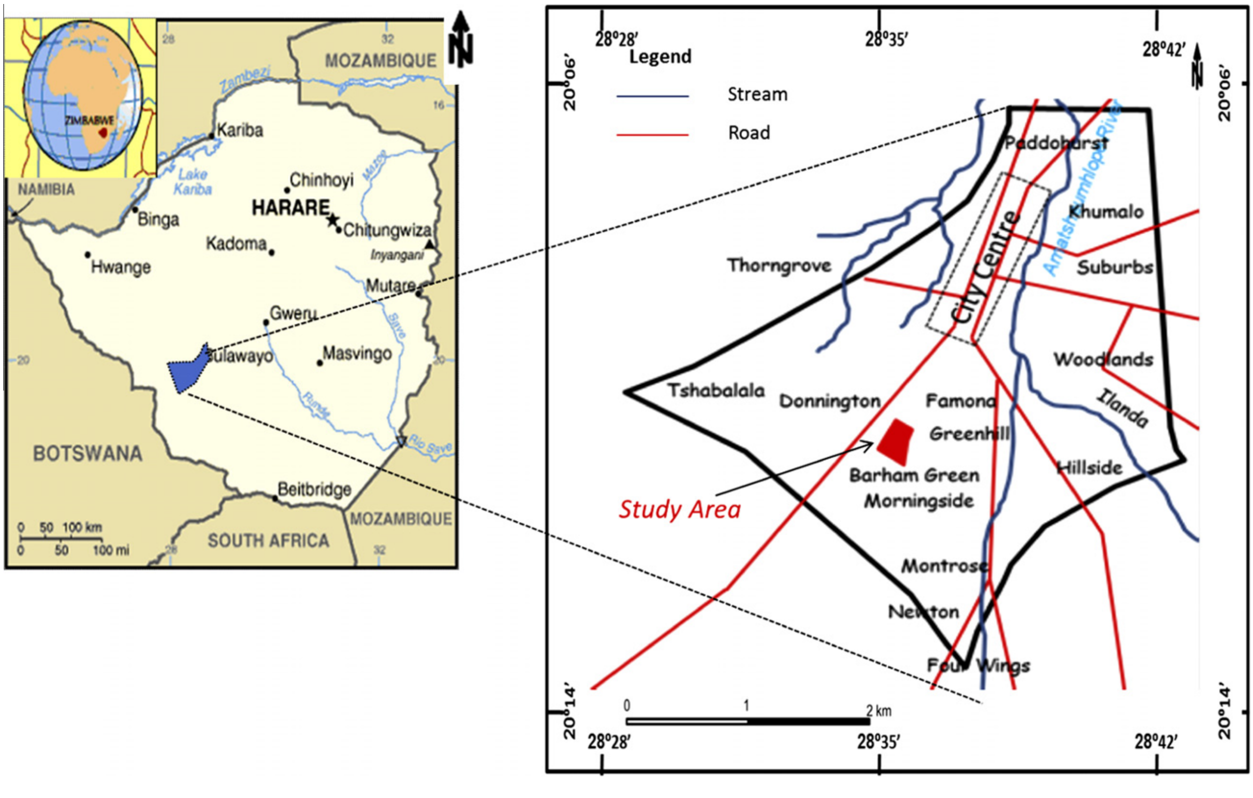

Fig. 1. Map of Matsheumhlope well field showing the study site (adopted from Rusinga and Taigbenu (2004).

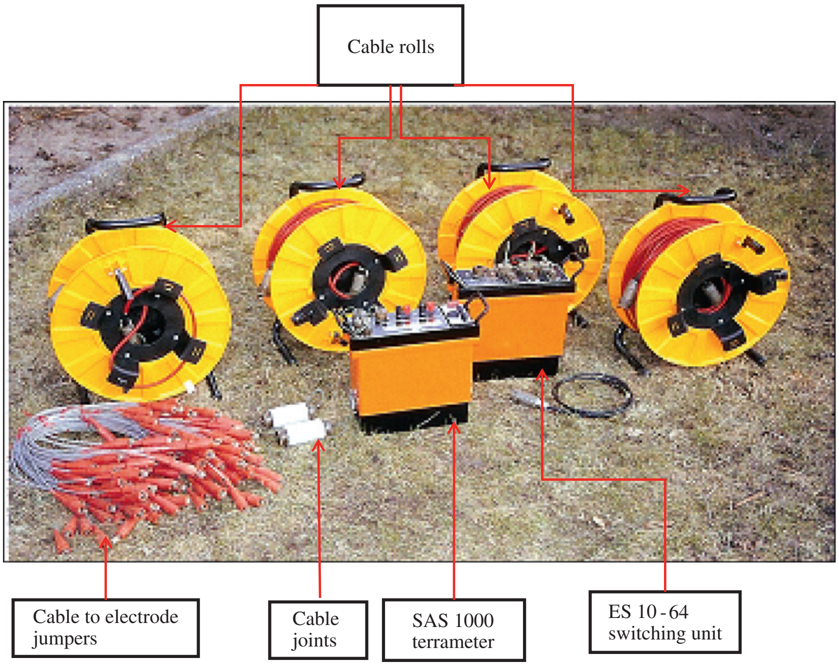

Fig. 2. The SAS 1000 LUND imaging system and the ES 10-64e switching unit, together with the multi-electrode cables which were used for the electrical resistivity tomography survey.

table fluctuates, an upper and lower saprolite tends to develop relative to current or previous water table elevation. In addition, weathering of the basal brecciated zone also occurs where rock fragmentation is largely unaccompanied by mineralogical changes. The regolith is the main groundwater storage compartment, with its hydraulic properties largely controlled by faults and shear zones. The average hydraulic conductivity of the aquifer is 0.55 m/day and sustainable yield ranges from 100 to 250 m^3/day (Rusinga, 2002). Although the aquifer is of regional extent, it responds to abstraction in a ‘discontinuous’ fashion, either due to discontinuities and barrier boundaries within the fracture system or to the constraints of the low-permeability regolith.

3. Materials and methods

The resistivity data acquisition system used in this survey was the SAS 1000 ABEM Lund Imaging System (Dahlin, 1996), together with a relay switching unit (Electrode Selector ES 464), four 100-m multiconductor cables, and steel rod electrodes (Fig. 2).

A hybrid Wenner–Schulumberger array (Loke, 2000) was used for this study. This array arrangement is moderately sensitive to both horizontal and vertical structures and has a horizontal coverage and depth of penetration that is about 15% larger than the Wenner array. Each survey line utilized 20 electrodes, spaced 5 m apart, giving a depth of penetration of approximately 18 m (i.e., 1.8% of the maximum electrode spacing) (Loke, 2000). An input current of 100 mA was used and values of apparent resistivity were manually filtered during the survey. Three parallel N–S oriented ERT lines were surveyed 50 m apart (Fig. 3). As a follow up to the observed results, an ERT line was surveyed along the E–W direction, at the 55-m point on N–S line, to determine the lateral extent of an observed low resistivity region (Fig. 3).

Apparent resistivity data were processed using RES2DINV (ver3.42d) (Loke, 2000). This program uses an inversion routine based on the smoothness constrained least-squares technique (de Groot-Hedlin and Constable, 1990; Sasaki, 1992). It automatically creates a 2D model by dividing the subsurface into rectangular blocks and chooses optimum inversion parameters for the data which include the damping factor, vertical to horizontal flatness filter ratio, convergence limit, and number of iterations. The user can modify the inversion parameters to suit different data types. The program calculates the apparent resistivity values of the model blocks using either a finite difference or finite element method and compares these to measured data. The resistivity of the model blocks is adjusted iteratively until the calculated apparent resistivity values of the model agree with the actual measurements (Loke and Barker, 1996). The program generates both a pseudo-section, which is a qualitative way of presenting the spatial variations of the measured or calculated apparent resistivities, and an inverse model section, which is a tomogram representing the modeled depth and formation resistivities.

Since the depth of investigation of the 2D survey only covers the top 18 m of the regolith, VES surveys were performed to obtain deeper measurements. Similar to ERT, increasing the separation of the current electrodes increases the depth of current penetration, which allows for a deeper depth of investigation (Fig. 4).

In a VES using the Schlumberger array, the effective depth of penetration is generally 20–40% that of the outer electrode spacing (AB), dependent on the earth resistivity structure (Edwards, 1977). The current flow and equi-potentials are distorted as they pass from one resistivity medium to another. VES is useful in determining the depth of overburden, thickness, structure, and resistivity of flat-lying sedimentary beds and possibly the basement, if it is not too deep (Telford et al., 1990). Two VES profiles were obtained in the N–S orientation using the Schlumberger array with a maximum AB/2 spacing of 100 m.

4. Results

4.1. ERT results

In all profiles, a low resistivity zone (20–150 Ωm) along the center of the survey lines between the 50–60 m mark, extends to depths beyond 16.5 m (Fig. 5).

The possible extension of this low resistivity zone suggests the presence of a fracture zone. Low resistivities on the central section

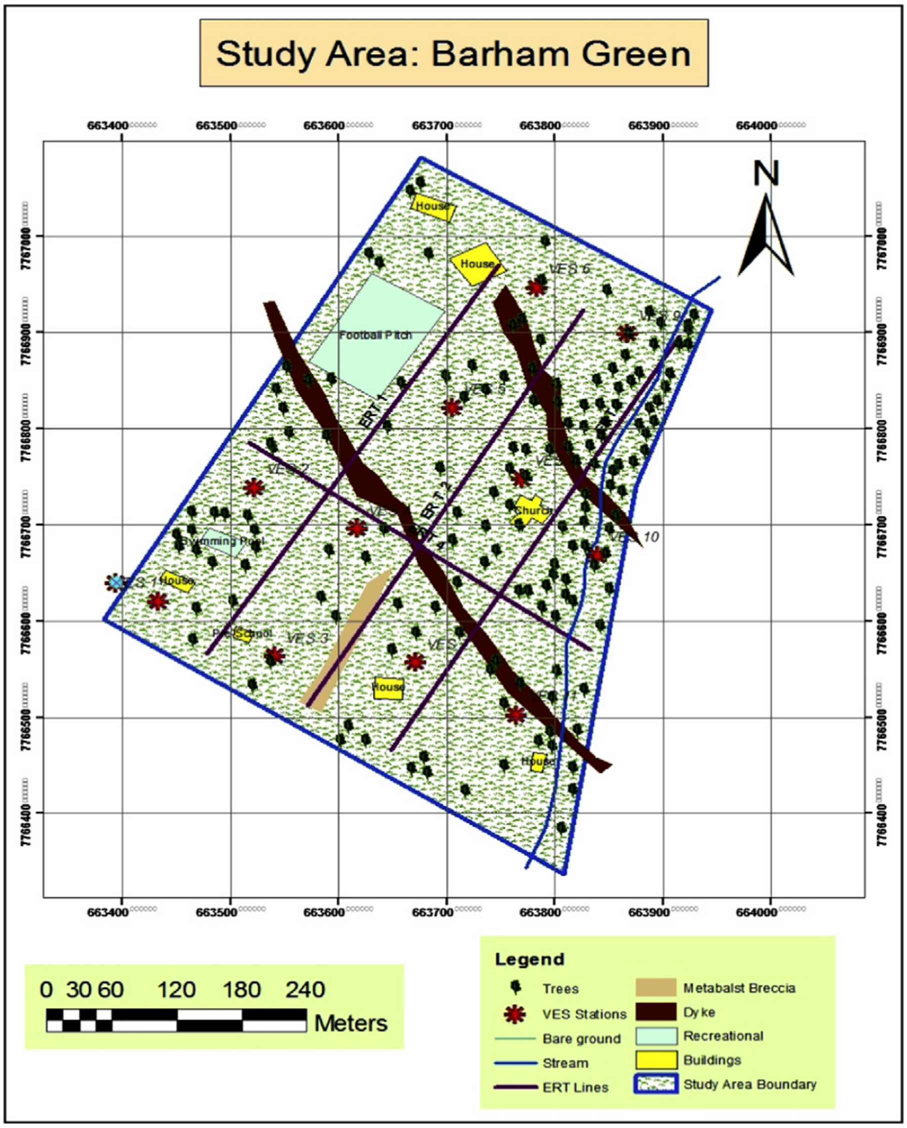

Fig. 3. Location of electrical resistivity tomography and vertical electrical sounding survey lines within the study site.

of the ERT could be due to the presence of deep seated fractures acting as water conduits to the vadose zone. The ERT lines also suggest that the dykes characterizing the study area are deep seated in the eastern side and protrude closer to the shallow subsurface in the western side of the study area, as evidenced by high resistivity values in the ERT results and zones underlying the dykes for Line 2 (Fig. 6).

An additional ERT line, along the E–W direction, in the central region of the study site was surveyed with the aim of locating the zone of the low resistivity anomalies observed in the three profile lines (Fig. 7). A distinct low resistivity section (<50 Ωm) between the 48–60 m mark is found below at depths >7 m. This zone is the most likely a potentially water-bearing fracture that feeds the shallow subsurface of the study site.

4.2. VES results

The apparent resistivity data obtained from VES sites were plotted against half the current electrode spacing (AB/2) using a VES 1.30 freeware (Cooper, 2000) which interprets resistivity sounding curves using curve matching techniques. This involves matching small segments of a field curve with an approximate theoretical curve to determine both the thickness and apparent resistivity of particular layers in a half space. A three layered model consisting of the topsoil, regolith and bedrock was produced from the field data (Figs. 8 and 9). Values of thickness and apparent resistivities (volume average resistivity of a heterogeneous half-space) were varied until the field and theoretical curves had the least possible misfit.

Results from Fig. 8 suggests that the resistivity model whose calculated apparent resistivity best fit the measurements, with a misfit factor of 20 out of 1000, is characterized by a top layer with a thickness of 7.4 m and apparent resistivities of 30 Ωm, a value characteristic of wet soil. The second layer is approximately 34 m thick, has an apparent resistivity of 94 Ωm. The range of apparent resistivity values and thickness of the second layer is interpreted as the weathered overburden saturated with pore water for such, as suggested in Martinelli and Hubert (1985). The third layer has an apparent resistivity of 2620 Ωm and is presumed to be the bedrock. The depth to bedrock is about 41 m, which is deep enough for areas where water is expected to originate from the weathered zone (Ndlovu et al., 2010).

In the second VES survey, a resistivity model with the least possible misfit of 19.5 out of 1000 (1.95%) is characterized by a top

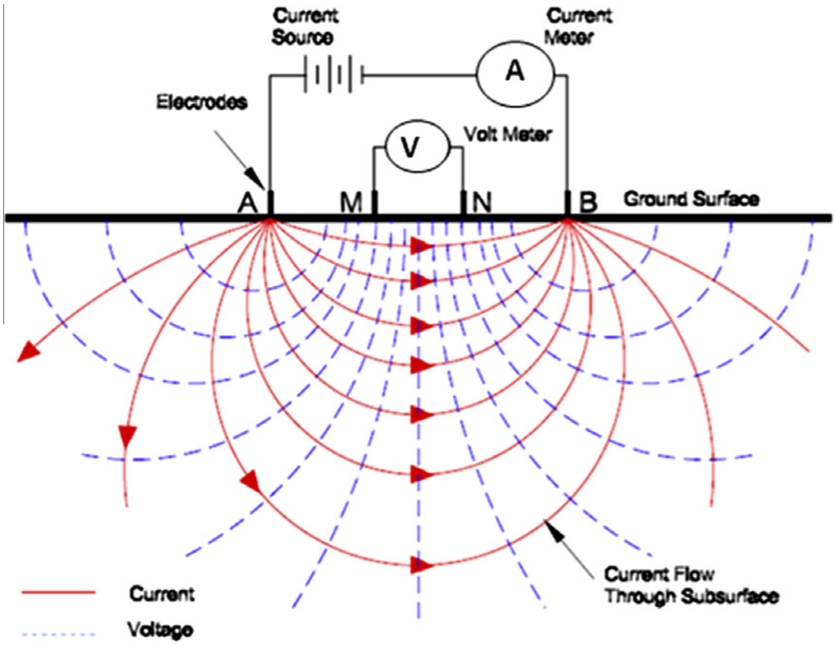

Fig. 4. Illustration of the basic measurements using the method of electrical resistivity (adopted from Marescot et al. (2009)).

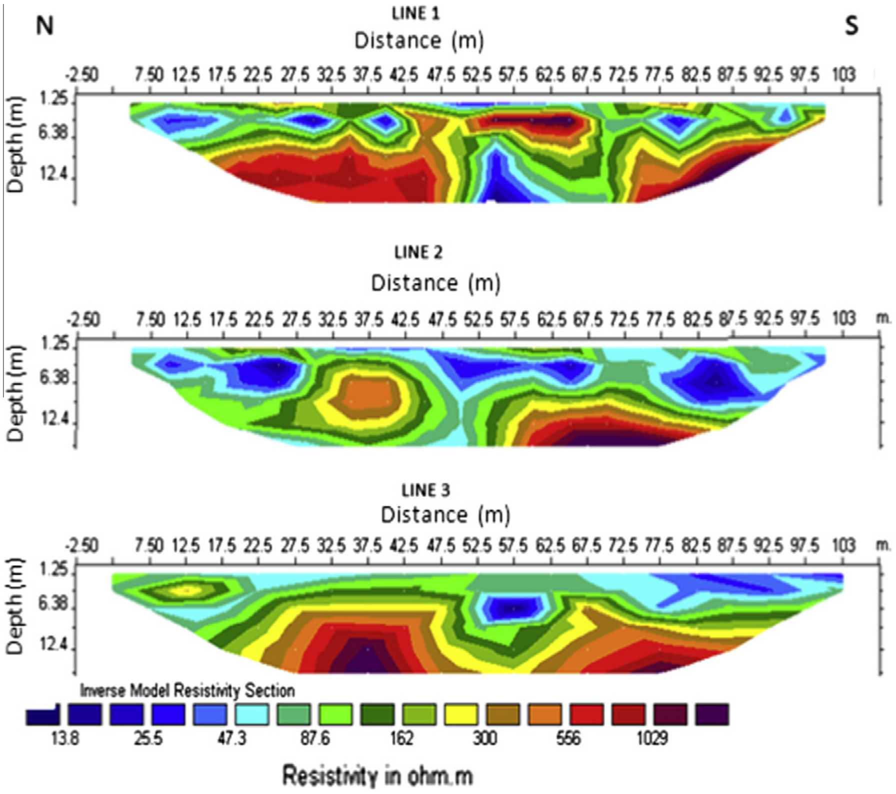

Fig. 5. Inverse model resistivity sections along of the sections along lines 1–3.

layer with a thickness of 7.4 m and apparent resistivities 56 Ωm and a second layer has an apparent resistivity of 130 Ωm with a thickness of approximately 11 m. Martinelli and Hubert (1985) suggested that such thickness of the weathered overburden (i.e., between 10 and 20 m) is associated with a borehole success rate of around 25% and thus the groundwater potential in this particular region may be low.

5. Discussion and conclusions

The objective of this study is to evaluate the water potential and investigate the shallow subsurface moisture distribution of the study area using a combination of ERT and VES. The extent of fracturing proposed by these surveys can be used to indicate a high ground water potential at the study area. In the ERT

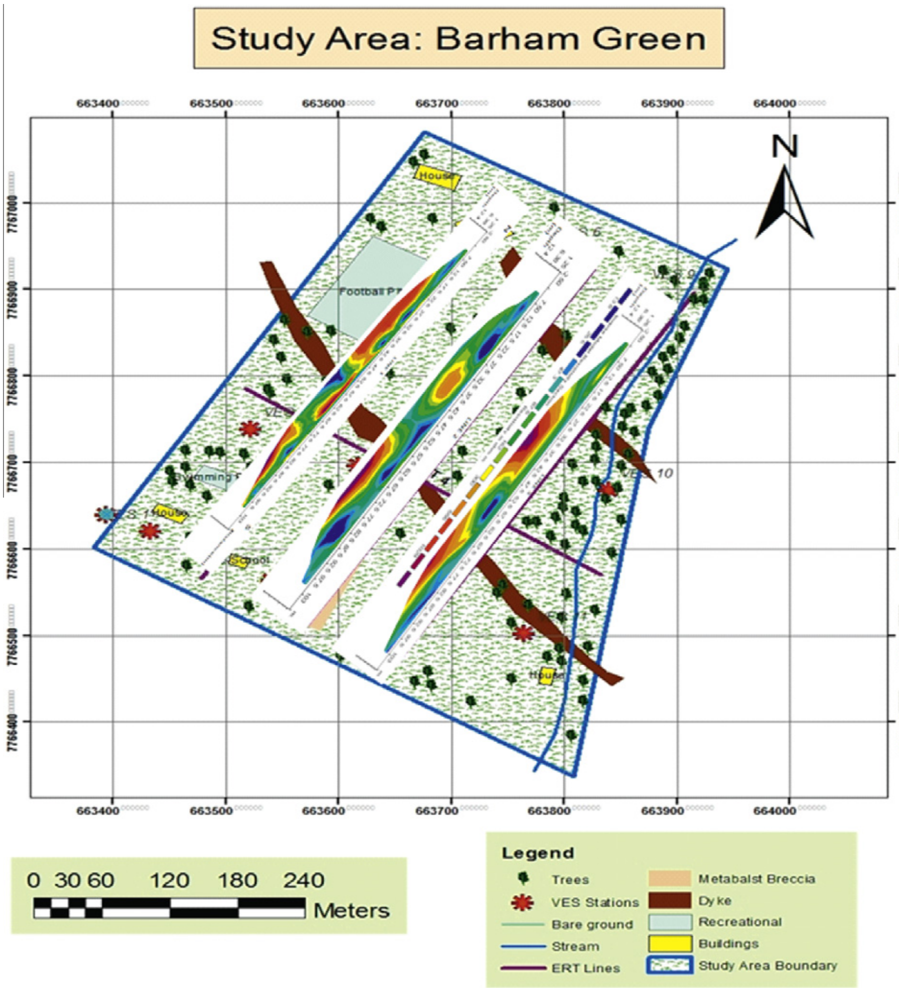

Fig. 6. A cross section of the inverse model resistivity profiles showing the existance of two deep seated dykes protruding toward the surface in the western side of study area.

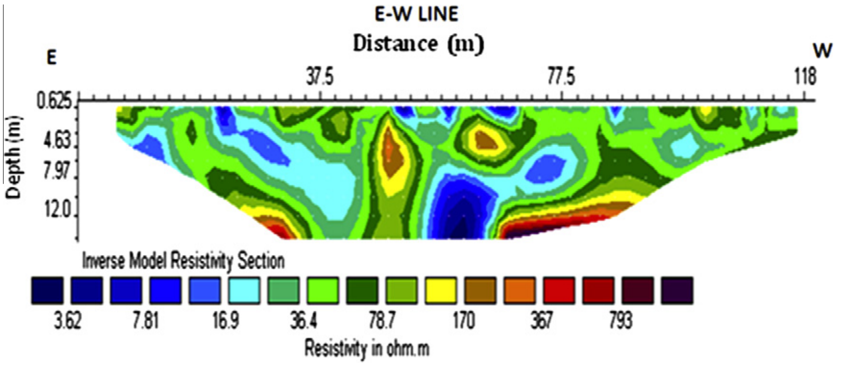

Fig. 7. Inverse model resistivity section along the east–west direction.

surveys, a low resistivity zone along the central region of the study area suggests the possibility of a fracture zone. This was also suggested by Houston and Lewis (1988) from boreholes around the well field where a higher frequency of fractures was found on the upper 20 m of the bedrock, below the regolith interface. The low resistivity region along survey Line 2 may suggest the presence of a fracture zone in this region. This also agrees with earlier studies by Rusinga (2002) who suggested that the geological features of the study area consists of basement formations in which groundwater tends to occur within residual overburden (regolith) and the fractured zone. The presence of fractures, as interpreted from the ERT tomograms, is also consistent with the hydro-geophysical study conducted by Martinelli and Hubert (1985) and Weaver et al. (1992) who suggested that the occurrence of groundwater in the study area is solely controlled by secondary porosity due to presence of weathered

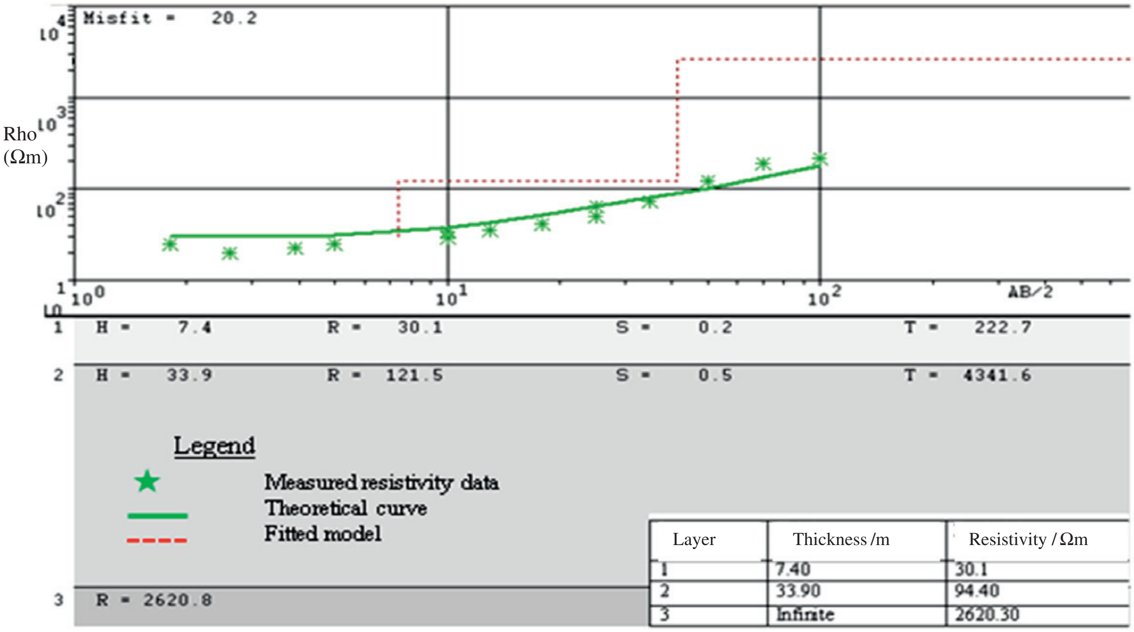

Fig. 8. Vertical electrical sounding model of the low resistivity region in the study area. The table summarizes the layer thicknesses and resistivities.

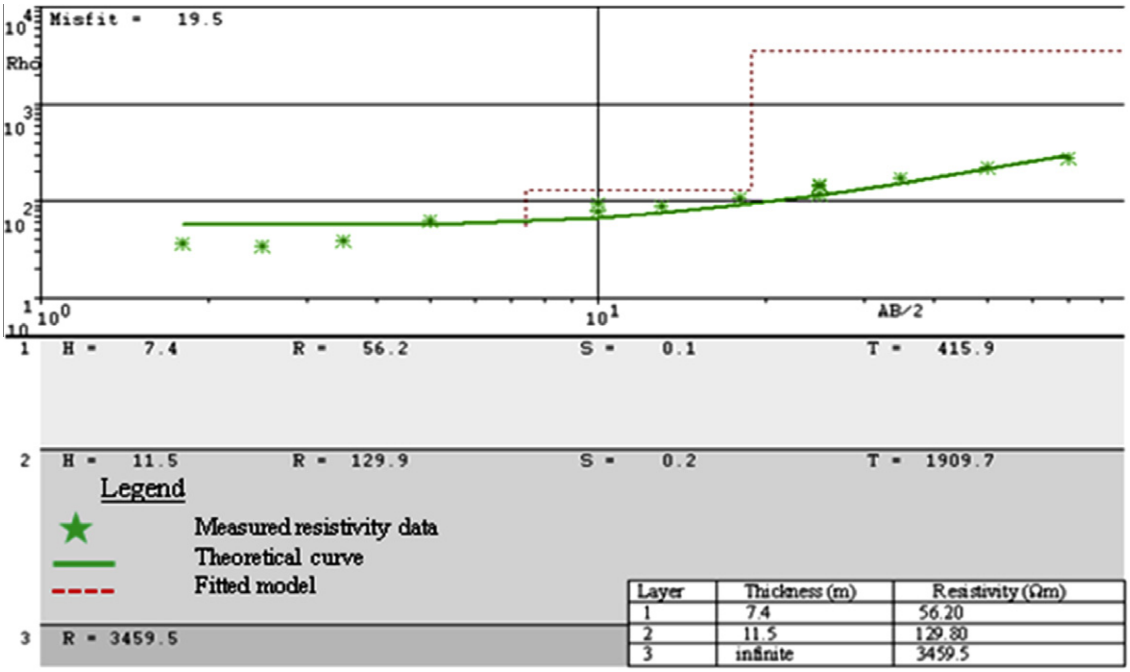

Fig. 9. Vertical electrical sounding model along Line 3 in the north–south direction. The table summarizes the layer thicknesses and resistivities.

fractures along the underlying bed rock. One of the main challenges in the management of the Bulawayo urban aquifer has been the inadequacy of hydrogeological data to reliably model the occurrence of groundwater throughout the well field. These results may be integrated into the technical groundwater management of the well field.

The study demonstrated the efficiency of using electrical resistivity in imaging the subsurface from which subsurface structures and extent of fractures that influence the occurrence of groundwater in basaltic greenstone rocks may be interpreted.

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