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Introducing exploration geophysics to students using Ohm's law: A case study of prospecting for groundwater by Hlangabeza high school students in Nkayi rural district of Zimbabwe

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Abstract

This study sought to explain how a familiar physics topic of Ohm's law of electricity can be used to explore the interior of the earth. The paper gives the theory on the resistivity method of exploration and how it is used for constant separation traversing and vertical electrical sounding. A fieldwork done by physics students from Hlangabeza high school, in Nkayi district, Matebeleland north province, Zimbabwe is given in detail. This involved locating a drilling site for a groundwater borehole. The Schlumberger depth sounding data where interpreted using a computer freeware. This was used to computer a layered earth model using least square technique to match the theoretical apparent resistivity curve as close as possible to the field curve. This provided depth information of the weathered layer above the bedrock at selected site. The overall results suggest that teaching physics can easily be done through putting theory into practice. The fieldworks demonstrated that they prop up the development of expert science behavior in students.

Key words: Aquifer, Electrode, Exploration, Groundwater, Resistivity.

Introduction

In teaching, a worrying prevalent misconception is that giving students access to information means they will learn something. This fallacy seems especially misplaced in relation to the teaching of earth science, as there seems to be an implicit assumption that viewing something in the textbook, is somehow interactive and that creation of knowledge in students' brain is virtually automatic (King and Kennett, 2002). It is sometimes more reasonable to expect meaningful learning when students, do practical or go for fieldworks designed to encourage learning. This is where knowledge generation is involved, rather than simply absorbing a product. This results in a more constructivist approach that can be useful and recommended for students (Etkina, Lawrence and Charney, 1999).

When in 1827 Georg Simon Ohm published, "The galvanic circuit investigated mathematically," little did he know how important this would make to the study of the earth science possible (Gee, 1969). It was Ohm who, through many experiments using wires of various dimensions, voltaic cells and thermocouples came up with the relationship between current and voltage. His law states that, the electric current in a conductor is directly proportional to the potential difference between its ends, other quantities (especially temperature) remaining constant (Johnson, Hewett, Holland and Miller, 2000). That is

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$\Delta V = IR$ where ΔV (volts) is the potential difference between two points in a conductor, I (amperes) is the current flow and R (ohms) is the constant of proportionality called resistance.

For Ohmic materials the resistance of a conducting object is found to be directly proportional to the length, L of the object and inversely proportional to its cross-sectional area A. The constant of proportionality in this case is called resistivity, ρ of the conductor (Tipler, 1982), that is:

$$R = \frac{\rho L}{A}. \qquad (1)$$

This relationship holds for earth materials as well as simple circuits.

and therefore $$\rho = \frac{RA}{L} \qquad (2)$$

Resistivity is measured in ohm-metre (Ωm). The inverse of resistivity $\frac{1}{\rho}$ is called conductivity (σ) and is measured in milliSiemen per metre (mS/m). Resistivity depends on the property of the material and is a geometrically- independent quantity that describes a material's ability to transmit electrical current. It is the quantity investigated using the electrical resistivity surveying method. Mapping this property in the shallow subsurface of the earth provides information on the geological structure and man- made additions of environmental interest. For example residual contaminants from ex-industrial site or the occurrence of groundwater (GW) may change the resistivity of the soils or rocks into which they are emplaced. This is due to electrolytic conduction which occurs in aqueous solutions that contain free ions. The water molecule is polar (it has a permanent electric dipole moment) with a strong electric field which breaks down molecules of dissolved salts into positively and negatively charged ions. The ions in the electrolyte are mobilized by an electric field which causes a current to flow. The resistivity of rocks is strongly influenced by the presence of GW, which act as an electrolyte (Lowrie, 1997). The minerals that form the matrix of a rock are generally poorer conductors than GW, so the resistivity in sediments decreases with the amount of GW it contains. As a result the resistivity survey method is used for GW exploration in alluvium and hard rock formation aquifers. It is also an inexpensive method used to determine depth, thickness and boundary of an aquifer (Lashkaripour, 2003).

High schools physics curricula in Zimbabwe contain little or no earth science related topics. This makes it difficult for pupils to relate the physics they learn to the earth around them. It is recognized that the learning of physics is enhanced by providing context and relevance to learners, and that disadvantaged groups in particular gain from using relevant approaches (King and Kennett, 2002). This article aims to demonstrate ways in which exploration geophysics can be introduced to high school students using Ohm's law. The main purpose is to make the learning experience more interactive and also to provide a more practical learning experience within the high school setup. The teaching of Ohm's law of electricity can be made more relevant to students by setting the physics content in the earth science contexts that pupils can relate to and understand.

The Resistivity Survey Methods

The resistivity survey method involves passing current (I) into the ground by means of two electrodes and then measuring the potential difference (ΔV) between a second pair. From the value of the ΔV, the applied current and the electrode separation, the resistivity can then be calculated. Any subsurface variations in resistivity, alters the distribution of electric potential. The degree to which the potential difference is affected depends on the size, location and resistivity of the material in the subsurface (Telford, 1990). This gives the possibility of obtaining valuable information about the subsurface distribution of materials, from measurement of ΔV made at the surface. The resistivity of some rocks and minerals is an extremely variable property. As an example clays have resistivities of a range (1- 20) Ωm, whilst the granite range is between 3x 10^2 Ωm ^{to} 3x10^6 Ωm (Mussett and Khan, 2000).

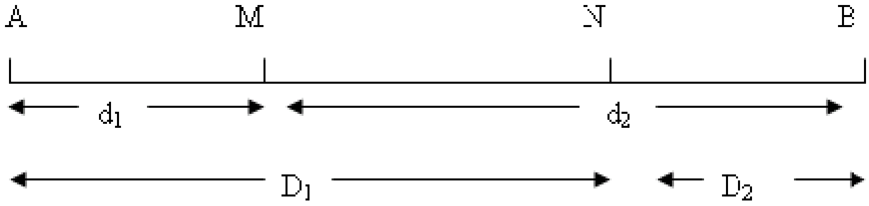

Figure 1: General electrode arrangement for resistivity measurements.

The simplest method of conducting a resistivity survey is to arrange the four electrodes in a straight line on the surface of the ground as shown in Figure 1.

The distances between the different electrodes A and B are current electrodes whilst M and N are potential electrodes. The conventional nomenclature for a four electrode array like the one mentioned is a CPPC, meaning current is passed through the outer two electrodes and potential difference is measured between the inner two (Hobbs, 1999).

The recordings we make in resistivity methods are surface measurements of the potential field distributed due to the current passing through the ground. This is a solution to Poisson's equation, $\nabla^2 V = 0$ where ∇ is a second derivative operator and V is the potential. For the potential, V, at a distance r from the current source I on the surface of the earth (an infinite half space below), the solution is given by

$$V = \frac{I\rho}{2\pi r^2} \tag{3}$$

It can be also demonstrated that potential at points M and N are given by equations (4) and (5) respectively:

$$V_M = \frac{\mathrm{I}\rho}{2\pi}\left(\frac{1}{d_1} - \frac{1}{d_2}\right) \tag{4}$$

and

$$V_N = \frac{\mathrm{I}\rho}{2\pi}\left(\frac{1}{D_1} - \frac{1}{D_2}\right) \tag{5}$$

as a result the potential difference between M and N is given by,

$$\Delta V = \frac{\mathrm{I}\rho}{2\pi}\left[\left(\frac{1}{d_1} - \frac{1}{d_2}\right) - \left(\frac{1}{D_1} - \frac{1}{D_2}\right)\right] \tag{6}$$

By solving equation (6) for resistivity we can determine the resistivity of the subsurface region. Because the earth is neither homogeneous nor isotropic, a measured potential difference gives a resistivity value that is average over the path length the current follows. Hence the resistivity is,

$$\rho = \frac{\Delta V}{2\pi I}\left[\frac{1}{\left(\frac{1}{d_1}-\frac{1}{d_2}\right)-\left(\frac{1}{D_1}-\frac{1}{D_2}\right)}\right] \tag{7}$$

$$\rho = \frac{\Delta V}{\mathrm{I}}\mathrm{G(r)} \tag{8}$$

From equation 8 the term $\frac{\Delta V}{\mathrm{I}}$ is simply the resistance between the points M and N. The problem with using resistance as a measurement is that it depends not only on the material from which the object is made, but also the geometry of the object. If we were to increase the length of the object, the measured resistance would increase. Also, if we were to decrease the diameter of the object, the measured resistance would increase. G(r) is called the geometric factor. It depends on the relative spatial positions of all four electrodes in the survey (Musset and Khan, 2000). If the spacing between adjacent electrodes is a, then geometric factor becomes

$$\left[\frac{1}{2\pi}\left(\frac{1}{a}-\frac{1}{2a}-\frac{1}{2a}+\frac{1}{a}\right)\right]^{-1} = 2\pi a \tag{9}$$

Thus as a result resistivity may be calculated using

$$\rho = 2\pi a R. \tag{10}$$

$$\rho = G(r)R. \tag{11}$$

The resistivity computed using equation (11) is referred to as the apparent resistivity ρ_a. We call it the apparent resistivity for the following reason. If the Earth does not have a constant resistivity (that is if the resistivity varies with depth or horizontally), the resistivity computed by equation (11), will not represent the true resistivity of the Earth. The difference between the apparent and the true resistivity of the medium is not a function of any noise that might be associated with the measurements we are attempting to record. The difference rather comes from the fact that our measurement, in some sense, averages the true resistivities of some region of the earth, yielding an apparent resistivity that may not represent the true resistivity at some specific point within the earth (Telford, 1990). Equation (10) shows that the product of the measured resistance and the electrode spacing is a constant, related to the resistivity.

Current Flow in the Ground

Geophysical resistivity techniques are based on the response of the earth to the flow of electrical current. Figure 2 shows schematically how current flows in the ground. The diagram shows a vertical cross section of current flow in the ground between two current electrodes. If the resistivity of the ground is constant, the shape of the current flow pattern will be the same for all electrode spacing, just the scale will change. Most of the current flows at a relatively shallow depth in the ground and about half the total current flows in the space interval between the ground level and the bold lines. If the electrode spacing is doubled, the cross-sectional area through which current flows will increase fourfold, while the length of each current path will double. Equation (1) shows that the resistance will halve. Consequently, for the same configuration of electrodes, the product of resistance and electrode spacing will be a constant (Lowrie, 1997).

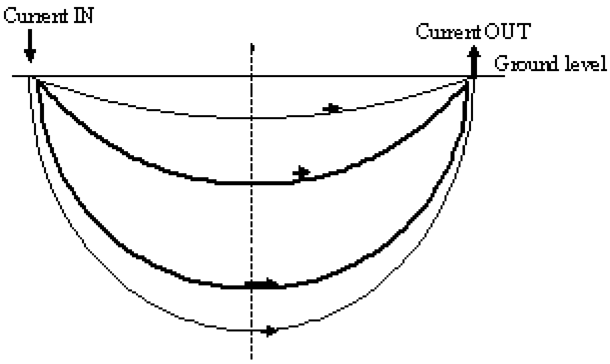

Figure 2: A vertical cross section of current flow lines in the earth

They are several alternative electrodes configurations in use, some being suited to particular targets. The collinear array used in this study is the Wenner (constant separation traversing) and Schlumberger (depth sounding) arrays.

The constant separation traversing (C.S.T) Array

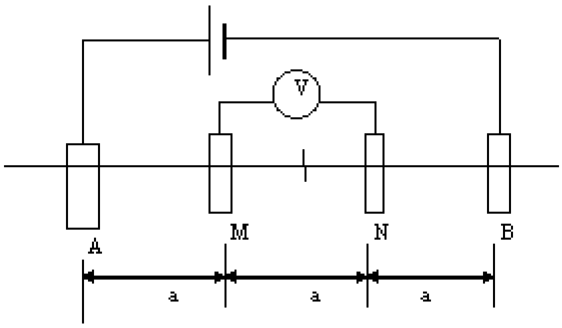

Figure 3: The Wenner electrode Array used for constant separation traversing.

Electrical profiling, known as constant separation traversing, uses collinear arrays to determine lateral resistivity in the shallow subsurface at a more or less fixed depth of investigation. The current and potential electrodes are moved along a profile with constant spacing between electrodes. The Wenner configuration shown in Figure 3 is the best adapted for lateral line profiling to obtain precise location of the resistivity anomalies (Batte, Muwanga and Sigrist, 2008). The separation of the current electrodes is chosen so that the current flow is maximized in depths where lateral resistivity contrasts are expected (Lowrie, 1997). The Wenner generally provides for high signal – to – noise ratios, good resolution of horizontal layers, and good depth sensitivity. Conversely, the Wenner array is not good at determining the lateral location of deep inhomogeneities (Ward, 1990). Results from profiles may be compiled into a resistivity map of the area under investigation. The survey method reveals the horizontal variation in resistivity within an area at a particular depth. It is best suited to locating steeply dipping contacts between rocks with strong resistivity contrast, faults or dyke contrast / lithological contacts along which GW may accumulate.

Vertical electric sounding Array

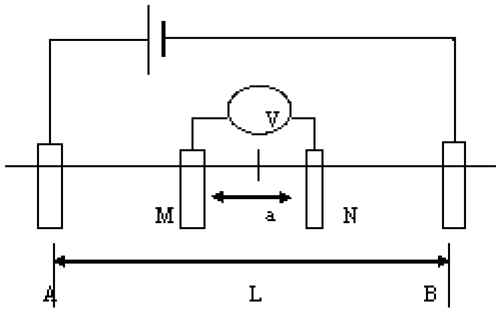

Figure 4: The Schlumberger electrode array used for depth probing.

The vertical electrical sounding (VES) is used to observe the variation of resistivity with depth. The Schlumberger array of electrodes provides for high signal- to- noise ratios, good resolution of horizontal layers, and good depth sensitivity (Ward, 1990). The technique is best adapted to determining depth and resistivity for flat- lying layered rock structures, such as sedimentary beds. The mid point to the array is kept fixed while the distance between the current electrodes is progressively increased. This causes the current lines to penetrate to greater depths. The Schlumberger configuration shown on figure 4 is commonly used for VES investigations; this method is mostly carried out to solve problems of GW in alluvium, caustic and other hard rock formation aquifers as an inexpensive and useful method. It is used in groundwater to determine depth, thickness and boundaries of the aquifer (Lashkaripour, 2003). In practice, apparent resistivity calculated for a particular model is compared with already measured and approved apparent resistivity and the model parameters adjusted until acceptable agreement is interpreted geologically, environmentally or in engineering context.

Methods and Materials

The study was carried at a high school in rural Nkayi district. A growth point in Matabeleland north Zimbabwe and is located about 100 km west of Kwekwe and 168 km north-east of Bulawayo.

Firstly a hydrogeological reconnaissance of the area to determine where the geophysical measurements were to be carried out was done. As a second step, a group of advanced level students in physics carried out the geophysical exploration. This was done to locate a drilling site for a GW borehole. The electrical resistivity equipment comprising of Abem terrameter SAS 3000C transmitter/receiver system was used on this survey project. The equipment was borrowed from the local district development fund, water division. SAS stands for Signal Averaging System, a method whereby consecutive readings are taken and the results averaged continuously. Stainless steel electrodes were used. These are strong and resistant to corrosion (Telford, 1990). A Wenner fixed electrode separation array was chosen for profiling. Four students armed with hammers, moved and manned the current and potential electrodes. The hammer was used to drive the electrodes into the ground. A fifth student took readings from the terrameter. The students moved horizontally the whole array of current and potential electrodes. The electrode separation distance was selected to allow an investigation depth of 20 m. One electrical resistivity line profile 1000 m long was performed in the study area.

The Schlumberger array was used for VES. The potential electrodes in this array are much closer together, though still placed symmetrically about the centre of the array. The current electrodes were moved progressively and symmetrically apart after every reading. Moving the current electrodes has two advantages: there are fewer electrodes to move, and with the potential electrodes fixed the readings are less affected by any lateral variations that may exist (Musset and Khan, 2000). However, at some point the expansion of the current electrodes causes the value of the potential difference to be too small to measure precisely. The students manning the potential electrodes then moved them much further apart to overcome the 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 allowed the increase in depth of investigation. We took an average of four hours to complete the whole survey.

Results and Discussions

An implicit assumption for interpreting such measurements is that the subsurface is approximately horizontally layered (sensibly one dimensional).The apparent resistivity data obtained from the line profile measurements were plotted against the length of the profile. Figure 5 shows that the apparent resistivity of the area is on average low but then falls even lower to values of 54Ωm at a distance of between 350 m to 600 m from the origin. This is presumed to be a contact zone which may act as suitable aquifer. This site was chosen for VES to probe the depth of the aquifer.

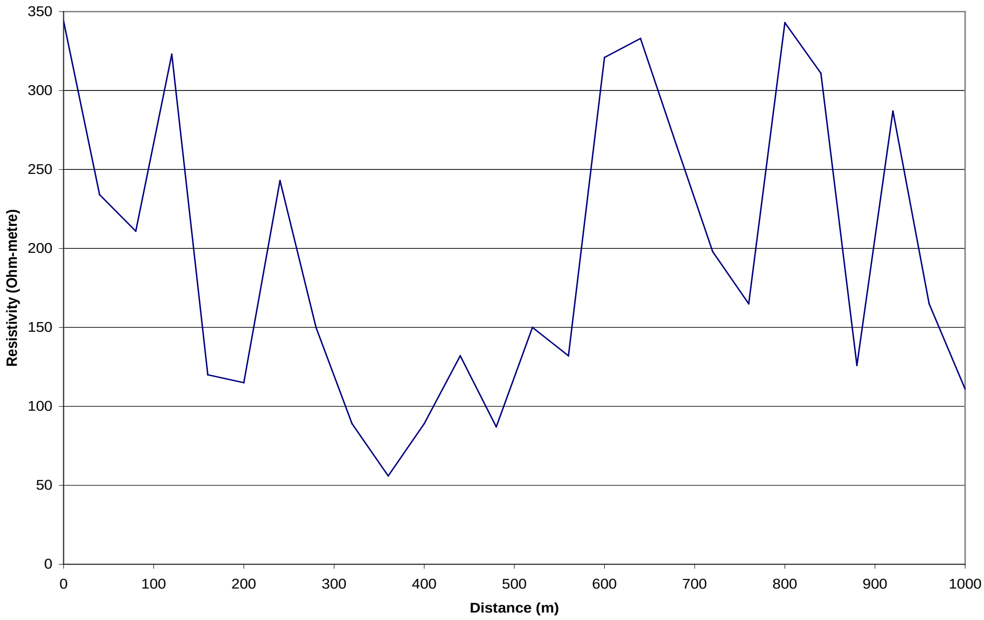

Figure 5: A plot of constant separation traversing apparent resistivity data against the length of the profile.

The apparent resistivity data obtained from VES site where plotted against half the current electrode spacing using a VES 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 layers of the subsurface are shown as in Figure 6. These layers consist of the topsoil, regolith and bedrock. Depth and thickness of subsurface layers were also identified.

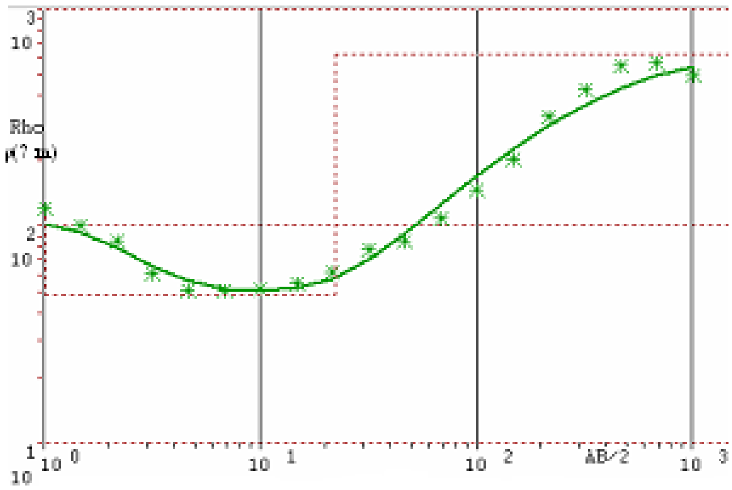

Figure 6: Observed and computed resistivity Schlumberger depth sounding curve obtained.

Figure 6 shows results of VES over the borehole site at the school garden. A resistivity model, whose calculated apparent resistivity fit the measurement well, shows a weathered layer of a 74.8 m thick conducting band of apparent resistivity of 59.00Ωm. This is interpreted as the weathered layer saturated with pore water. Above this band is 3.06 m layer of topsoil of apparent 100.60Ωm and the bedrock forms the base. A borehole was drilled at this site to a depth of 60 m. It struck water at various levels with a static water level at 22 m below ground level.

Conclusions

The development of science curricula across the world requires science teaching to be set in relevant contexts and the earth provides ideal context for this purpose. Students from Hlangabeza high school were highly motivated by the application of Ohm's law in the method used to finding GW. It became clear that Ohm's is applicable in solving community problems not only measuring resistance of pieces of wires in the laboratory.

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