Inexpensive Resistivity Instruments for Groundwater Exploration: Experiences of African National Geophysical Teams

Type: Long Paper

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Abstract/Summary
Geophysical technology is an important component in exploration for groundwater resources and siting of wells. Electrical resistivity methods have often been used with great success by hydrogeologists to determine depth to aquifers and to improve the probability of completing a successful water well. However, the excellent resistivity instruments now commercially available cost many thousands of dollars and so are unavailable to low-budget well drillers in the majority world. We have developed a simple resistivity instrument that can be assembled for less than $800. Our free software on a laptop aids in interpretation of the resistivity data. The Water4 organization has used this method in siting over 150 wells. Accurate records exist for 64 of these wells indicating that the predictions from the inexpensive resistivity device were correct 86% of the time. Nine (9) teams are currently working in six (6) African countries with varying geophysical settings of mountain ranges, rift valleys, plains, and sedimentary basins.

Introduction
Groundwater is an important source of safe water for rural communities. Where springs are not prevalent, wells provide the usual means of accessing this resource. However, it is expensive and time consuming to drill or dig a well and the desired outcome of a successful well may not be achieved. Choosing a well drilling site is therefore very important. Low-budget drillers often consider offset distances from surface sources of contamination as the only guideline for siting a well. In Tanzania well drillers using a small LS-100 mud rotary drill rig drilled 50 wells in one year but 18 of those wells did not produce water because the decomposed granite aquifer overlying hard granite bedrock was either too shallow and therefore above the water table or too deep, beyond the depth limit of the drill rig (Clark et al., 2011). These dry boreholes could have been avoided if accurate subsurface properties had been known. Geophysical methods are a common means of interrogating the subsurface and have been shown to be highly effective. In one study in Zimbabwe using a data set of 370 wells the success rate increased from 50% to 85% when commercially available geophysical resistivity instruments were used for borehole siting (R. D. Barker, et al. 1992). Other authors have similarly stressed the usefulness of geophysical methods to site water wells (MacDonald et al., 2005, Kirsch, 2006, Rubin and Hubbard, 2006, Clark et al, 2011, Clark et al. 2016). In fact some national policies now require that a geophysical survey be performed and reported at each well site. Despite this general appreciation for geophysical methods the use of these instruments has been limited due to their considerable expense. The purpose of this paper is to describe the successful use of a very inexpensive resistivity instrument by African geophysical teams supporting Water4 water well drilling. The instrument cost of $800 is well within the budget of any well driller.
The Inexpensive Resistivity Instrument:

Figure 1: Illustration of current lines (solid) and voltage contours (dashed). Current is supplied through electrodes A and B. Voltage is measured at electrodes M and N. The distance between electrodes A and M, between M and N, and between N and B is equal to “a”, the a-spacing. For vertical electrical sounding “a” increases allowing current to penetrate deeper. For horizontal electrical profiling the electrode a-spacing is maintained at a constant value while all four electrodes are moved laterally.

Figure 2: Circuit schematic of the inexpensive resistivity instrument. Total cost, excluding the inverter and car battery, is under $25. DPDT is a double pole double throw switch.

Context, aims and activities undertaken

The Inexpensive Resistivity Instrument:

Figure 1 illustrates the relatively simple function of any resistivity instrument. A current generated by the device enters the ground through two electrodes (A,B). This current, $I$, is measured by an ammeter. While the current flows the voltage drop, $V$, between two other electrodes (M, N) is also measured. As the spacing between the electrodes, $a$, increases the current penetrates deeper into the earth. The apparent resistivity is defined as $\rho_a = \frac{2\pi a V}{I}$. If the earth is homogeneous then $\rho_a$ remains constant as the a-spacing increases. But if the resistivity changes at depth, either through lithology change or water saturation, then this change is reflected in a change in apparent resistivity. There are two complicating factors however. If the current flows for more than a few seconds in one direction an induced charge builds up at the electrodes which affects the current magnitude.

Also the earth has a natural voltage, the spontaneous potential, which affects the measured voltage. Both of these negative influences can be avoided if the current reverses about once every second. The reversing current eliminates charge buildup and if an even number of reversals occur (e.g. 4 of them) the average voltage value eliminates the spontaneous potential effect. This method is common to all resistivity instruments.

Therefore in principle the instrument is very simple (Figure 2) and consists of an inverter to increase the voltage from a 12 V battery to 220 volts AC; a bridge rectifier and capacitor to produce a high DC voltage; two reversing switches to manually reverse the current and the voltage reading; and two digital multimeters to measure current and voltage. The excellent commercial resistivity instruments (e.g. ABEM Terrameter, Sting) automatically reverse the current and measure the current and voltage with no operator input. The value of apparent resistivity is then displayed, requiring no calculations. These instruments are also capable of very high voltage generation and therefore deeper current penetration. Our opinion is that the added convenience of operation and increased knowledge of deeper earth structures is not necessary for well siting under most rural situations where a hand pump is to be installed and a low-cost drilling method is used. If an operator is willing to manually switch the current four times, read the multimeters, average the results, and do the simple calculation for $\rho_a$ then adequate estimates of apparent resistivity are possible. Figure 3 shows the excellent agreement between the apparent resistivity data of our
simple instrument to a Sting commercial resistivity instrument at a site in Nigeria. Although the maximum depth achieved with our instrument is somewhat dependent upon the actual resistivities of the earth layers, our experience has been that depths less than 35 m can be measured reliably. Under most rural conditions this depth is not a limitation as manual drillers also prefer drilling within this depth range. The majority of Water4 wells in sub-Saharan Africa have depths between 18 and 25 m.

Although the measurement of apparent resistivity does not require a laptop computer, the interpretation of a subsurface earth model (i.e. layer thickness and associated resistivity) is most easily determined using software to fit the data with the most likely earth resistivity model. Again excellent commercial software is available that can produce 1-, 2- and even 3-dimensional reconstructions of the subsurface. But we have developed free software for use on a Windows based laptop predicting one-dimensional vertical earth structure usually called vertical electrical sounding (VES). The software also calculates apparent resistivity from the raw data and plots the data (http://cs.wheaton.edu/~jclark). Most of the instrument cost is the wire cable connected to the electrodes. The inverter can also contribute significantly to the total expense. The digital multimeters do not have to be of high quality and the electrodes are 10-inch lag screws or nail spikes. The “control” box is the least expensive of all items. The entire system can be assembled in a few hours with a total cost less than $200. But our experience is that continual use under harsh African conditions requires a more robust unit that costs $800 (Figure 4). A low-end PC laptop computer can often be purchased for under $300. In addition to its use in resistivity data interpretation, the laptop can also be used for writing reports, calculating spreadsheets, communicating with email, and making presentations. Free open source geographic information system (GIS) software such as QGIS (2014) or SAGA (2015) can also be used on the laptop to record and display exact locations of wells and associated resistivity and well log data.

**Context and Activities:**
Water4 is an organization committed to sustainable, low-cost solutions through empowerment and capacity building of the private WaSH Enterprises. The organization requires local community involvement as an important component of sustainability and only works through existing local organizations, businesses, and non-profits. In Africa, Water4 currently partners with organizations in the following countries: Togo, Cameroon, DR Congo, Kenya, Uganda, Rwanda, Malawi, Zambia, Ghana, Ethiopia, Niger, Mali, and

![Figure 3: Comparison of apparent resistivity measurement between the commercial Sting instrument and our inexpensive device. There is excellent agreement in this vertical electrical survey.](image3)

![Figure 4: The Water4 resistivity toolkit consisting of control box, wire cable, spike electrodes, multimeters, measuring tapes, inverter and repair supplies.](image4)
Sierra Leone. Table 1 lists all of the country partners and the number of wells drilled to date. An ambitious endeavor is underway to train these nationally led drilling teams to sustainably provide wells in 19 African nations. This involves reducing failure rates, reducing the price of boreholes, and generating local income for each team’s continued operations through monetized and reticulating water systems.

<table>
<thead>
<tr>
<th>Country, region</th>
<th>Partner</th>
<th>Year Started</th>
<th>Number of wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Togo</td>
<td>Eau Pour Le Togo</td>
<td>2010</td>
<td>330</td>
</tr>
<tr>
<td>Zambia</td>
<td>Water Access Zambia</td>
<td>2009</td>
<td>338</td>
</tr>
<tr>
<td>Cameroon</td>
<td>Okla Foundation</td>
<td>2016</td>
<td>(In Training)</td>
</tr>
<tr>
<td>DRC, Bunia</td>
<td>Shalom University Bunia</td>
<td>2014</td>
<td>42</td>
</tr>
<tr>
<td>DRC, Mbandaka</td>
<td>Disciples for Water</td>
<td>2014</td>
<td>23</td>
</tr>
<tr>
<td>DRC, Katanga</td>
<td>Water Works Katanga</td>
<td>2014</td>
<td>28</td>
</tr>
<tr>
<td>Kenya</td>
<td>Tak Water</td>
<td>2014</td>
<td>9</td>
</tr>
<tr>
<td>Uganda</td>
<td>Young Men Drillers</td>
<td>2013</td>
<td>104</td>
</tr>
<tr>
<td>Rwanda</td>
<td>Water Access Rwanda</td>
<td>2014</td>
<td>27</td>
</tr>
<tr>
<td>Malawi (Blantyre)</td>
<td>Water Zone</td>
<td>2015</td>
<td>21</td>
</tr>
<tr>
<td>Malawi (Lilongwe)</td>
<td>MOMS Drillers</td>
<td>2013</td>
<td>55</td>
</tr>
<tr>
<td>Ghana</td>
<td>Access Development Ghana and World Vision</td>
<td>2012</td>
<td>90</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Access Development Ethiopia and World Vision</td>
<td>2014</td>
<td>200</td>
</tr>
<tr>
<td>Niger</td>
<td>Access Development Niger</td>
<td>2015</td>
<td>60</td>
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<tr>
<td>Sierra Leone</td>
<td>Willamette International</td>
<td>2011</td>
<td>175</td>
</tr>
<tr>
<td>Mali</td>
<td>World Vision Mali</td>
<td>2013</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 1: Water4 Country Partners and Total of Manually Drilled Wells as of May 1, 2016

In support of this drilling effort, Water4 has trained dozens of operators to use the inexpensive resistivity instrument to site wells. These teams determine the subsurface earth structure directly below a potential well location with the VES method outlined above. The VES teams work directly with the drilling teams, providing site selection based on their readings, local knowledge and the known capability of the tools and equipment the drillers possess. Each team performs at least two VES surveys at a proposed well location. The VES teams are part of a strong network that capitalizes on messaging apps to communicate among themselves and they improve their interpretive and site selection skills by sharing experiences and data from the different hydrogeology Water4 partners in other regions of Africa.

**Main results and lessons learnt**

Vertical electrical sounding methods have been used by Water4 teams to site more than 150 rural wells in Africa since 2014 and, in addition, have ruled out difficult or improbable drilling locations that would have wasted a drilling team’s time and resources. Although the collective results from all of the teams are in the process of being completely assembled, all indications are that the method is highly effective in guiding well siting. VES records are now available from 64 wells drilled since 2015 from Tanzania, Kenya, Rwanda and Uganda. Results in Table 2 indicate that VES correctly predicted the outcome of 55 of these wells (86% accuracy). Of the sited wells, the two that were dry were due to the lack of texture clarity from resistivity-based readings failing to predict low permeability layers in the aquifer. The method is most reliable in areas where water is situated on top of a sizable impermeable structure such as compact clay or rock within 30 m from the surface. Table 2 shows that if the VES indicates a location is suitable for a well there is a high probability (96%) that the well will be successful. If the VES indicates a well site is not suitable there is still a 41% chance that a successful well will result.

Of 64 wells the predicted outcome was accurate for 55 of them (86% accurate). The Chi-square value of 24.4 with 1 degree of freedom (significance level less than 0.001%) indicates it is highly unlikely that the results in the table are random.
Stratigraphic resolution decreases as depth increases which can often mask significant permeable structures surrounded by less favorable lithology. In rapidly varying soil this becomes problematic until a baseline understanding can be created from exploratory drilling. For example VES signatures from dry sand can be misinterpreted as bedrock. The most problematic structure for VES interpretations is saturated sedimentary rock. These structures may have high weathering in places but we are unable to predict this because the apparent resistivity between the saturated sedimentary rock and decomposed layers are poorly expressed in the data. The same is true for saturated clay layers that might contain permeable water-bearing zones such as sand or gravel. If there is not a clear resistivity differential exploratory drilling will be needed. Water4 is experimenting with low-cost seismic technology to complement VES readings with additional seismic velocity data. Despite these difficulties the majority of the wells sited with VES provided adequate supply for the installed hand pumps. In comparison to drilling a dry well, the cost of the instrument is small. If it even prevents drilling one unsuccessful borehole, then the cost of the instrument is repaid.

The time required to perform a VES survey, interpret the data and consult the global team is under 3 hours whereas a well takes several days to complete. Often the VES teams will assemble and use regional survey notes, latrine digger accounts and surface observations to aid in interpretation of the VES data. Many countries are now requiring that resistivity methods be used and reported to government officials before drilling a well. Of countries where Water4 is working Kenya, Uganda, Rwanda and Sierra Leone require a VES survey before drilling and our inexpensive instrument satisfies this drilling requirement.

**Examples and Applications: More Accessible Wells**

In Rwanda, since starting VES surveys in May of 2015, the local social enterprise Water Access Rwanda was able to site 14 successful boreholes and locate more than 20 sites where future borehole drilling can be conducted. Before these surveys, drillers only attempted water wells in the valley despite the fact that most settlements are located in the high mountains in Rwanda. Since starting a resistivity team, Water Access Rwanda has been able to site 4 boreholes at altitudes of 1400-1600 m providing water wells at locations which would have not been considered previously by drillers. An example of the data showing the relationship of apparent resistivity to a-spacing for Ngambi in the district of Gakenke is in Figure 5. Here residents no longer have to walk down the mountain to access water because it is now readily available close to their houses.

![Resistivity Data compared to Best Prediction](image)

**Table 2: Accuracy of VES predictions**

<table>
<thead>
<tr>
<th>VES</th>
<th>Successful</th>
<th>Unsuccessful</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>45 (Correct Prediction)</td>
<td>2 (False Positive)</td>
</tr>
<tr>
<td>Negative</td>
<td>7 (False Negative)</td>
<td>10 (Correct Prediction)</td>
</tr>
</tbody>
</table>

*Figure 5: The resistivity VES data for Ngambi where a shallow aquifer 3 m deep was found near the village on top of the mountain. The yield of the well has remained constant at about 35 liters/min, satisfying the needs of the 30 families who share the well.*
Examples and Applications: Avoiding Difficult Drilling Sites

Furthermore, the drillers are advised, through VES, of areas of lower apparent resistivity to drill in. Areas containing hard soil increases drilling team expenses from broken parts, however VES interpretations guide drillers to avoid such areas. For example, a VES team conducted surveys in an area with rolling hills, subject to granite outcrops and hard rocks and advised the drilling team where to drill (Figure 6).

Examples and Applications: Reduced Drilling Expense

Figure 6 (a) This site was avoided due to the high resistivity, saving drilling expense of approximately $3,000 (what it would have cost to drill through such rocks).

Figure 6 (b) This site was successfully drilled at 10 m and still provides clean water to the community.

Figure 7: Though the stones in this area can be discouraging, our VES team was able to determine that the layer was only 1 m thick so this Pygmy community in rural Rwanda now has water.
In Bunia, DR Congo, the local drilling team, Shalom Drillers provides wells for the residents and especially for the recently freed Pygmy population living deep in the rainforest (Figure 7). A well drilling team must travel more than 100 km over bad roads, often walking long distances up steep hills and crossing poorly constructed bridges. Traveling such a long distance and spending so many resources is wasteful and discouraging for drillers if the result is a dry hole. Now the drillers can send a recently trained VES team ahead to not only find sites with an aquifer but also to warn drillers of hard layers of granite occurring close to aquifers. Figure 8 illustrates several examples of VES taken in the same area.

Example and Applications: Dissemination and Expertise
These resistivity teams are spreading throughout Africa with teams training other teams to use the equipment. Now Rwanda, DR Congo and Togo each have two resistivity teams, and Uganda, Kenya, and Tanzania each have one team. These teams become very proficient in interpreting the raw resistivity data in their respective regions. Their expertise is multiplying through strategies to keep the teams in communication with one another (through WhatsApp groups) and regional coordination assured by French and English speaking coordinators. Training workshops and conferences are multinational allowing teams of VES surveyors to share insights about the use of the equipment and their own experiences and best-practice field methods.

Discussion:
Instrument improvements and additional inexpensive geophysical methods are now being investigated in the field and the laboratory. For example it is possible to use the resistivity instrument to make a horizontal electrical profile to determine lateral changes in lithology. For this type of survey the electrodes are fixed at a constant a-spacing, characteristic of the minimum depth of bedrock for a well in the region, and then moved laterally to record horizontal estimates of apparent resistivity. If this analysis indicates that an adequate aquifer depth is found then a vertical electrical sounding follows to verify the site as a good prospect for a successful well. To improve subsurface interpretation it is possible to use seismic refraction and induced polarization methods which provide additional lithologic properties helpful in untangling ambiguities in the VES data. Inexpensive seismic refraction methods (Clark et al., 2011; 2016) yield seismic wave velocities of rock layers. The laptop sound card and a geophone are the main components of.
this inexpensive instrument. The induced polarization method is similar to resistivity methods except readings of voltage are obtained after the current is turned off. The subsequent gradual decay in voltage is then tracked through time by rapidly recording many voltages. Results yield rock properties that are related to the electrical capacitance of subsurface layers. To take these readings it is necessary to incorporate an inexpensive computer (Arduino – about $25) into the existing resistivity instrument. This computer controls the current reversals and also records 50 voltage and current readings each second so that apparent resistivity and induced polarization are determined simultaneously. The instrument is functioning now and is well within the $250 design goal, but further improvement is necessary to insure it will operate reliably under field conditions (Clark et al., 2016).

Conclusions and Recommendations
It is well documented that geophysical instruments can greatly improve the success rate of drilling water wells in Africa. Our work indicates that even a very simple and inexpensive resistivity instrument that costs less than $800, though limited in operational ease and depth of penetration (less than 35 m), is adequate for siting most rural wells that are hand-dug or manually drilled. African nationals can operate the instruments extremely well and are proficient in interpreting the data to site wells. The expertise these teams are acquiring through extensive field work is helping other teams to form and to be more effective. If even one dry well is avoided through use of the resistivity instrument, the cost of the instrument is repaid. Our desire is that others will continue to improve these simple instruments and that they will help alleviate water stress in rural communities across Africa by providing safe water sources near communities through knowledge of underground layers and aquifer depth.

Acknowledgements
We thank Randy Jones and Ray McKee for their introduction to Water4 of the Wheaton College developed technology and software. They have undertaken hardware fabrication and improvement of the VES equipment and continue to supply funds to provide instruments, training, and active support for the resistivity teams in Sub Saharan Africa. They have been essential in the dissemination of the equipment and in support of the teams. We also thank the team of 4 VES leaders working with Water4 to monitor, evaluate and improve the water4 teams of operators; namely Olive Mukesharugo, Justine Olweny, David Afaya and Roderick Amula. We wish to thank Wheaton College for sabbatical leave support, the Wheaton College Alumni Association for support both in the development of the resistivity devices and for funding field work as the instruments were developed and refined, and the Wheaton College Global and Experiential Learning center for conference support.

References


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