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## Geophysical Investigations of a Rural Water Point Installation Program in Nampula Province, Mozambique

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### SUMMARY

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There are many projects in Mozambique for poverty reduction. One of these projects is funded by Millennium Challenge Account (MCA) and is aimed to install a total of 600 rural water points in the provinces of Nampula and Cabo Delgado. Each water point consists of a drilled well, a water pump and a communal washing basin.

Vertical Electrical Sounding (VES) was used for assessing the suitability of the drill sites but despite this many boreholes have come out with an insufficient yield and the failure rates in certain areas are as high as 50 %. Continuous Vertical Electrical Sounding (CVES), also known as Electrical Resistivity Tomography (ERT), was carried out in an attempt to explain the high failure rate. In total 11 sites were investigated, including seven boreholes with sufficient yield and five boreholes with insufficient yield. A perpendicular cross with two 400m survey lines were made over 7 boreholes and single 400m survey lines were made over 5 boreholes.

Due to lateral variation the geology in study area is best described in 3D therefore ERT appears to be a suitable method for groundwater exploration and could probably lower the failure rate.

## **Introduction**

Like other developing countries in sub-Saharan Africa, Mozambique is facing major challenges in water infrastructure. To address this issue the government of Mozambique was given a large five year grant by a U.S foreign aid agency (Design Report 1, 2010). Starting in September 2008 it has the overall objective of poverty reduction through economic growth. One of the key projects within the grant is to increase access to safe drinking water and sanitation and in order to do so a Rural Water Point Installation Program was started. A total of 600 rural water points each consisting of a well, a water pump and a communal washing basin, was to be installed in the province of Nampula and Cabo Delgado.

The survey method chosen was vertical electrical sounding (VES), but this method gives point information and the lateral variation is not accounted for. In a weathered and fractured zone this may give misleading results and could be a reason for high rate of unsuccessful boreholes. Therefore 2D Electrical Resistivity Tomography (ERT), also known as Continuous Vertical Electrical Sounding (CVES), was tested aiming to assess the lateral variation of the geology.

The well drilling reports were used as a base for interpretation of the results.

## **Hydrogeological Setting**

Nampula Province is located in the Nampula complex composed by granites and migmatite gneiss (Lächelt, 2004). These rocks have low porosity and hydraulic conductivity and hence low potential for groundwater abstraction (Design Report 1, 2010). Groundwater occurrence and transport is controlled by fractures, fissures and weathered layers.

The main aquifer types have been classified as type C1, C2 and C3, all rather shallow aquifers with a productivity flow from under 1-5m<sup>3</sup>/h. Type C1 are local aquifers that develop over the weathered mantle of the migmatite gneiss complex. They reach approximately 40 meters into the deeper regolith zones and their flow does not exceed 5m<sup>3</sup>/h. Type C2 is found where the weathering of the mantle is less developed. Aquifers in these settings are limited to faults below the weathered rock, there thickness seldom reaches over 20 meters and flow does rarely exceed 3 m<sup>3</sup>/h. Aquifers with limited, sporadic or no groundwater are classified as type C3. The average productivity of these aquifers is under 1 m<sup>3</sup>/h and is found in the gneiss-complex.

## **Method**

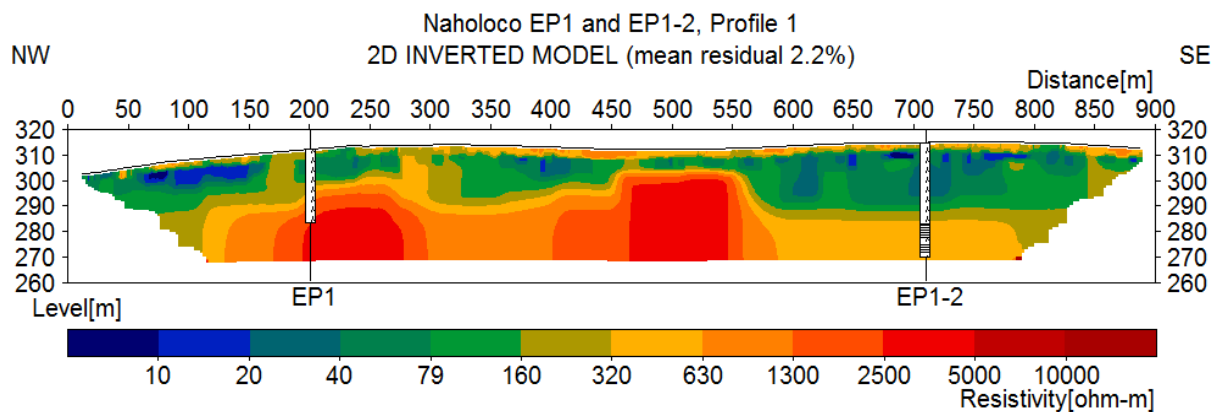
The ERT measurements were carried out using a version of ABEM Lund Imaging System based on Terrameter SAS4000 that allows measuring in 4 channels simultaneously using with multiple gradient array. The most significant advantages when using 2D measurements instead of VES-measurement, is the high vertical and lateral resolution along the profile and comparatively low cost thanks to computer controlled data acquisition. In total 11 sites were investigated using the roll along method, seven boreholes with sufficient yield and five boreholes with insufficient yield. Perpendicular crosses with two 400m survey lines were made over 7 boreholes, whereas single 400m survey lines were made over 5 boreholes due to physical limitations. The measured data was inverted in the program Res2dinv using robust inversion.

VES was the method used to identify the optimum points to site a borehole. Each borehole has a drilling report with information of drilling rate, borehole logging and casing and pumping test. The drilling reports were used as a base for interpretation of the ERT results and comparison with the VES. All reports are however not clear, and in many cases they lack information and contain contradicting information. This leads to difficulties in the evaluation of the results.

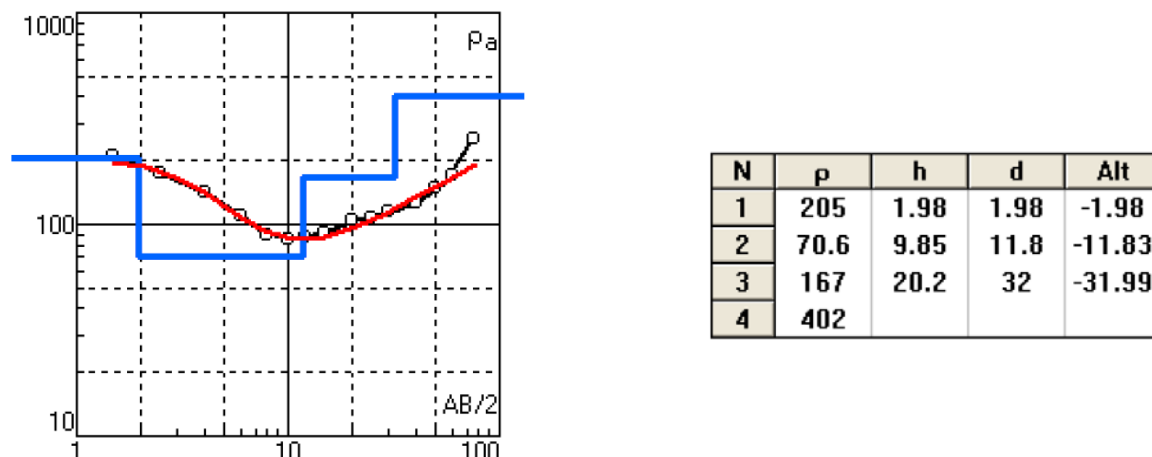
**Result**

The majority of the ERT inversions showed only small deviations from the measured readings. Two profiles had mean residuals over 10 %, one above 6 % and the rest ranged between 1.4 - 4.8 %. The result from the ERT suggested a geological 3D environment with vertical and lateral differences along the survey lines. The subsurface could generally be divided into three layers with varying resistivity. A high resistive surface layer is interpreted as coarse sand, a low resistive middle layer is interpreted as weathered crystalline rock consisting of humid clayey sand and a high resistive last layer is interpreted as fissured, fractured or fresh metamorphic rock.

An example inverted cross section of the subsurface resistivity is seen in Figure 1, Naholoco profile 1, displaying the result of a line with one borehole with insufficient yield (EP1) and one successful well (EP1-2). For this particular site it appears obvious that the successful well (EP1-2) is sited in a more favourable location than the failure (EP1), as interpretation of the inverted section suggests a shallower weathered profile underlain by high resistive fresh rock for the latter. Figure 2 shows the VES that was used as decision support for the drilling at EP1, and it is clear that the VES model suggests a much lower resistivity for the bottom layer. It is also clear from the plot that the model does not fit the steep rise at the end of the curve, but the model fit was not presented in the report. The layout direction of the VES is not documented, but at this point it is clear from the crossing ERT sections that an orthogonal pair of VES would have revealed that the 1D assumption is not valid.



**Figure 1.** Inverted ERT section for Naholoco profile 1. The vertical columns indicate position and depth of the boreholes, with screen position indicated for EP1-2.



**Figure 2.** Example VES curve from pre-investigation corresponding to EP1 on Naholoco profile 1.

A comparison between all the ERT and VES based on layer thickness, resistivity and position was made, bearing equivalence in mind. When comparing results both correlations and differences were found, as summarised in Table 1. The most notable difference is in the bottom layer where the VES gives much lower resistivities than ERT, as also illustrated in the example above. Even though the VES curves have very steep rise the bottom layer resistivity is generally only a few hundreded  $\Omega\text{m}$ , which is surprising as the VES inversion process could be expected to raise the bottom layer resistivity in an attempt to fit the last data points.

**Table 1.** Evaluation of correlation between VES and ERT.

Site	First layer(s)	Second layer(s)	Last layer(s)
<b>Cuhare B</b>	Correlate	Correlate	Difference in resistivity
<b>Matibane</b>	Correlate	Correlate	Difference in resistivity and depth
<b>Murothone</b>	Difference in thickness	Correlate	Difference in resistivity
<b>Naholoco Comunidade</b>	Correlate	Correlate	Correlate
<b>Naholoco EP1</b>	Correlate	Correlate	Difference in resistivity
<b>Namachilo Sede</b>	Difference in resistivity	Difference in thickness	Difference in depth
<b>Passala</b>	Correlate	Difference in resistivity	Difference in resistivity

## Discussion

The result of the field survey only reflects the resistivity values of the subsurface and not the actual geological environment. The appearance of the subsurface is based on assumptions and interpretations of the resistivity results. Consequently there are uncertainties of how well the interpretation of the result reflects the reality.

The interpretation is to a large extent based on Acworth (1987) and Palacky (1987), which were used to derive which resistivities correspond to which part of the weathering sequence and earth materials. A common difficulty is that the resistivities of common earth materials span over large value spectrums and that many materials share the same resistivity ranges. When adding variables like water content, degree of weathering, fractures etc. the material distinctions will be loosened up even more. Furthermore the conceptual model is general and can accommodate different interpretations. Thus the geological interpretation will also be relatively ambiguous.

Comparing the interpreted resistivity cross sections with interpreted material in drilling reports there are both correlations and differences. However the drilling reports vary in quality and degree of detail, and are in several cases obviously not trustworthy, and have thus been of limited use for making interpretations and validating the results. The more common difference is the thickness of the layers but there also differences in material, which makes interpretation questionable.

Regarding ERT and VES the comparison of the two methods is complex. The VES method does not account for lateral variations in resistivity as the measurements are conducted in 1D and the result is adjusted to a horizontally layered model. ERT on the other hand measures in 2D and takes lateral variations in resistivity along the investigation line into account. The ERT result is thereby more comprehensive. Comparison has thus been made at the position of the borehole and no account has been taken to resistivity, depth or layer thickness further away from the borehole. The lack of information on how the VES modeling and interpretation was made, and the lack of documentation of

layout directions, makes it even more difficult to assess correlations and differences of the two methods.

There are no apparent trends that distinguish boreholes with sufficient yields from boreholes with insufficient yields. The conditions in the inverted resistivity profiles look largely the same. There is thereby no clear explanation to the differences in yields. However since most productive boreholes were found in fractured aquifers it is questionable why drilling was stopped at rather shallow depths.

### **Conclusions**

The geology of the Nampula Rapale district is diverse. The subsurface is best described as a 3D environment with vertical and lateral variations. There are two main types of aquifers in the researched area; porous and fractured. Most wells are found in the fractured zone.

There is no straightforward answer from the ERT results that can give a geological explanation to why several boreholes have come out dry. One reason is that the drilling documentation used for interpreting the results is incomplete and partly erroneous. Undoubtedly ERT is a good method to use in this environment and it is possible to draw conclusions from the inverted models, but the complexity of the geology and the lack of relevant and reliable reference data make interpretation difficult.

A comparison between the VES and ERT surveys resulted in both correlations and differences. The bottom layers in the VES measurements show significantly lower resistivities than the corresponding layers in the ERT measurements. Consequently the extent of the weathered zone appears to be deeper in the VES models compared to the ERT models. The aquifer conditions can thus appear better when using VES results which raises questions about how the VES inversion was done.

The VES method is suited for a horizontally layered environment, and it is clearly easy to make misinterpretations using a 1D method in a 3D environment. It is strongly recommended to always measure orthogonal pairs of VES as differences between the layout directions will show if the approach is not valid. ERT surveying is to prefer in this area as it will handle the lateral variation in a better way. Furthermore it contains more information, is more expressive than the VES curves and easier to interpret. It does however require more expensive equipment and can be more time consuming than VES. It is also important to be aware that the 3D environment can affect the 2D models and give misleading results, but this can often be addressed by measuring perpendicular lines.

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