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

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ABSTRACT
There are many projects in Mozambique for poverty reduction. One of these projects is funded by Millennium Challenge Account (MCA) which is aimed to install a total of 600 rural water points each consisting of a well, a water pump and a communal washing basin in the province of Nampula and Cabo Delgado. The proposed investigation method was Vertical Electrical Sounding (VES) and despite research and field investigations several boreholes have come out with an insufficient yield and the failure rates in certain areas are as high as 40 %. Electrical Resistivity Tomography (ERT) were carried out to explain the high failure rate. In total were 11 sites investigated, 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 four single 400m survey lines were made over 5 boreholes. Due to lateral variation the geology in study area is well described in 3D therefore ERT has proven to be a suitable method for groundwater exploration and could lower the failure rate.
Keywords: water supply, borehole failure, groundwater, resistivity, VES, ERT

1.0 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 MCA (Cowater & Salomon) 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. In order to do so, the Rural Water Point Installation Program started. A total of 200 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.

Vertical electrical sounding (VES) was used as survey method but this method gives point information (Kirsch, 2006). This method worked well in unconsolidated rock area but in weathered and fractured zone they faced high number of unsuccessful borehole. The high failure rate, i.e. a high percentage of boreholes with insufficient yield or unsuitable water quality in fractured or weathered zones, motivated this study.

Electrical Resistivity Tomography (ERT) was tested aiming to assess the lateral variation of the geology and its influence in the VES results. ERT method is widely used in groundwater investigations (Owen et al, 2005) with advantage to be extended for long distance by applying the roll along technique (Dahlin, 2001). In total 11 previously drilled boreholes were investigated in Rapale District, Nampula province. The investigated boreholes, 7 has sufficient yield and 4 were discontinued due to insufficient yield (2) or completely dry (2). The resistivity measurement at each investigated borehole was made in two perpendicular 400 m sections except in four borehole that was only a single 400m section. The aim of the study is to investigate the lateral variation of underground´s resistivity, to identify different geological layers close to the borehole and to correlate the result of both VES and ERT. The main finding of this investigation is that there is no correlation between these two methods regarding the last layer due to heterogeneity that increases with depth and highly influence the VES results.

2.0 THE SUDY AREA

Rapale district is located in 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 (Fetter, 2001). The Groundwater in Nampula complex is controlled by fractures, fissures and weathered layers (Costa, 1981).
The Mozambican Hydrogeological map classifies the aquifers as (A) continuous and productive aquifers, (B) discontinuous and medium production and (C) discontinuous and low productive or with no water (DNA, 1997). The class A aquifers are non-consolidated sedimentary rocks and classes B and C are igneous, metamorphic and consolidated sedimentary rocks.

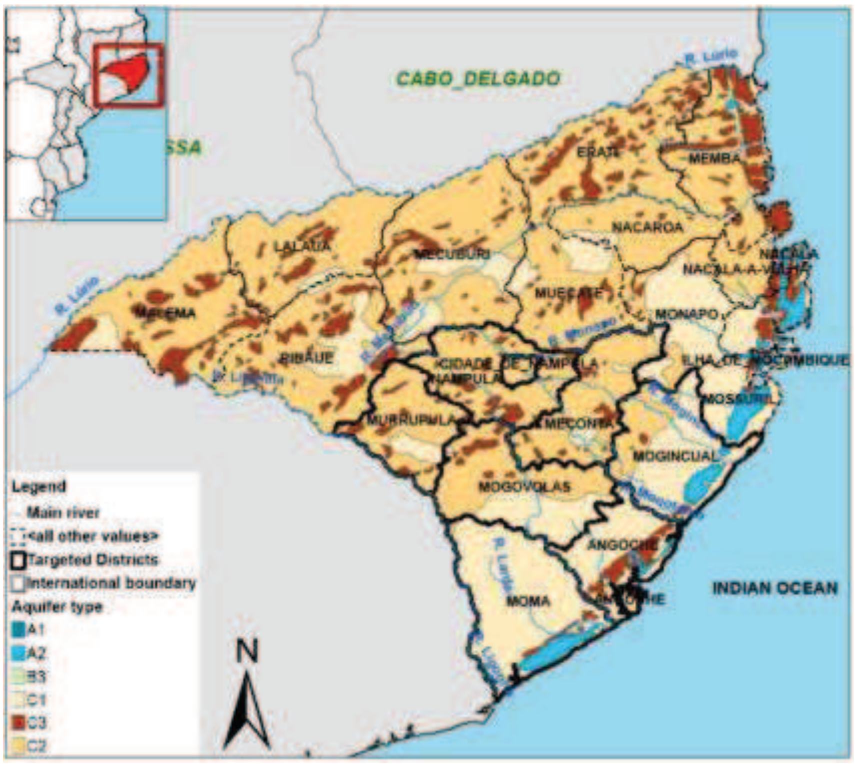

Figure 1. Map over types of aquifers in Nampula province. The map is adapted from Design report 2 (2010).

Figure 1 shows different types of aquifers in Nampula province. In the study area, the main aquifer types found are Type C1, C2 and C3, all rather shallow aquifers with a productivity flow from under 1-5 m^3/l. 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 5 m^3/l. Type C2 is found where the weathered layer is less developed (DNA, 1997). 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^3/l.

Aquifers with limited, sporadic or no groundwater are classified type C3. The average productivity of these aquifers is under 1 m^3/l and is found in the gneiss-complex.

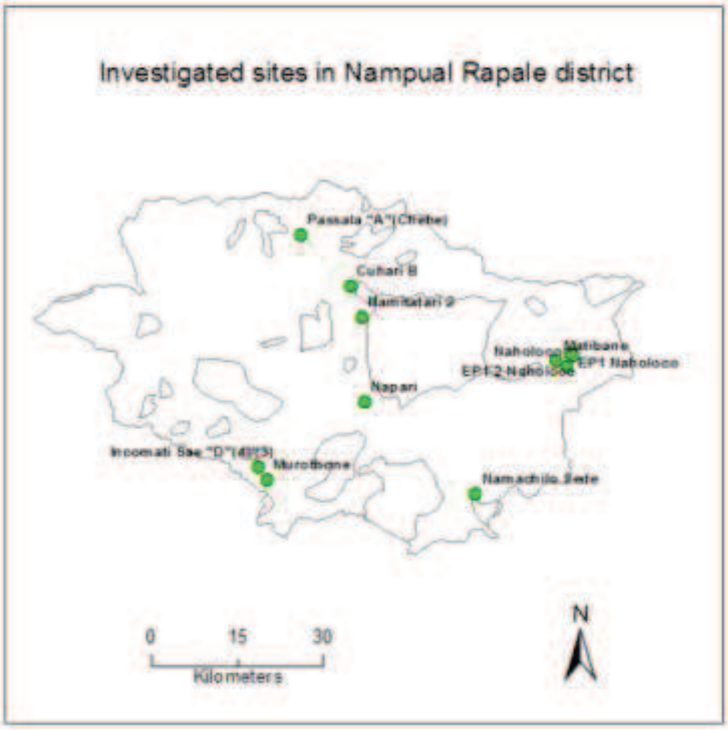

Figure 2. Map of 11 investigated sites in Rapale district. The boreholes with sufficient yield are Cuhare B, Incomati Sae, Matibane, Murothone, Naholoco, EP1 And EP2 Naholoco and EP1 Naholoco. Boreholes with insufficient yields are Namachilo Sede and Namitatare. The boreholes completely dry are Napari and Passala.

3.0 METHODODOLOGY

The geoelectrical 2D measurements (ERT) were carried out using a version of ABEM Lund Imaging System that allows measuring in 4 channels simultaneously using ABEM SAS4000 with multiple gradient array (Dahlin & Zhou, 2006). The most significant advantages when using ERT instead of VES is the high vertical and lateral resolution along the profile and comparatively low cost thanks to computer-driven data acquisition (Dahlin, 1993). In total 11 sites were investigated using the roll along method, 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 four single 400m survey lines were made over 5 boreholes. The single lines were determined by accessibility to the site and also due to valialbility of 400m to perform the study. The measured data were inverted in the program Res2dinv using robust inversion (Loke, 2003). The program was set to a minimum damping factor of 0.25 and no change in model discretization because the quality of data was enhanced by removing bad data points manually.

The drilling project used VES method to identify the optimum points to site the boreholes.

In this method, the current is sent to the ground through 2 electrodes (current electrodes - AB). The terrameter SAS 100 will measure the potential with other two electrodes (potential electrodes- MN). The variation in position of current electrodes will provide the potential of the subsurface downward. The instrument will measure the apparent resistivity of the subsurface in one dimension because it considers that subsurface has no lateral variation (Kirsch, 2006).

The VES data was inverted using IPI2Win software. This software gives an automatic interpretation of the apparent resistivity (Kirsch, 2006).The VES layer models were correlated with the ERT results both the thickness and resistivity value of each identified layer.
A drilling report was prepared for each borehole with information about drilling rate, geological logging, casing, pumping test and water quality. This information was used in the interpretation of the results together with other information such as hydrogeological and geological maps.

5.0 RESULT

The result from the ERT suggested a geological 3D environment with vertical and lateral differences along the survey lines. The majority of the 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 subsurface was generally divided into three layers with varying resistivity. A high resistive surface layer interpreted as coarse sand, a low resistive middle layer interpreted as weathered metamorphic rock consisting of humid clayey sand and a high resistive last layer interpreted as fissured, fractured or fresh metamorphic rock. A typical inverted cross section of the subsurface resistivity is seen in figure 3, displaying the result of a borehole with insufficient yield in Namchilo Sede.

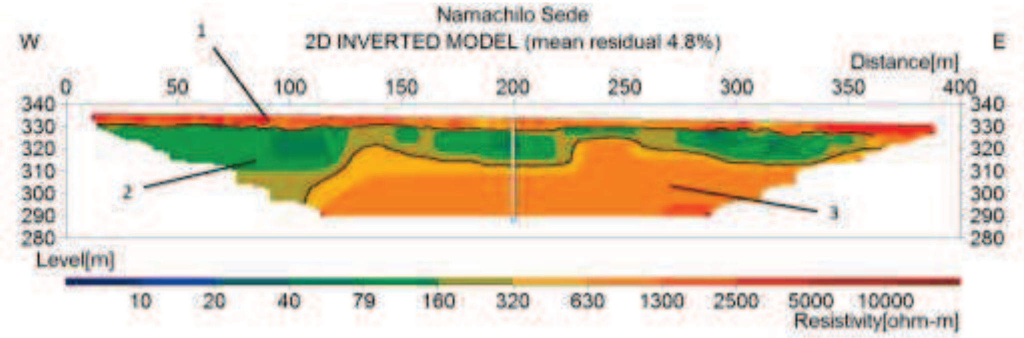

Figure 3. Result of resistivity surveying at Namachilo Sede.

Figure 3 shows the different resistivity layers at Namachilo Sede. There is a surface layer with high resistivity values (630-5000 Ωm) indicated as layer 1 at figure 3. This layer is followed by a low resitivity layer (79-320 Ωm) indicated as layer 2. The layer 3 is a high resitivity layer (320-2500 Ωm). Layer 1 is interpreted as dry coarse sand, layer 2 is interpreted as extensively weathered metamorphic rock, consisting of humid clayey sand and layer 3 is interpreted as fissured and fractured metamorphic rock. The white line at 200m indicates position and depth of the borehole.

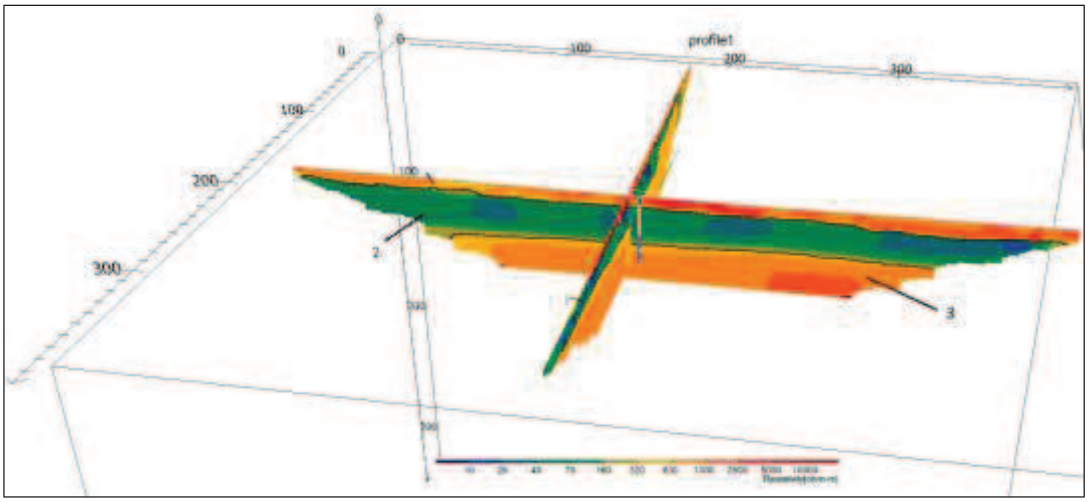

Figure 4. Resistivity variation in two perpendicular profiles at Cuhare B.

Figure 4 is an example of two perpendicular geophysical profiles. The same measurement was made in other 7 boreholes. All gave same result of 3 different geophysical layers. At Cuhare B (figure 4) the surface layer 1 and bottom layer 3 have high resistivity values (630 – 2500 Ωm). They are separated by a low resistive layer (10 – 79 Ωm) indicated as layer 2. These values are in accordance with other studies in weathered (Owen at al, 2015). The borehole, indicated in figure 4 as a vertical white line in the centre, is extracting water from layer 2 and layer 3 which are interpreted as porous media and fractured zone respectively. The thickness of all 3 layers varies in all directions as result of complexity of the geology in this area. The complexity will also influence the quality of the aquifers both in thickness and yield.

Table 5. Location and number of screens in porous and fractured aquifers, divided on investigated sites.

Site	Number of screens in porous medium	Number of screens in fractured medium
Cuhari B	1	1
Incomati Sae "D"	1	2
Matibane		2
Murothone	1	1
Naholoco comunidade		2
Namachilo Sede		2
Naholoco EP1-2		2
Total:	3	12

Table 1 shows the number of screens allocated in each borehole. It is an indication that the fractured aquifer is the main water source and in case of Cuhari B, Incomate Sae "D" and Murothone the groundwater is also extracted in the weathered aquifer. It is an important finding because future groundwater investigation in Rapale district should consider the weathered zone as the main target.

Table 6. Correlations and differences between ERT and VES measurements of investigated sites based on resistivity value and thickness of each layer.

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

Table 2 indicates the correlation of the results of the ERT and VES measurements. The correlation takes into consideration the range of resistivity value from ERT of each layer with the absolute value of VES. Therefore it is considered as correlated layers if the value of VES falls into Range of resistivity values of ERT. The first layer (table 2) is well correlated for both methods in terms of resistivity value but there is difference in thickness in two boreholes. The second layer is also well correlated both thickness and resistivity value. The third layer however, shows differences either in resistivity value or in thickness of the layer (table 3).

6.0 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.

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 (table 1) it is questionable why drilling was stopped at rather shallow depths.

The interpretation is to a large extent based on “The resistivities of common earth materials” by Palacky (1987), which is used to derive which resistivities correspond to which earth materials. The main difficulty is that the resistivity of common earth materials scope 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 broad and can accommodate different interpretations. Thus the geological interpretation will also be relatively broad and can not be seen as precise.

Comparing the interpreted resistivity cross sections with interpreted material in drilling reports there are both correlations and differences (table 2). The more common difference is the thickness of the layers but there also differences in material, which makes the interpretations questionable. However the drilling reports are not a hundred percent trustworthy and have thus not functioned as reference data in the way planned for making interpretations or validating the results.

It is complex to compare ERT and VES. The VES method does not account for lateral variations in resistivity as the measurements are conducted and interpreted using an assumption of a horizontally layered earth. ERT on the other hand measures in 2D and takes lateral variations in resistivity into account. Table 2 is a tentative way to compare the results of both methods. It showed that the layer 3 is not correlated both in resistivity value and in thickness. For both methods the accuracy decreases downward. The VES results are highly influenced by the complex geology underground and for the reason not correlated with results of ERT. The ERT results are thereby more comprehensive. Comparisons were 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 the VES modeling and interpretation made it even more difficult to assess correlations and differences of the two methods.

7.0 CONCLUSIONS

There is no straightforward answer whether ERT surveys can give a geological explanation to why several boreholes have come out dry. The complexity of the geology makes the interpretation difficult, and the insufficient quality and detail plus missing data in the drilling documentation is a problem. Comparisons between the VES and ERT surveys resulted in both correlations and differences. The last layers in the VES measurements show significantly lower resistivities than the corresponding layers in the ERT measurements. Consequently the propagation of the weathered zone appears to be deeper when interpreting the VES measurements compared to the ERT measurements. The aquifer conditions can thus seem better when using the VES models in this case. The VES method is based on the assumption of a horizontally layered environment. Thereby no consideration is taken to the 3D environment, which is certain to influence aquifer conditions and particularly the groundwater gradient. Clearly it is easy to make misinterpretations using a 1D method in a 3D environment. ERT surveying is thereby to prefer in this area, it is intuitively easy to interpret, more expressive than the VES curves and contain more information.

8.0 ACKNOWLEDGEMENTS

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