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# ISGEAG, 1st Technical Report, Geophysics near Kajido Town

1st Technical report within the ISGEAG VIA Water project

Final Report

KenGen Energy for the nation · SamSam WATER · Wiertsema & Partners · amref health africa · ACACIA WATER

## Executive summary

The geophysical experiments described in this technical report were carried out for the project: ‘Improving Sustainable Groundwater Exploration with Amended Geophysics’ (ISGEAG)a partnership between Amref Health Africa, Kenya Electricity Generating Company Limited (KenGen Ltd.), Acacia Water and SamSamWater Foundation, relevant local stakeholders, (Earth Water Consultants) and students from University of Nairobi (UoN) and Kenya Water Institute (KEWI). The project is funded by the Dutch innovation program VIA Water.

Main objective is to investigate the added value of new geophysical techniques in Kenyan groundwater exploration in comparison to the common practices in using conventional methods like VES soundings and HEP profiling as well as to address the limitations and commonly encountered pitfalls in Kenyan ‘borehole siting’ practices.This report gives the outcomes of a field campaign in the basement geology near Kajiado Town. Two more ISGEAG pilots are foreseen in the Coastal area of Kwale and in a Volcanic rock area. The final report will be issued after these 2 pilots (spring 2019).

Colophon

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# Table of contents

# List of abbreviations and acronyms

| | |
|---|---|
| Amps | Amperes, current |
| AMT | Audio-frequency Magno-Telluric soundings |
| DOI/ DOE | Depth of investigation (exploration): up to what depth can the method find a solution |
| EM | Electro magnetic |
| ERT | Electrical Resistance Tomography |
| Equivalence | Non-uniqueness, there are more (geological) models having the same good fit on a single data set |
| HEP | Horizontal Electrical Profiling |
| Hz | Hertz is the derived unit of frequency |
| ISGEAG | Improved Sustainable Groundwater Exploration with Amended Geophysics |
| KEWI | Kenya Water Institute |
| NIA | Neighbors Initiative Alliance in Kajiado |
| TDEM | Time-domain Electromagnetic (soundings) |
| UoN | University of Nairobi |
| VES | Vertical Electrical Sounding |
| WAK | WASH Alliance Kenya |
| WRA | Water Resources Authority |

# Abstract

ISGEAG (Improving Sustainable Groundwater Exploration with Amended Geophysics) is a research project which main objective is to combine relatively new geophysical techniques and the correct application of known, conventional geophysical methods for a better conception of the groundwater aquifer systems in Kenya. This is essential for a sustainable groundwater exploration.

The project is a partnership between Amref Health Africa, KenGen Ltd. Earth Water Consultants, Acacia Water, SamSamWater Foundation and other relevant Kenyan stakeholders. Students from Nairobi University (UoN) and Kenya Water Institute (KEWI) are actively involved in the project. The project is funded by the Dutch innovation program VIA Water.

The ISGEAG research will be implemented at three different locations. This report gives the results of the first pilot application in typical basement geology near Kajiado Town. Two more ISGEAG pilots (2018) are foreseen in the Coastal area (sedimentary rocks) in Kwale County and in an area with volcanic rocks.

In the first mission (Kajiado) two periods of fieldwork were performed. During the first period (February 2017) conventional geophysical methods were applied by Earth Water Consultants Ltd, partly to support another VIA Water project (Sponge City Kajiado). In the second period (April 2017) the more advanced methods (ERT, AMT, TDEM) were successfully executed by KenGen on two selected profiles northwest of Kajiado town, one crossing the Kajiado River and one across one of the main storm water runoff gullies. Additional VES and HEP measurements were executed by AMREF.

### Summarized results of the Kajiado geophysical campaign

- The ERT method (2D electrical resistivity tomography) gave the best results especially in lateral resolution; It should be kept in mind that with ERT the exploration depth, the lateral extend of the exploration depth and the vertical and horizontal resolution of ERT is depending the electrode distance and measuring protocol (Wenner, Schlumberger, Dipole-Dipole etc.);
- Exploration depth of the electrical methods, like VES and HEP, depends on the maximum electrode distance used and is - as a rule of thumb - 1/6 of this length, in fact depending subsurface resistivity distribution. Many Consultants' reports wrongly assume a much deeper exploration depth.
- HEP profiling results can be misleading because anomalies are mostly the effect of superficial (top 25m) layers and are therefore not an indication for deeper structures;
- The exploration depth of TDEM with a similar “transmitter loop size” as compared to the ERT (AB) is much deeper than ERT. Lateral unconformities within the measurement zone can influence the quality of the measurements, because the method assumes horizontal layering;
- Standard TDEM instrumentation and AMT methodology lack information of the first tenth of meters and are poor in resolution compared to ERT. However new developments in instrumentation (WalkTem) can achieve a much higher vertical resolution even (under certain circumstances) than ERT.
- Increasing resistivity with depth (as is the case in Kajiado) increases the problem of equivalence with TDEM; TDEM is less sensitive in relatively high resistive areas than ERT.
- To derive proper resistivity information from AMT measurements, AMT has to be combined with TDEM soundings, the quality of the TDEM soundings will affect the quality of the AMT inversion;
- Single TDEM and AMT require less labor than VES soundings and (under favorable conditions) ERT, however the method is less straightforward, instrumentation and interpretation are more complex; Due to the recent development of instruments like WALKTEM and software like SPIA this is changing rapidly.

- Interpretation based on individual soundings (VES, TDEM, and AMT) assumes horizontal layering. This assumption is not valid when the geology changes within the 'spread' of the measurement. Therefore, detailed information on the location and geometry of faults cannot be obtained in complex geology with small scale lateral change (when lateral change is within the size of the (transmitter) spread. With VES because of the relatively large spread compared to the other methods this effect is most severe.
- A hydro-geological concept for the Kajiado river investigated area has been developed. The combination of a major fracture zone and an old buried river valley may have excellent potential for sustainable groundwater exploitation. Due to the lack of specific geological drilling information the concept is still hypothetical. Verification by test wells is required to decide on the area's exploitation to a sustainable water supply.

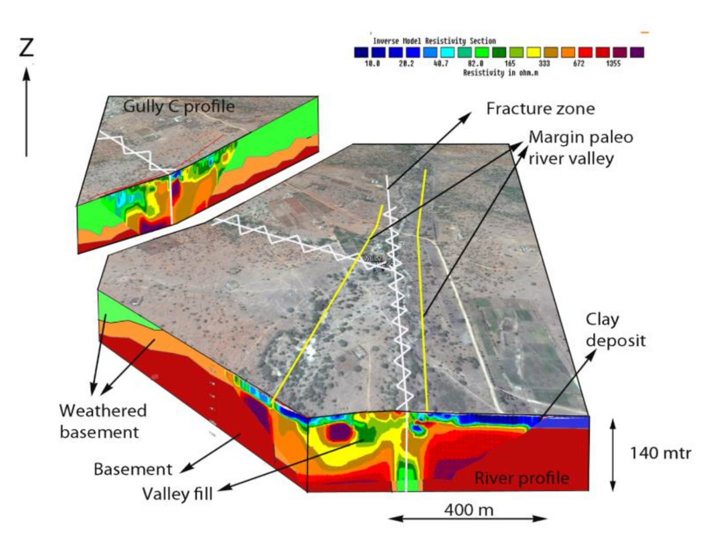

Figure 1. Hydrogeological concept based on Kajiado results

## General recommendation

Only when the application and interpretation of all the methods is used with skills and conclusions are based on multiple soundings, profiles and extra information, it will lead to an increase of successful boreholes and more insight in the hydrology. This is why it is urgent that more attention has to be paid to consultancy reports. They should be easy to acquire, the information of the reports should be complete, correct and reproducible in a way that the data can be of use in future programs and help to get more insight in the hydrogeology. This ongoing process of gaining and increasing knowledge is fundamental for sustainable groundwater exploration.

# Acknowledgement

Without our partners the Kajiado campaign would not have been successful as it was. We are grateful to the KenGen teams for sharing their experience, their flexibility, creativity in the field work (they will measure in any landscape no matter how harsh the circumstances are) and their enthusiasm in the late night 'joined learning' sessions.

A special word of thanks goes to AMREF and the Amref hydrogeologist for reliably facilitating transport and office, for making the crucial arrangements with landowners, the execution of additional VES soundings, his great help in the difficult quest for technical reports and -above all – being good company. Thanks also to the students for their inspiring discussions ('exploration depth for VES is typically 1/6 of the length (L), where L is AB) and their harsh Terrameter work.

Thanks goes to the EarthWater team for doing a great job in the February field work.
We wish to thank the many residents who agreed to do the fieldwork on their land, in particular Pastor Mr. Stephen Maripel (Edukaya Olkeju) and Mr. Osman (Haraf Traders Ltd).

We were very grateful to ABEM, Sweden: Peter Persson, Anders Edsen (www.guidelinegeo.com ), who gave us the opportunity to work with the new and wonderful, very easy to apply TDEM instrumentation (WalkTEM). This instrument is really a next step in TDEM sounding. We are also very thankful to AGS (Aahrhus software, www.aahrhusgeosoftware.dk ) who kindly let us use, for free, their user friendly, easy to access and very efficient inversion software. We really would like thank them, also for their support during the fieldwork.

This project was only possible due the role of Acacia Water in project management. Especially we are very thankful to Stefan Wildt in his role as project manager, He helped us taking unforeseen and for us incomprehensible obstacles in a very efficient and fast way. Thank you Stefan!

Last but not least we are grateful to VIA water, in the way they supported us with our project proposal resulting in the funding of this very nice project and there patience.

***All ISGEAG reports will be made available on the VIA Water and SamSamWater websites[1].***

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[1] ISGEAG: https://www.viawater.nl/projects/kenya-improving-application-of-geophysical-groundwater-exploration,
Sponge City Kajiado: https://www.viawater.nl/projects/kajiado-sponge-city-kenya
SamSamWater: http://www.samsamwater.com/projectdata.php?projectid=81

# 1 Introduction

The ISGEAG ('Improving Sustainable Groundwater Exploration with Amended Geophysics') research project aims to improve geophysical assessment methods for sustainable groundwater exploration. The project is funded by the Dutch innovation program VIA Water.

The project introduces 'new' geophysical methods (Time domain Electromagnetic soundings (TDEM), Electrical Resistance Tomography (ERT), Audio Frequency Magneto Telluric soundings (AMT). Comparison and combination of 'new' and conventional methods, like VES soundings and HEP profiling, will lead to better understanding of Kenyan aquifers. A brief explanation of these geophysical methods is given in Box 1 on the next page.

One of the ISGEAG goals is to improve the application practices of the different methods, at the same time pinpointing the limitations and pitfalls of all the (new and conventional) methods. In this respect also existing Kenyan survey reports are being reviewed and re-interpreted.

Executing Kenyan partners are KenGen Ltd, EarthWater Consultants and Amref Health Africa in Kenya. The Dutch associates are Acacia Water, Wiertsema & Partners and SamSamWater Foundation. Important non-executing stakeholders to be informed and involved are the Kenyan Water Resources Authority (WRA), University of Nairobi (UoN), Kenya Water Institute (KEWI), Wash Alliance Kenya (WAK), Neighbours Initiative Alliance in Kajiado (NIA) and Kajiado County Department of Water and Irrigation

In Kenya there is existing experience with the 'new' geophysical methods for the use in prospecting locations for geothermal energy. This is why KenGen plays an important role as a partner in the project; they have state of the art instrumentation and excellent experience in the conducting and interpretation of ERT, AMT and TDEM.

Amref Health Africa plays a key role in field operations because their know-how and experience in water and sanitation, their experience with the local water authorities, communities, landowners, and execution of additional VES soundings. EarthWater Consultants has excellent records in executing and interpretation of conventional geophysics. Most of the VES and HEP soundings were conducted by Earth Water. Students from UoN and KEWI are being involved in the ISGEAG missions. University should play an important role is the dissemination of the new gained knowledge. The two Dutch associates bring their professional experience in the application and interpretation of geophysical methods into geohydrology.

This report gives the results of the first pilot application in typical basement geology near Kajiado Town. Two periods of fieldwork were performed. During the first period (10 – 20 February 2017) conventional geophysical methods were applied by Earth Water Consultants Ltd, to pre-assess the best ISGEAG research locations and to support a related VIA Water project (Sponge City Kajiado). The specific findings from the February fieldwork are reported separately [Rolf, 2017]. In the second period (16 April – 1 May) (this report) the more advanced methods (ERT, AMT, TDEM) were executed by KenGen on two selected transects. In this report the results of all the methods from both periods, at two profile lines are compared.

Two more ISGEAG pilots (2018) are foreseen in the Coastal area (Kwale County) and in an area with Volcanic rocks (probably Naivasha).

### Box 1: Brief explanation of used geophysical methods

| Abbreviation | Description |
|---|---|
| **AMT** | Audio-Magneto Telluric (AMT) Sounding is a one-dimensional (1D) electro-magnetic (EM) method, using a natural source, low frequency EM field induced by thunderstorm lighting and Cosmic radiation (solar wind). The AMT receiver antenna should be exactly oriented according to the true magnetic north. Investigation depths up to 300m or more below ground can be achieved depending on the recorded frequencies. In urbanized areas AMT measurements are not possible due to artificial EM noise. The apparent resistivity can be calculated from the measurements. Layered models can be calculated with special software from a combination of TDEM and AMT. |
| **VES** | Vertical Electrical Sounding (VES) is a widely used, one-dimensional sounding based on direct current (DC). With 2 current electrodes a DC current is induced. Two potential electrodes measure the potential induced by this DC electrical field. Apparent resistivity is calculated with depth by increasing electrode distances. Typical depth of investigation of a VES is approximately one-sixth (1/6) of the electrode range AB. Layered, true resistivity (horizontal) layered models can be derived with special software. This process is called 'geophysical inversion'. |
| **HEP** | Horizontal Electric Profiling (HEP) is typically used for rapid location or delineation of lateral variations in apparent resistivity of the medium and usually involves moving an electrode array of constant separation horizontally along the surface. Exact depth of the anomalies is typically difficult to establish. No layered inversion is possible. |
| **ERT** | Electrical Resistivity Tomography (ERT) is a two-dimensional (2D) direct current method. Basically, it is a combination of many HEP and VES measurements in one single, integrated data set, and is therefore alternatively referred to as a CVES (Continuous VES). Long cables with many electrodes are in use. With repetition the method can be scaled up to a 3D model. Exploration depth is the basically the same as with VES. 2D layered models can be calculated ('inverted') with special software. |
| **TDEM** | Time Domain Electro-Magnetic (TDEM) is based on an intermitting primary electrical electric field in a transmitter antenna (or loop). The secondary field (so-called 'Eddy Currents') is induced due to the change of this primary field to zero (shutdown). This decreasing secondary field over time (micro seconds) is measured in a receiver loop after each shut down of the primary field. The time versus magnitude (Nano-micro Volts) graph is calculated into an apparent resistivity depth graph. With special software a layer model can be derived (inversion). The method is more sensitive to relative conductive (low resistivity) layers. ZONGE, WalkTEM and airborne TDEM (e.g. SkyTEM) are specific TDEM instruments. |

### Box 2: Brief explanation of some geophysical concepts and definitions

#### Apparent resistivity

The apparent or bulk resistivity is the actual measured resistivity (in ohmmeter) with a specific method; it is the total resistivity due to the resistivity distribution of the subsurface up to the exploration depth. Every single layer contributes, depending its depth and contrast.

#### Specific resistivity

This is the resistivity combined with a specific depth and thickness calculated from the apparent resistivity (inversion).

#### Inversion

The calculation process in which apparent resistivity is calculated into specific resistivity's and depths.

#### Model

The, with the inversion, calculated layers (depth and resistivity) resulting in a layered model consisting of specific resistivities and depths.

#### Equivalence 1

A single field graph (sounding) has more than one inversion solutions or models, Equivalence will vary with the different methods. The more data points the less equivalence.

#### Equivalence 2

A specific calculated model can be interpreted into different geology concepts:
Clay can have the same (low) resistivity as sand with brackish groundwater. Basement can have the same (high) resistivity as a top layer of very dry sand.

#### Residual

Residual (or fit or RMSE) is a figure (in %) that expresses how a calculated model differs from the actual field data. Every calculated model combines to its own synthetic apparent resistivity data, the difference between this calculated graph and the actual field graph is the fit or residual.

#### Forward modelling

This is the process were a resistivity model based on a geological concept is calculated into synthetic field data.

# 2 Kajiado pilot area and fieldwork set-up

The first pilot area is Northwest of Kajiado Town (Figure 2). Geologically, the area is in Precambrian Basement system, as part of the Mozambique belt, consisting of metamorphic rocks (gneisses, quartzite's and at some locations metamorphic limestones). The geology is described by Matheson, [1966].

In Kajiado, the producing boreholes are mostly related to local deeper weathered basement. Differences in weathering depth (or depth to basement) are related to faults, rock composition, buried river valleys or combinations of those.

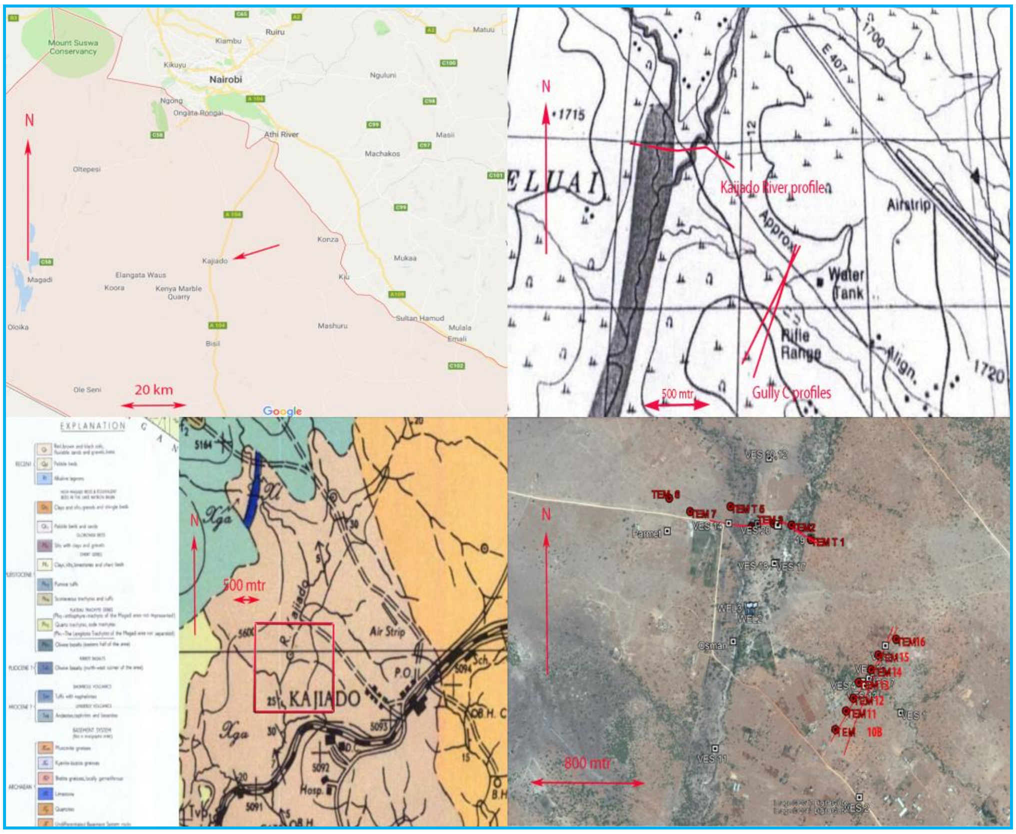


Figure 2. Overview of research location, topography, geology and profile locations.

Part of the fieldwork (February 2017) was done for the VIA Water Sponge City project. This first fieldwork was intended to evaluate potential locations with HEP profiles and VES soundings that might be favorable for artificial recharge of storm water. For the Sponge City project, the geophysics was executed in the urbanized town area itself and near two of the main storm water runoff gullies.

The HEP profiles and VES soundings in February were executed by a team of Earth Water, assisted by Amref and NIA staff and hired casual workers. Only a very limited amount of VES soundings from Kenyan survey reports were available. These were evaluated and re-interpreted. The findings for Sponge City were reported in a separate report [Rolf, 2107]
The second fieldwork in April was focused on the application of the 'new' ERT, TDEM and AMT techniques at the same transects as the HEP profiling in February. This fieldwork was conducted by 3

KenGen teams, using KenGen equipment. The field layouts, instrument set-up and interpretations were done in close collaboration by a team of geophysicists and hydrogeologists of KenGen, Acacia water, Wiertsema and partners and SamSamWater. For further comparison, additional VES soundings were done by Amref on specific locations, based on preliminary ERT and TDEM results. Students from Nairobi University (UoN), Kenya Water Institute (KEWI) and interns from Amref, actively joined the April fieldwork.

The ISGEAG pilot fieldwork was focused on two transects Northwest of Kajiado town (Figure 2):

- A cross section over the Kajiado River, just north of the Haraf Traders borehole, assumed to be the best yielding borehole in Kajiado (Haraf Traders ltd). The borehole is located close to a distinct lineament, where the two rivers merge.
- A cross section over the Osiligi storm water gulley - ‘Gulley C’ - selected in close collaboration with the Sponge City-Team because of its possibility for artificial storm water infiltration.

On both transects a combination of several geophysical methods was applied:

- ERT (Electrical Resistivity Tomography)
- TDEM (Time Domain Electro Magnetic Sounding)
- AMT (Audio Magneto Telluric Sounding)
- HEP (Horizontal Electric Profiling)
- VES (Vertical Electrical Sounding)

# 3 Conventional methods (VES and HEP)

Direct current 1D Vertical electrical sounding (VES) is a widely used geophysical technique for groundwater exploration in Kenya. Since the eighties, VES and the related horizontal electrical profiling (HEP) are the common standard, practiced by many consultants in hydrogeological investigations siting for the best borehole locations.

In Kenya, to qualify for a water abstraction permit, the results should be reported in hydrogeological survey reports in a standardized format that must comply with the Schedule of the Water Resources Management Rules (WRA).

Despite the proven usefulness at a variety of applications, these methods have strict limitations which are not always recognized by consultants and project supervisors in the field. This can lead to misleading interpretations, disappointing results, wrong siting of wells and even more important with regards to sustainability, a misunderstanding of the aquifer system.

With ISGEAG we want to address the limitations, misunderstandings and common pitfalls with VES and HEP, so that practices in the application and interpretation can be improved.
In paragraph 3.1 some of the common issues are addressed, which in this stage of reporting are presented as a list. The various subjects will be further elaborated and illustrated in the course of this project when they have been discussed with project partners and when findings from other ISGEAG locations are available.

Paragraph 3.2.1 contains a summary overview of all ISGEAG VES results, including the Sponge City soundings as well as the re-interpreted results of soundings from existing survey reports.
Paragraph 3.2.2 comments on some challenges encountered in the existing survey reports
The results of HEP and VES on the two ISGEAG cross sections are discussed in paragraphs 3.3.1 and 3.3.2. In Chapter 7 the results of the conventional methods are compared to ERT and TDEM.

## 3.1 VES and HEP methodological issues

In this section some of the main limitations and common misunderstandings on the VES and HEP method, are listed.  Because this report is a just a review of the first ISGEAG location a more elaborated discussion on VES and HEP ‘learning points’ will be held at the end of the project when also the data of the other locations is evaluated and incorporated.

- *Exploration depth of VES soundings*

  As a rule of thumb, the depth of investigation of a VES sounding is approximately 1/6 of the electrode range AB, which can be understood as: a maximum AB electrode spacing of at least six or more times the depth of interest is necessary to assure that sufficient data have been obtained. In other words: if one wants to explore a certain target, e.g. high resistive basement rock, up to a depth of 100 m, a maximum electrode distance of at least 600m is required. The actual exploration depth is also depending on the resistivity distribution of the sub surface.

- *Long electrode distances and ‘lateral changes’ in VES soundings*

  For deep exploration depth, a VES sounding with a long (AB) distance between the electrodes is required. This often conflicts with the VES assumption of horizontal layers: the electrodes at wide range may (and often will) have passed a zone of fracturing or another significant lateral change in the geology.

- *Discontinuity in the VES sounding graphs*

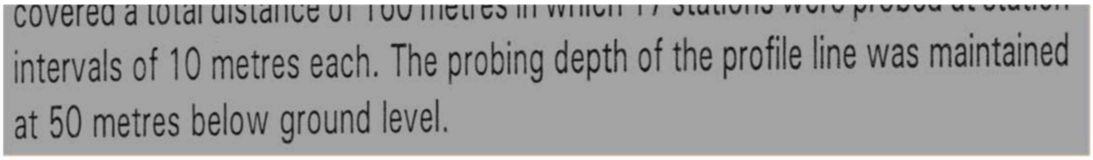
  The measured line of apparent resistivity is in principle a smooth curve when the underground has only vertical variations in resistivity (1D assumption, horizontal layering). Particularly at depth, even large changes in resistivity produce only small differences in measured apparent resistivity. Thus, when horizontal layering is the case, single outliers will be most probably caused by lateral changes or electrode contact problems. They should be ignored with the inversion calculations based on the assumption of horizontal layering.

- *Discontinuity in the VES sounding graphs at the change of potential electrodes.*

  If the measured VES curve shows a (vertical) offset (or shift) especially when changing potential electrodes, a lateral geological inhomogeneity (the more close to the surface the more severe) became into the reach of electrodes. The question is what to do with such an offset/shift in the measured line in the interpretation: leave out, yes/no correct the shift? Then, in what way the shift will influence the inversion and the calculation of the formation resistivity of the deeper layer? Even so: can the offset in the measured line be used to provide information on the direction and distance of the lateral change?

- *HEP profiling exploration depth*

  It should be realized that each measurement in the HEP profiling is the same as one single measurement in a VES sounding. Thus, the 'rule of thumb' on the exploration depth also applies to HEP. And with HEP only the apparent resistivity is measured. A common misunderstanding is that a HEP is 'looking' at the changes in electric resistivity one specific depth, the 'probing' depth. In this respect one of the Kajiado survey reports explains:



covered a total distance of 100 metres in which 17 stations were probed at station intervals of 10 metres each. The probing depth of the profile line was maintained at 50 metres below ground level.

  The term 'probing depth' is a clear misunderstanding of the HEP profiling method. In a Wenner profiling with an array of a=50m (AB=150m, which is a common used distance), each HEP measurement gives the weighted average resistivity of only the top ~17 m (150/6). This is the so called the apparent resistivity. In fact the measurements are dominated by the changes in resistivity of the topsoil. As will be shown in chapter7, the variations in the HEP profile over the Kajiado River cross section just reflect the presence or absence of clay layers in the topsoil. The question may even rise whether HEP profiling makes sense if groundwater is at large depths. At least two Wenner distances should be applied to distinct the effect of the top layers.

- *AB/2 is not depth (VES and HEP)*

  Another misconception is about the AB/2 on the x-axis in the measured graph. Sometimes this axis is wrongly taken as the depth below ground surface. It should be realized that the measured graph is giving the apparent resistivity, as measured at the specific half current electrode distance AB/2. Following the DOI rule of thumb, it gives the weighted average of a 'block of subsurface' of roughly AB/6 thickness. This effect can be seen after the inversion calculation, were the model is plotted in the same graph; the depth of a specific layer is always smaller than the half AB of its measured (apparent) value.

- *Interpretation and inversion (VES)*

  A major challenge in the inversion of VES sounding data is the problem of equivalence/non-uniqueness: the conversion of the (apparent resistivity) measured curve to a layer model of 'true' resistivity's has no one-and-only unique solution. The 'goodness of fit' between the measured and the theoretical curve is quantified by the RMSE (Root Mean Squared Error).

  When adding layers in the software an optimal (minimum) RMSE will be reached at -say- three or four layers. Adding additional layers will not further reduce the RMSE and the added layers are not realistic unless there is independent layer information e.g. from borehole logs. In several Kenyan survey reports one can observe VES layer models with (too) many layers. Some of these reports also seem to interpret deep basement layers (the final layer in the inversion), far beyond the DOI (1/6 AB depth of investigation). Our re-interpretation of existing survey reports shows that such deep layers are insensitive to the solution (RMSE fit) and are in fact meaningless. The 'best' model has a minimum number of layers having the minimum RMSE fit up to the exploration depth. Any additional layers with the same good fit are fictitious, unless there is proof of such layers e.g. from existing nearby boreholes. In this case the method is not sensitive (suitable) for detecting these layers. This applies also for the other methods.

- *Model Uncertainty*

  The (90%) uncertainty range of model parameters (layer depth and resistivity) can be quantified in most of the inversion software (as in the SchlumBG software used here). For correct interpretation of the outcomes of the VES sounding the uncertainty range should be taken into account. In this study, the inversion of the apparent resistivity data to layer models is done by SchlumBG software vs. 2. One of the features of the software is the calculation of the (un) certainty range (or 'confidence interval') of the layer parameters: depth and resistivity. It gives the range of possible parameter values with a 90% confidence. The uncertainty increases with the depth of the model layers. Alternative layer model concepts can give a different confidence interval.

## 3.2 Application of conventional methods in Kajiado

### 3.2.1 VES soundings Kajiado Town, an overview

Within the ISGEAG Kajiado campaign and the related Sponge City project, a number of conventional VES soundings and HEP profiles have been conducted and measurements from existing reports have been re-interpreted. The specific findings for Sponge City are discussed in a separate technical report [Rolf, 2017]. This chapter presents an overview of all the VES sounding results and an evaluation of the findings from existing survey reports. Three groups of VES soundings are distinguished:

1. Soundings from existing survey reports

Although there must have been many borehole surveys according to the amount of production boreholes, in and around Kajiado town, unfortunately only 7 survey reports could be recovered with the essential help of AMREF and NIA staff. From these reports only four (4) could be re-interpreted. The other (3) reports did not comprise the measured field data (raw apparent resistivity data), and therefore re-interpretation is impossible.

2. Soundings conducted in February 2017

A reconnaissance mission was done for ISGEAG and the related Sponge City project in February. 13 VES soundings and 8 HEP profiles were conducted by Earth Water Consultants Ltd in the Kajiado town center at two major rainwater runoff gullies and near the Kajiado River.

3. Soundings conducted in April 2017

7 additional VES soundings were conducted for ISGEAG to compare the conventional VES method to the findings from TDEM soundings and ERT and AMT tomography.

For each sounding a concise interpretation report is separately available in pdf 'VES soundings Kajiado Town [Rolf, 2017]. The layer model results of all the VES are summarized in Table 1, Table 2 and Table 3. The locations are given in Figure 3 and Figure 4.

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[2] SchlumBG for Windows, C.J. Hemker and V.E.A.Post, http://www.microfem.com

Table 1. Layer model interpretation of all ISGEAG and Sponge City VES soundings, including confidence range

**Sponge City/ ISGEAG soundings February and April 2017**

|  |  |  |  |  |  | Interpreted geo-electric resistivity model |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | coordinates (WGS84) |  |  | Electrode | RMS | surface layer |  |  | Layer 2 |  |  |  | Layer 3 |  |  |  | Basement (Rho≈≥1000 |  |  | REMARKS |
| name/ location | VES nr. | LAT (S) | LONG (East) | Elev (mas) | spacing AB/2 (m) | error x10-2 | TOP (m) | Rho (Ωm) | *confidence* | TOP (m) | *confidence* | Rho (Ωm) | *confidence* | TOP (m) | *confidence* | Rho (Ωm) | *confidence* | TOP (m) | *confidence* | Rho (Ωm) |  |
| Gulley C VES1 | 1 | 01°49'39.5" | 36°46'31.2" | 1690 | 320 | 3.6 | 0 | 26 | *(23 - 29)* | 2 | *(1 - 4)* | 50 | *(40 - 80)* |  |  |  |  | 15 | *(12 - 30)* | >>>1000 | discontinuities in meas. |
| Gulley C VES3 | 3 | 01°49'26.8" | 36°46'27.8" | 1710 | 320 | 3.5 | 0 | 90 | *(80 - 120)* | 1.7 | *(1,5 - 2)* | 30 | *(23 - 40)* |  |  |  |  | 50 | *(40 - 60)* |  | discontinuities in meas. |
| Gulley C VES4 | 4 | 01°49'34.7" | 36°46'22.9' | 1685 | 320 | 9.2 | 0 | 2 | *(1 - 5)* | 2.5 | *(2-8_* | 50 | *(30 - 1000)* |  |  |  |  | 4 | *< 8* | >>1000 | discontinuities in meas. |
| Gulley C VES7 | 7 | 01°49'33.0" | 36°46'24.3' | 1690 | 400 | 1.2 | 0 | 30 | *(25 - 60)* | 2.5 | *(2 - 3)* | 300 | *(290 - 320)* |  |  |  |  | 90 | *(80 - 100)* |  |  |
| Gulley C VES13 | 13 | 01°49'34.4" | 36°46'23.4' | 1682 | 63 | 5 | 0 | 10 | *(6 - 12)* |  |  |  |  |  |  |  |  | 4.5 | *(4 - 5)* | >>1000 | on gulley river bed |
| Gulley C VES16 | 16 | 01°49'31.9" | 36°46'25.2" | 1687 | 500 | 3 | 0.1 | 250 | *(220  -280)* | 11 | *(9 - 15)* | 57 | *l(arge)* | 15 | *(large)* | 500 | (250-1000) | 76 | *(40-160)* | (1000-1500) | some discontinuity |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| VES2 (road) | 2 | 01°49'55.1" | 36°46'22.0" | 1720 | 320 |  | unreliable sounding |  |  |  |  |  |  |  |  |  |  |  |  |  | unreliable (reason ?) |
| Gulley B VES9 | 9 | 01°50'17.3" | 36°46'17.2" | 1710 | 500 | 1.2 | 0 | 290 | *(250 - 300)* | 1 | *(1 - 2)* | 145 | *(130 - 150)* | 9 | *(8 - 13)* | 90 | (85 - 110) | 55 | *(50 - 70)* | (700 - 900) |  |
| Town VES5 | 5 | 01°50'21.7" | 36°46'59.1" | 1720 | 130 | 1.7 | 0 | 170 | *(150 - 200)* | 0.5 | *(0 - 1)* | 65 | *(60 - 70)* | 9 | *(8 - 12)* | 190 | (150 - 300) | ? | *>40* |  | short AB line |
| Town VES6 | 6 | 01°50'24.1" | 36°47'28.8" | 1735 | 130 | 1.6 | 0 | 5 | *(1 - 12)* | 3 | *(2 - 4)* | 43 | *(40 - 55)* |  |  |  |  | 45 | *(20 - 90)* |  | short AB line large disc. |
| Town VES8 | 8 | 01°50'27.8" | 36°47'25.3" | 1732 | 63 | 1.8 | 0 | 53 | *(52 - 56)* | 11 | *(9 - 13)* | 100 | *(90 - 110)* |  |  |  |  | ? | *>75* |  | short AB line large disc. |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Kajiado River:** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Kaj. R VES10,12 | 10,12 | 01°48'50.9" | 36°46'02.3" | 1680 | 500 | 2 | 0 | 35 | *(35 - 50)* | 1 | *(1 - 2)* | 48 | *(44 - 70)* | 12 | *(10 - 15)* | 400 | (300 - 500) | 130 | *(120 - 200)* | >>>1000 | two perpendicual VES's |
| Kajiado R VES11 | 11 | 01°49'46.3" | 36°45'50.6" | 1670 | 500 | 1.5 | 0 | 320 | *(150 - 500)* | 0.7 | *(0- 1)* | 4 | *(large)* | 0.8 | *(large)* | 130 | (100 - 200) | 35 | *(25 - 43)* | (>3000) |  |
|  |  |  |  |  |  |  |  |  |  |  |  | ***VES11 layer4:*** |  | 27 | *(large)* | 25 | (<90) |  |  |  | (VES11  has layer 4) |
| Kajiado R VES14 | 14 | 01°49'03.4" | 36°45'53.4" | 1675 | 100 | 6 | 0 | 40 | *(10 - 50)* | 1 | *(0.5 - 1.4)* | 3 | *(<5)* |  |  |  |  | 7 | *(3 - 9)* | >> 1000 |  |
| Kajiado Ri VES15 | 15 | 01°49'03.5" | 36°45'59.8" | 1692 | 500 | 1.5 | 0 | 480 | *(340 - 700)* | 7 | *(2 - 12)* | 200 | (185 - 210) |  |  |  |  | 80 | *(65 - 95)* | >800 | large discontinuity |
| Kajiado R VES17 | 17 | 01°49'11.0" | 36°46'03.8" | 1675 | 250 | 4 | 0 | 60 | *(large)* | 0.3 | *(0 - 3)* | 20 | *(12 - 40)* |  |  |  |  | 13 | *(11 - 15)* | >>>1000 |  |
| Kajiado R VES18 | 18 | 01°49'11.1" | 36°46'03.5" | 1675 | 160 | 2.3 | 0 | 600 | *(300 - 1500)* | 1.2 | *(1 - 3)* | 3 | *(1 - 10)* | 1.7 | *(large)* | 240 | (50 - 600) | 80 | *>30* |  | discontinuity |
| Kajiado R VES19 | 19 | 01°49'06.2" | 36°46'11.6" | 1675 | 500 | 1.9 | 0 | 1200 | *(large)* | 0.7 | *(0 - 5)* | 80 | *(30 - 150)* | 9 | *(3 - 30)* | 500 | (300 - 800) | 33 | *(>25, uncertain)* |  | major disconinuity |
| Kajiado R VES20 | 20 | 01°49'03.7" | 36°46'04.3" | 1680 | 200 | 1.7 | 0 | 800 | *(250 - 2600)* | 1.2 | *(1 - 4)* | 5 | *(large)* | 2.4 | *(large)* | 300 | (140 - 700) | 90 | *(>45, uncertain)* |  | short AB reach |

Table 2. Layer model re-interpretation of VES soundings from existing survey reports

2) **re-interpreted from existing survey reports**

| | | coordinates (WGS84) | | | Electrode | Interpreted geo-electric resistivity model | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | RMS | surface layer | | | Layer 2 | | | | Layer 3 | | | | Basement (Rho≈≥1000 | | | remarks |
| name/ location | VES nr. | LAT (S) | LONG (East) | Elev (mas) | spacing AB/2 (m) | error x10-2 | TOP (m) | Rho (Ωm) | *confidence* | TOP (m) | *confidence* | Rho (Ωm) | *confidence* | TOP (m) | *confidence* | Rho (Ωm) | *confidence* | TOP (m) | *confidence* | Rho (Ωm) | |
| MTTI VES1 | MTTI | 01°51'16.0" | 36°46'55.3" | 1720 | 200 | 1.87 | 0 | 350 | *(300-400)* | 1.5 | *(1 - 2)* | 100 | *(20 - 500)* | 25 | *(10 - 40)* | 200 | *(100 - 300)* | ?? | *> 80* | | detail coordinates missing |
| MTTI VES2 | MTTI | 01°51'16.0" | 36°46'55.3" | 1720 | 160 | 0.95 | 0 | 10 | *(8 - 12)* | 1.5 | *(1 - 2)* | 75 | *(70 - 80)* | 25 | *(20 - 30)* | 340 | *(220 - 460* | ?? | *> 80* | | |
| MTTI VES3 | MTTI | 01°51'16.0" | 36°46'55.3" | 1720 | 200 | 1.88 | 0 | 15 | *(10 - 20)* | 3 | *(1 - 5)* | 85 | *(70 - 100)* | 10 | *(8 - 14)* | 210 | *(190 - 240)* | ?? | *>130* | | |
| MTTI VES4 | MTTI | 01°51'16.0" | 36°46'55.3" | 1720 | 200 | 1.72 | 0 | 120 | *(90 - 160)* | 1.5 | *(1 - 2)* | 35 | *(28 - 40)* | 9 | *(5 - 10)* | 200 | *(130 - 230)* | ?? | *>50 or deep* | | correctness of last 3 points ? |
| Masai Stores | Masai St | 01°50'52.9" | 36°47'24.7" | 1730 | 200 | 1.28 | 0 | 75 | *(70 - 80)* | 1.5 | *(1- 2)* | 52 | *(50 - 55)* | 20 | *(15 - 25)* | 175 | *(100 - 400)* | 80 | *(50 - 130)* | >>1000 | survey report model gives BAD FIT |
| Osman town | Osman | 01°50'45.0" | 36°47'25.0" | 1730 | 250 | 1.31 | 0 | 14 | *(8 - 27)* | 0.7 | *(0- 3)* | 22 | *(21 - 23)* | 10 | *(10 - 11)* | 105 | *(93 - 130)* | ? | *>90* | | |
| Osman Kaj River | Osman | 01°49'26.0" | 36°45'54.5" | 1670 | 250 | 1.9 | 0 | 4 | *(3 - 5)* | 5 | *(4 - 6)* | 40 | *(15 - 50)* | | | | | 30 | *(15 - 40)* | >>1000 | inconsistent interpretation in report |

Table 3: Layer model interpretation of VES soundings from existing survey reports (without field data)

| | | coordinates (WGS84) | | | Electrode spacing | Interpreted geo-electric resistivity model | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | RMS | surface lay | | Layer 2 | | Layer 3 | | Layer 4 | | Layer 5 | | Basement ≥1000 Ω | | remarks |
| Name/ Location | VES nr. | LAT (S) | LONG (East) | Elev (mas) | AB/2 (m) | error x10-2 | TOP (m bgs) | Rho (Ωm) | TOP (m bgs) | Rho (Ωm) | TOP (m bgs) | Rho (Ωm) | TOP (m bgs) | Rho (Ωm) | TOP (m bgs) | Rho (Ωm) | TOP (m bgs) | Rho (Ωm) | |
| Itinyika | | 01°50'40.0" | 36°45'40.0" | 1660 | ? | ? | 0 | 70 | 2 | 30 | 8 | 100 | 16 | 200 | 50 | 80 | 100 | 700 | field data missing |
| Empeut | VES1 | 01°50'3.54" | 36°47'42.0" | 1720 | ? | ? | 0 | 79 | 0.8 | 17 | 1.4 | 53 | 19 | 1150 | 36 | 81 | 100 | 1000 | field data missing |
| Empeut | VES2 | 01°50'0.97" | 36°47'40.4" | 1720 | ? | ? | 0 | 16 | 1 | 30 | 11 | 93 | | | | | 42 | 1000 | field data missing |
| Parmet | | 01°49'05.0" | 36°45'40.0" | 1685 | ? | ? | 0 | 90 | 2 | 15 | 7 | 100 | 40 | 250 | 80 | 125 | 125 | 1200 | field data missing |

Figure 3. VES locations in and around Kajiado Town. The locations from existing survey reports are given by names (e.g. 'Empeut', 'Masai St.', etc.); the ISGEAG VES locations are numbered (e.g. '9' for VES-9.

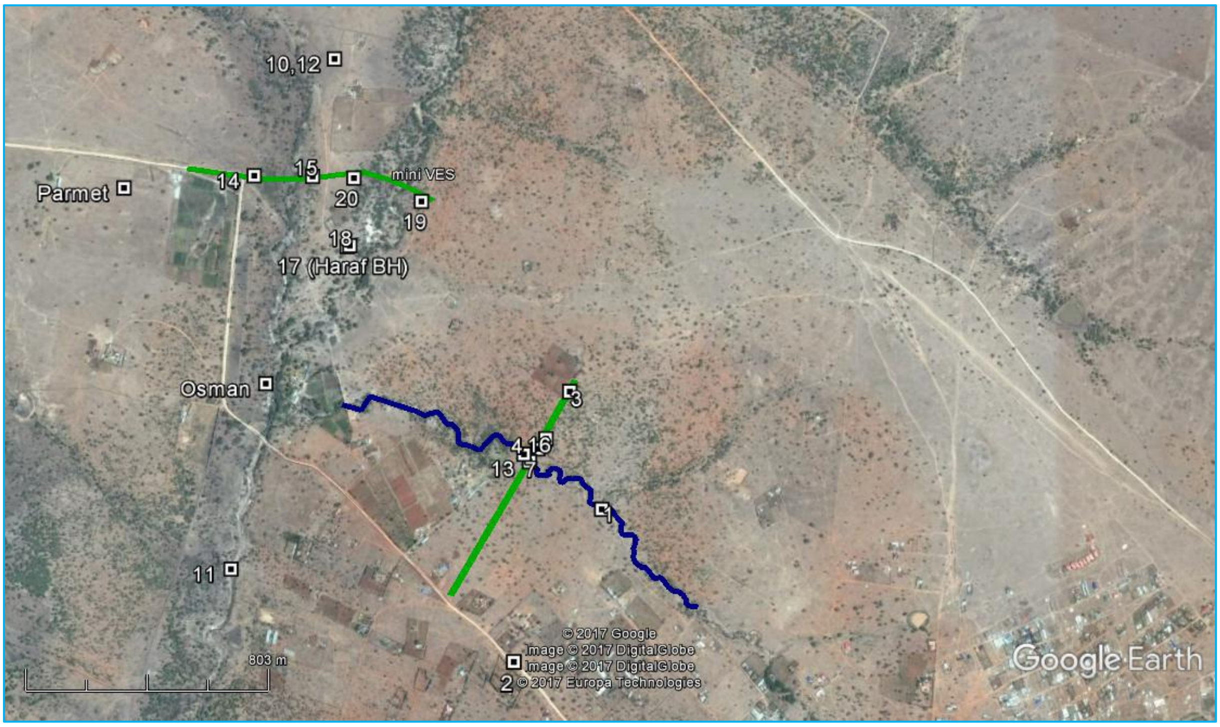

Figure 4. VES locations and HEP lines (in green) near the two ISGEAG transects.

### 3.2.2 VES soundings from existing survey reports

There at least 50 boreholes in- and around Kajiado town (see Sponge City water point mapping by NIA). According to the Kenyan regulations there must have been as many survey and borehole reports. Still only 7 survey reports and even fewer borehole completion reports could be traced, even with a lot of effort. The evaluation of the survey reports and the re-interpretation of the reported VES soundings give reason for comments[3] given below

In general, geophysical tools like single VES cannot directly indicate where you can find water. After inversion of the apparent resistivity to a resistivity layer model, this model needs to be translated and interpreted to geology and to a hydrogeological concept. The geophysical results have to be combined with all existing information from previous surveys, boreholes, topography, geology, satellite images etc. All this information should lead to a conceptual understanding of the groundwater system.

In the (few) recovered survey reports the evaluation, based on which arguments a specific location is the best option for a borehole is often missing. Also, the reasoning for the advised drilling depth is not clearly evaluated in relation to the exploration depth of the method used.

#### General remarks on the data as produced in survey reports

*Field data*

Not all reports include the raw apparent resistivity field data, giving no option to re-interpret and verify the correctness and reliability of the inversion results. In this case 3 out of the 7 reports did not include these data and could therefore not be re-interpreted and verified.

*'Shifted' measurements*

It often occurs that the measurements show an offset at changes of potential electrodes distance. This is mostly due to lateral changes in geology. Since the method assumes 1-D horizontal layering a lateral change will affect the interpretation. This is the reason why in most reports the measurements are corrected (by vertical shifting of the graph segments in between the half AB were the potential shift occurs) to a smooth field curve. Apart from the question whether this is correct or acceptable, it should be clear which measurements are affected and if shifting has been applied. Shifted field curves can often be recognized by the absence of double measurements at potential electrode changes. For future use of the data, it is strongly advised to at least list the original, un-shifted measurements in the report.

*Azimuth*

Reports do not always include the azimuth (compass direction) of the soundings. The azimuth is important when the geology has dominating structural changes.

*Coordinates/maps*

(GPS) coordinates are missing in some reports. In other cases, coordinates are in Arc1960 grid system (suitable for Kenya/Tanzania/Uganda) and not in WGS84. Some reports do not indicate the used grid system. It is strongly advised at least to report the used type of grid system. Most reports have hand-drawn maps or no maps at all. This may lead to confusion or miss-locating. Nowadays the WGS84 system is more common worldwide and it can be used directly for Google Earth mapping.

#### Interpretation and inversion challenges

From our re-interpretation of VES soundings, some prominent challenges were encountered:

- No information on the uncertainty of the interpreted layer model parameters;
- In the inversed layer model often (too) many model layers are given. The reason for this was obviously to achieve a better fit but this often results in non-realistic models;
- In fact, in many cases, the fitted model is effected by lateral change while de inversion calculation is constrained to horizontal layering;
- The interpreted depth of the layer model is far beyond the actual exploration depth of the sounding. Most of the soundings reach a total (AB) electrode distance of 400 meter implicating

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[3] Remark: these issues are just mentioned here. They will be further elaborated and illustrated with practical examples in the final ISGEAG report

an exploration depth in the order of only 70 meter, while models are interpreted far beyond 100m, resulting in drilling depth beyond the exploration depth which may not be realistic and could concequence into a waste of money.

- Verification of the reported layer model: when the depth and resistivity parameters are given as (fixed) input in the SchlumBG inversion program, the fit is – in some cases - significantly worse than the reported fit. In some reports even, the model presented in the main report is not consistent with the model given in the Annex of the same report.

#### Conclusions

1) Lack of documented information (e.g. survey and borehole reports) is seriously hampering quality of hydrogeological studies. This information is essential for the development of a sustainable groundwater exploration;
2) VES interpretations need more attention on non-uniqueness of solutions and confidence of layer depths and resistivity;
3) VES exploration depth and interpreted depth and advised drilling depth should be in the same order or based on a sound explanation.
4) The licensing authority (and the client if possible) could improve in verifying the quality of the report and the correctness of interpretation of VES soundings via a checklist. Such checklist should at least include: sounding coordinates, azimuth, raw unshifted data, software program, verification of the layer model inversion, digital map (preferably Google Earth) giving locations and direction of soundings and profiles, and inversion results explained in a hydrogeological context, reasoning and argumentation on the advised drilling location and depth.

## 3.3 ISGEAG VES soundings and HEP profiles

For ISGEAG several geophysical methods are applied and compared along two selected transects: 'Gully C' and 'Kajiado River' (see Figure 3 and Figure 4 for locations).

### 3.3.1 Gulley C (Isioli location)

On the 'Gully C' transect, 3 HEP profiles (150 and 30m electrode reach) and 6 VES soundings (VES's 3, 4, 7, 13 and 16) were conducted.

Figure 5. HEP profile line (green) across Gully C (blue) and VES locations looking to the NW VES sounding results

The raw, uncorrected measured curves are in Figure 6. The inversion of each sounding is given in a separate technical report [Rolf, 2017]. The model layer inversion results are summarized in Table 1.

Note: Almost all the inversions layers are ending with a resisitivity of the last layer of at least 1000 Ωm. This is interpreted as the start of 'basement'. The resistivity of fresh basement bedrock itself will be much higher. In the section of the graph where the field curve ascends with 45 degrees, layer depths and resisitivty are not possible to establish due to equivalence.

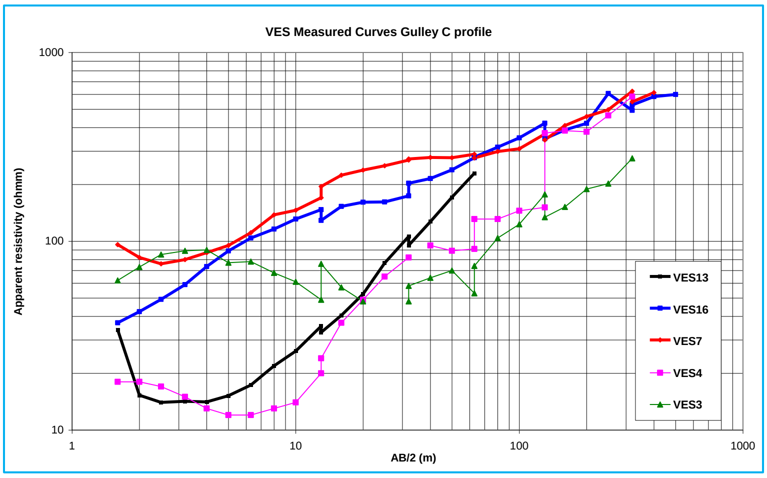


Figure 6. Field curves: apparent resistivity measurements of VES soundings at transect Gully C, for convenience the measuring points are inter-connected

Although there were 6 soundings conducted on the transect line, 3 of them are the most relevant. VES 2 (which is not shown in Figure 6), is located on the South-end of the transect (on the road). This sounding is unreliable. This is most possible due to bad (electrode) contacts. VES4 and VES3 were conducted in the direction of the transect line, thus perpendicular to the expected geological structure; both field curves show large discontinuities and offsets due to lateral changes and are not further presented here. VES soundings 7, 13 and 16 were done perpendicular to the HEP line (parallel to the assumed geological change) and are consequently the most useful ones. VES 13 was conducted on the top of the gully bed.

A visual way of presenting the VES interpretation is given in Figure 7. In this figure the model layers are presented with their 90% uncertainty range. The skewed black line gives the 90% max and minimum depths of the layers in meters MBGS (Meters Below Ground Surface). The skewer the line, the more uncertain the result is. The dot on the line gives a 'most likely' depth value. Along the right side of the column the resistivity values are given as 90% uncertainty range. The indication "L" stands for "large" meaning that the uncertainty is so high that it could not be quantified. The different colors reflect the resistivity according to the color classification (which is approximating the classification as used for the ERT results). Multiple colors within a layer mean that the resistivity range is exceeding more than one section of the classification.

Note: the length of the layer columns is not (yet) corrected for the investigation depth (DOI, being in the order of 1/6 AB). For instance, for VES13, AB/6 is only 21m; the long column gives a wrong impression. In fact, the VES13 sounding can just 'see' a 4-5 m low resistive clay layer (blue color) on top of very high resistive rock (in purple). The latter may be interpreted as a hard cap due to chemical weathering, or remnants of Basalt flow or even basement (which is not logic); At least anything below 21 m is unknown.

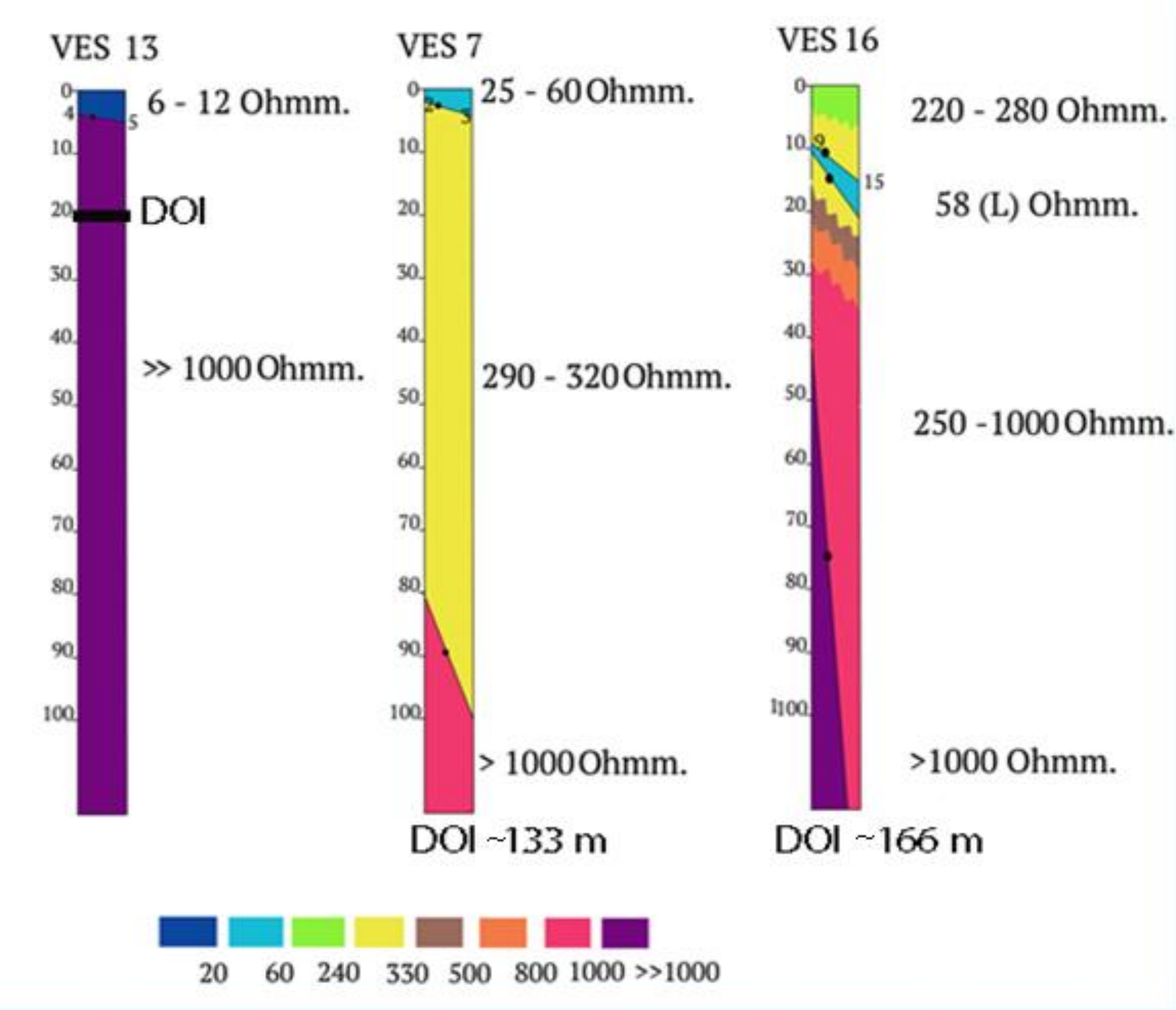


Figure 7. VES sounding interpretation, AB/6 is resp. in VES13 21m, VES7 133m, VES16 166m.

The visual presentation clearly shows that the uncertainty increases with depth which is inherent to the measurement methodology and VES principle. The uncertainty of VES16 is extra-large due to large discontinuities in the measured curve.

Reliable soundings are too few to draw a useful resistivity profile in relation to the scale of lateral changes. Most relevant is the difference between VES nr.13 (on the gulley bed) and the nearby VES nr.7, just 50 m north of the gully: while VES13 shows high resistive, fresh bedrock, or a hard cap at shallow depth (4 – 5 m) covered by clay. In VES7 the basement is deeper than 80m. Obviously, there is a major anomaly near the gulley. In Chapter 7 the VES results are compared to the ERT tomography results.

### HEP profile Gully C

Apparent resistivity graphs of the Gully C HEP profiling are presented in the graphs below, Figure 8. The profiles were conducted with different electrode arrays: relatively long (AB=150 m) range Wenner and Schlumberger. A more superficial short range (AB=30m) Wenner profile is executed on the same transect, close to the gully (Figure 9).

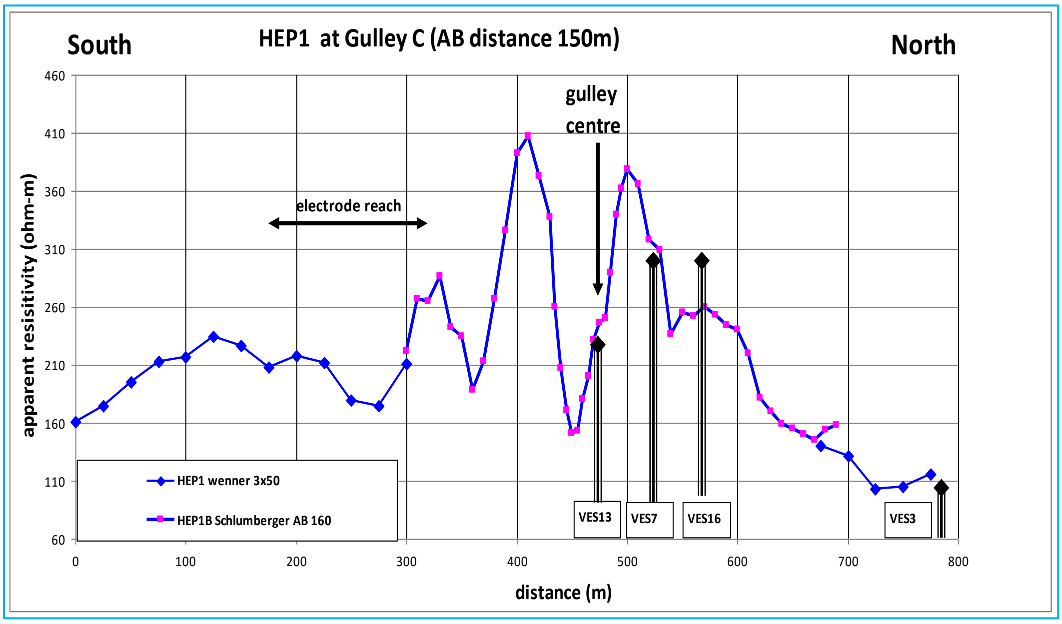


Figure 8. Measured apparent resistivity of the long electrode reach HEP1 profile, Schlumberger AB=160, MN=50. Wenner AB=150 (a=30)

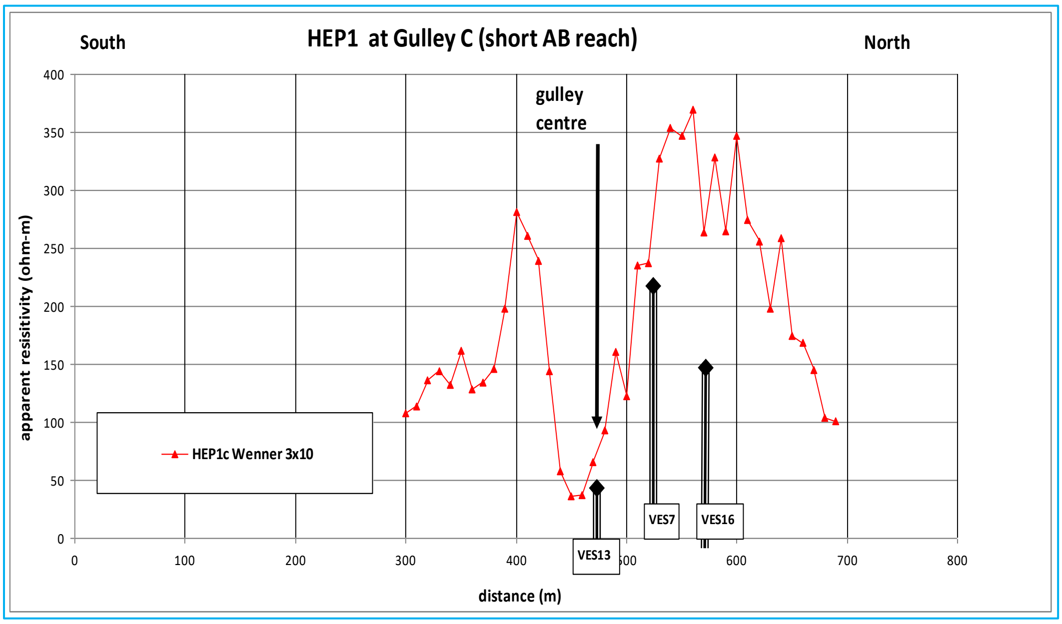


Figure 9. HEP profile 1c, crossing Gully C, Wenner (a=10m, AB=30)

Like the two VES soundings, the HEP results indicate a major anomaly near the gulley bed, both in the AB=30 m and AB=150 m. HEP. From VES13 and hand drilling it became clear that the Gulley bed and banks are filled with some meters of very conductive clay on top of high resistive, most probably un-weathered isolated rock or a hard cap.

A question was whether the HEP anomaly is caused by the clay or by the shallow rock. In March 2017 (before the second field campaign) an exercise was done by 'forward modelling', see Annex 1. The exercise indicated that the anomaly was mainly due to the superficial clays near the gulley. In Chapter 7 the HEP results are compared with the measured ERT cross section which was conducted over the same transect line.

### 3.3.2 Kajiado River profile (Ildamat, Osiligi)

On the Kajiado River transect, one HEP profiling (Wenner a=50m, AB= 150 m) and 4 VES soundings (VES's 14, 15, 19 and 20) were conducted (figure 8). Some more VES's were done north (VES10, 12) and south (Ves17, 18) of the profile line in February. They are discussed in the Sponge City and interpretation report [Rolf, 2017].

Figure 10. VES locations on the HEP profile line (in green) Kajiado RIver

#### VES sounding results

6 soundings were conducted on the transect line to verify and compare with the HEP and ERT results. The model layer inversion results are included in table 1. The measured field curves are in Figure 11.

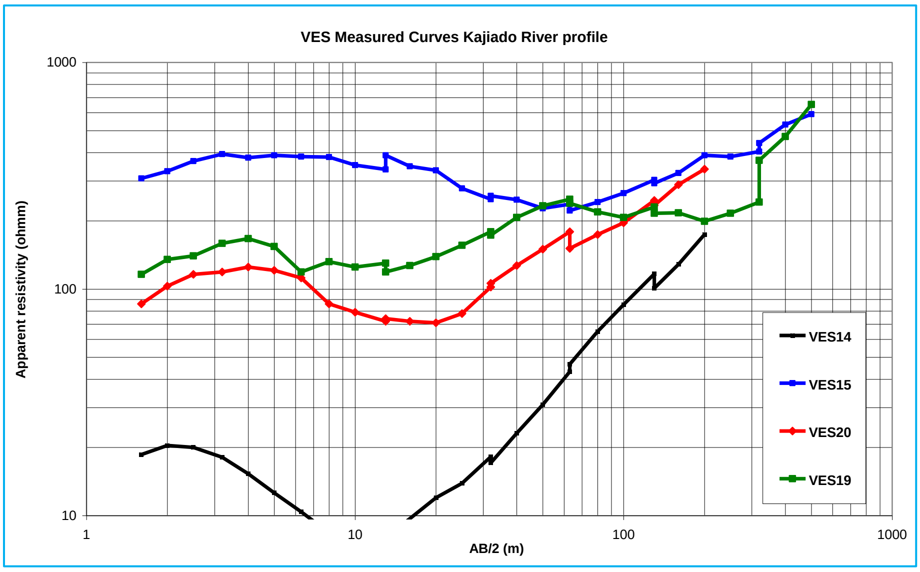


Figure 11. Field curves: apparent resistivity measurements of VES soundings at the Kajiado River transect. For convenience the data points are connected.

The uncertainty of VES 19 is large due to discontinuity and the major offset at AB/2 = 320m. The curves of VES20 and 14 typically indicate shallow clays. The soundings were all done perpendicular to the profile line. The visual view of the layer model interpretation is presented in Figure 12.

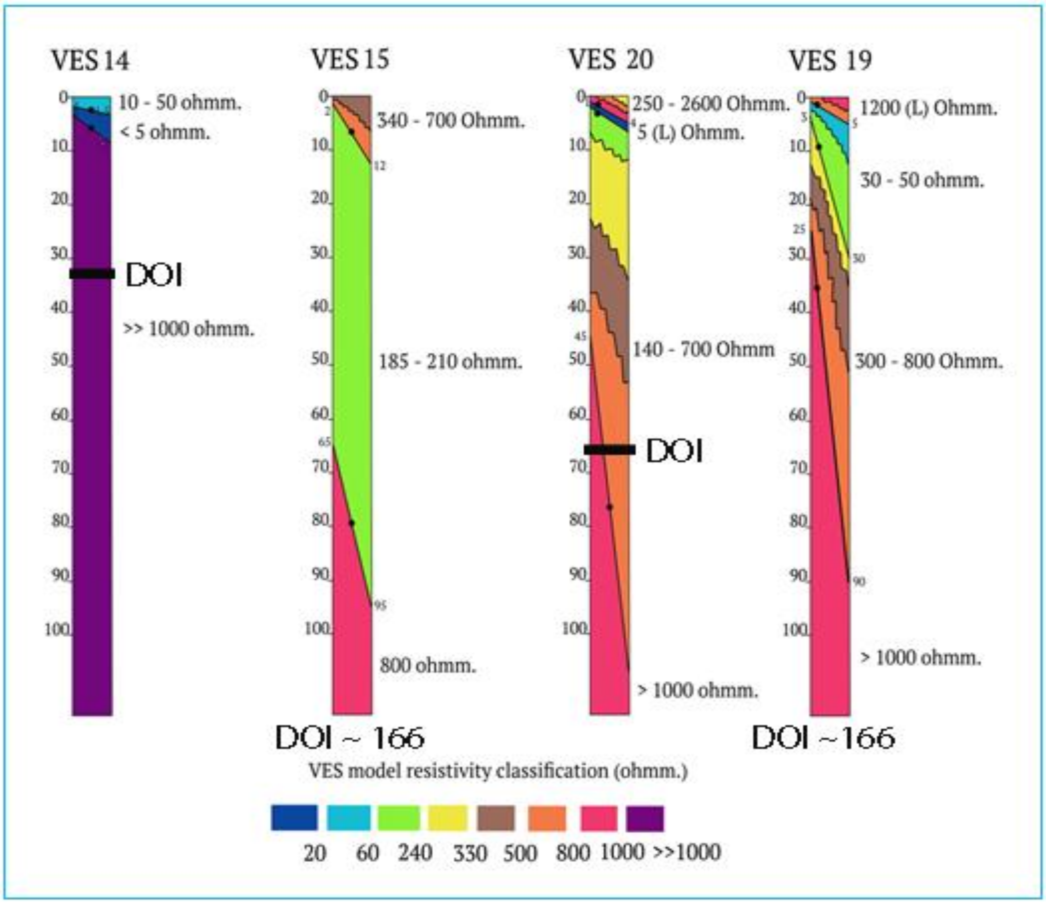


Figure 12. Interpretation of VES soundings Kajiado River. AB/6 of VES 14, 15, 20 and 19 are respectively 33, 166, 66 and 166m.

The calcultated model layers having a resisitivity of more than 1000 Ωm are interpreted as 'basement'. There are large differences between the VES's along the transect. VES14 indicates a 3 to 9 m thick clay layer right on top of a high resistive formation, while VES 15 shows relative deep basement (in between 65 and 95 mbgl), the difference indicates a major anomaly in between. Basement depth in VES 19 and 20 is uncertain due to discontinuity/offset in the measured curve (VES19) and the relatively short (AB=400m) electrode range inVES20.

Figure 13 presents the results of a HEP profile (Wenner, a=50-meter, AB=150) crossing the Kajiado river, Ildamat, Osiligi. The black lines and boxes at VES positions give the AB/2=75m apparent resistivity values as measured in the VES sounding, perpendicular to the transect. These VES values should be comparable to the HEP values.

## HEP profile Kajiado River

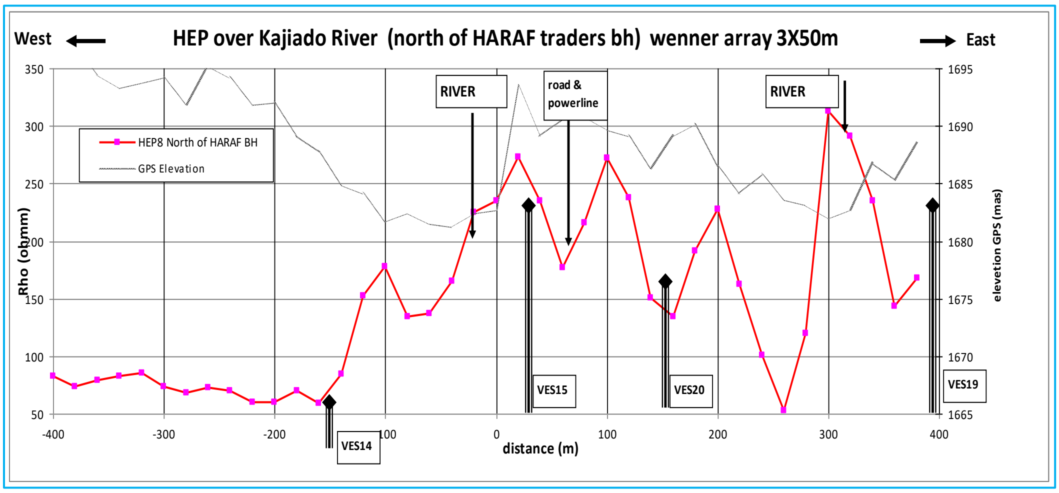


Figure 13. Result of a HEP profile (Wenner, a=50-meter, AB=250) crossing the Kajiado River, Ildamat, Osiligi.

The HEP profile shows considerable variation. The most prominent anomalies are found at the stations in between 250 – 300 m (close to the east river crossing) and the remarkable transition to low resistivity's at the west end of the line. One of the research questions was whether the HEP variations are caused by deep geological structures, maybe even indicating fracture zones. A comparison with ERT (Chapter 7) shows that the variations are caused by the resistivity variations in the superficial, shallow underground.

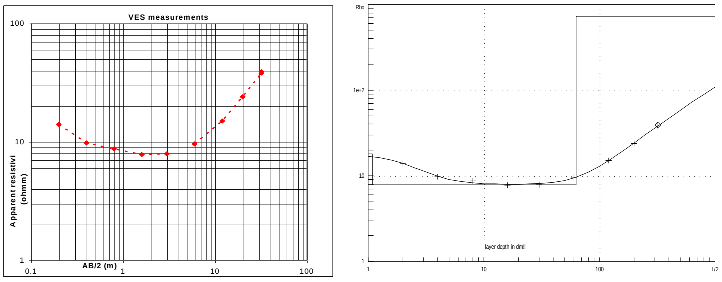
On the east side of the profile (at the 260m distance - the low value - in the HEP graph) a 'mini VES' was conducted, see Box 2 on the next page.

### Box 2: Mini VES

The so-called ‘mini VES’ sounding was conducted at a location where compact clays were found (and confirmed by shallow hand drillings), to find the resistivity of the clay and for the purpose of training.

The electrode distances are very short, starting with potentials (MN/2) at only 5 cm and current electrodes (AB/2) at only 20 cm from the center point (see photo). The electrode distances were increased in small steps, from 20 cm, 40cm, etc. up to AB/2 of 32 m.

| DATA table | | |
|---|---|---|
| | | Mini VES |
| MN/2 | AB/2 | Rho |
| 0.05 | 0.2 | 14 |
| | 0.4 | 9.8 |
| | 0.8 | 8.7 |
| | 1.6 | 7.8 |
| | 3 | 7.9 |
| | 6 | |
| 0.5 | 6 | 9.6 |
| | 12 | 15 |
| | 20 | 24 |
| | 32 | 38 |
| 5 | 32 | 39 |



From left to right: measurements, apparent resistivity field curve, model inversion (x-axis in decimeters)

The field curve shows apparent resistivity initially going down and consequently going up when the current starts passing the bottom of the clay layer. The inversion accurately reveals a clay resistivity of 7.5 Ωm (7 – 8 Ωm) and the clay thickness of 6.2 m (5.9 – 6.5 m).

# 4

# Application of Electrical Resistivity Tomography (ERT)

## 4.1 Introduction

Based on the results of the first fieldwork, two transects were selected on which ERT, TDEM, AMT and additional VES soundings measurements were executed: the Kajiado river transect and the Gully C transect (see Figure 14).

In this chapter a general introduction on the ERT methodology and its application in Kajiado is presented. ERT (Electrical Resistivity Tomography) is a direct current method. In fact, it is a combination of many HEP and VES measurements in one single, integrated data set. The method is alternatively named as CVES (Continuous VES). The system hooks up to hundred or even more electrodes, the exact amount is depending the system and brand in use. The electrodes are individually connected to one or more cables and the cables to a switch box. This switchbox is often integrated with a computer.

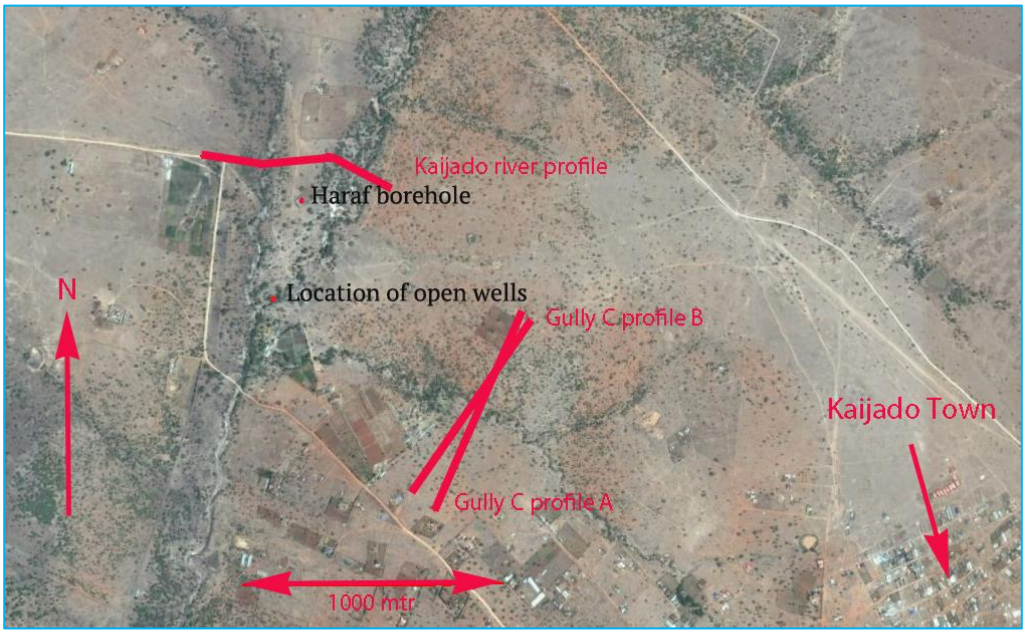


Figure 14. Location of the ISGEAG transects northwest of Kajiado town

The maximum individual electrode distance with the cable in use, when it is fully stretched, is 10 meter (with the ABEM LUND cables as used by KenGen) which will result in a maximum profile length of 800 meter. Of course, smaller distances are also possible. Cables can be ordered as desired according to customer's wishes. Various electrode measurement configurations can be selected (Wenner, Schlumberger, Dipole-Dipole, Pole-Pole, Gradient), each of them influencing the resolution, exploration depth and the sensitivity to horizontal layering and/or vertical structures. Different configurations can be executed on the same profile.

A profile of 800 meter will result in an exploration depth of roughly 800/6 which is approximately 130 – 150 meters. A profile can be extended in two directions. It is possible to continue in the same direction at the same line or to go backwards from the first measuring point, as with HEP profiling.

This so called “roll-along” is faster than the first set up because not all the data points need to be measured when rolling along. Please note that extending the profile in this way (roll-along) will not give an increase of exploration depth. For details on e.g. electrode configurations and many other practical issues, the reader is referred to the ABEM SAS4000 Terrameter Manual[4].

Interpretation, the so-called inversion, is basically the same as for VES soundings, which is the determination of a layered ‘true’ resistivities’ model from the measured apparent resistivity. In ERT this is a so-called smooth layered model, see Figure 15. It is ‘smooth’ because the resistivity contrast of the layers is calculated in a smooth way. The spacing’s between the color bands (each color band represents a different resistivity range) indicate the contrast between the layers. Because ERT is in fact an endless amount of VES’s on the same transect line, the inversion has far less equivalence (multiple amount of possible layer models) than a single (VES) data set.

Interpretation (inversion) is done with dedicated software like RES2DINV, GEOTOMO (*www.geotomosoft.com*). The so called “model fit” is the difference between the apparent resistivity data as measured in the field and the calculated apparent resistivity data that belongs to the generated smooth layered model. This fit is also called residual or RMS factor, see Figure 15. This factor, (in %), is an indication for the reliability of the model, it should preferably far below 5%. Figure 15 gives an example of an ERT inversion: on top: the raw field data (measured apparent resistivity), in the middle: apparent resistivity, which belongs to the smooth model, and below: the smooth layered model. The fit in this case is 1,93%, being the difference between the middle and top picture. Note: the top two pictures with the apparent resistivity are also called ‘pseudo sections’.

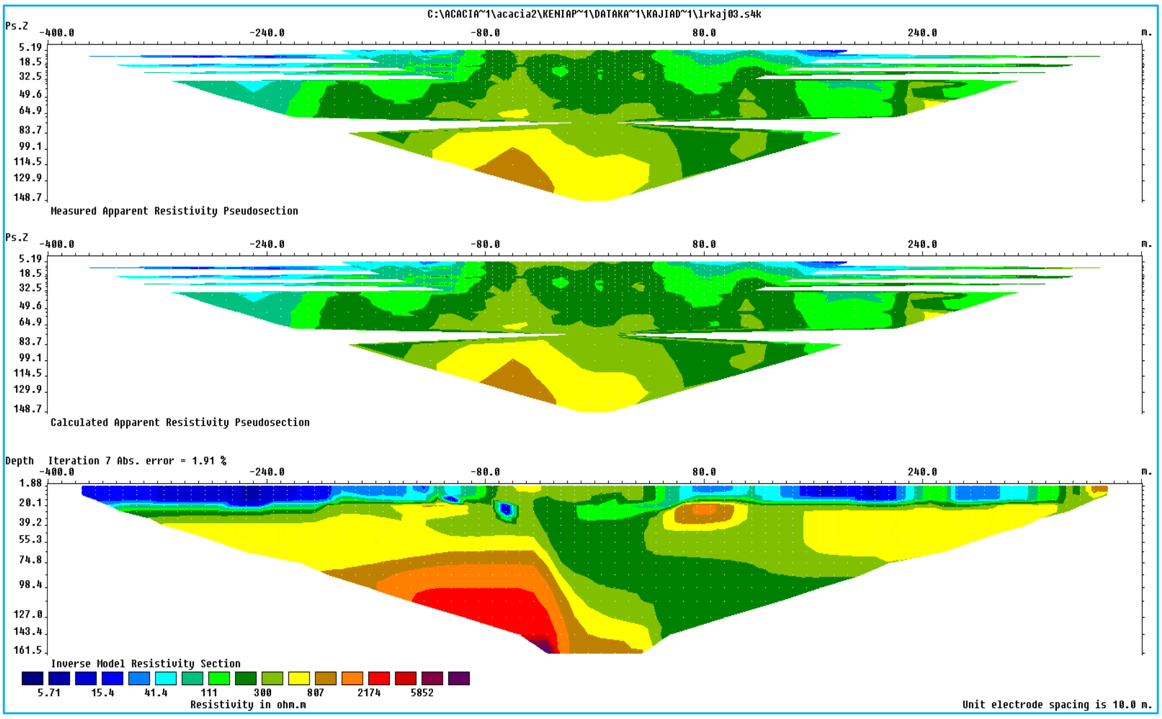


Figure 15: Example of ERT inversion

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[4] Manual ABEM SAS4000 manual, *http://www.guidelinegeo.com/wp-content/uploads/2016/03/Manual_Terrameter.pdf*

Figure 16. Connecting ERT cables by KenGen in Kajiado

Figure 17. Overview of ABEM ERT instrumentation: four reels are interconnected, with in the center an ABEM Terrameter LS. This photo was selected because of the good overview. The location was in the Netherlands, electrode distances were very short in order to monitor the development of shallow fresh water lenses over time due to new irrigations systems. Exploration depth with this set up is only 7 meter, with a very high resolution.

## 4.2 ERT methodology

This paragraph explains the general steps in field procedures of ERT (see also ABEM terrameter manual[5]).

1. If necessary ***start with forward modelling*** (see Annex 2 for further explanation on forward modelling). Forward modelling generates a synthetic smooth ERT model based on the ideas on the local hydro-geological (resistivity) concept from existing hydro-geological information (geology, VES surveys, boreholes). Forward modelling will help to decide whether resolution and exploration depth is within the proposed ERT methodology and instrument capacity. Forward modelling was applied on the ISGEAG VES and HEP data from the February 2017 campaign: synthetic ('forwarded') HEP profiles were extracted from a 'forwarded' ERT model, by which the sensitivity of shallow layers on the HEP profile (at Gulley C) was examined. Forward modelling was also applied on the ERT data of Kaijado to examine the shape and resistivity contrast of the target (fracture zone), see also annex 2.

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[5] Manual ABEM SAS4000 manual, *http://www.guidelinegeo.com/wp-content/uploads/2016/03/Manual_Terrameter.pdf*

2. ***Determine the required exploration depth***. As a rule of a thumb, the initial profile length (total length of the cables in use, or the amount of electrode (minus 1) times the electrode distance) should at least be six times the desired exploration depth. Exploration depth is also sensitive to the electrode configuration and the actual local resistivity profile. Exploration depth can also be examined by forward modelling.
3. ***Establish the direction and required length of the profile (including extension)***, mostly in the direction of the lateral change of the geology. A profile can be extended with the so-called 'roll-along' procedure. In this case the exploration depth of each section will stay the same.
4. ***Choose the desired electrode configurations***, this depends on the study object (target), its size, geometry, resistivity contrast with the surrounded layers and expected electrode resistance with the soil. As an example, Schlumberger and Wenner are more suitable for horizontal layered geology, Dipole-Dipole has better resolution for vertical structures but the exploration depth can be slightly less than Schlumberger depending the protocol and instrumentation. At the same time, Dipole-Dipole has a better lateral coverage but is more sensitive for noise. When circumstances are difficult (high top layer resistivity) Wenner is favorable because of its relative large distance of potential electrodes, giving a better signal to noise ratio. The resolution of a Wenner configuration is less than Schlumberger or Dipole-Dipole because the total amount of data points is less. Electrode configurations can be selected via dedicated protocol files in the instrument. Multi-channel instruments (like ABEM Terrameter LS and ABEM SAS 4000) contain special protocols that combine multiple configurations in one measurement session. The electrodes should be placed at least 80% of its length into the soil to ensure good contact. The electrode positions should be marked with a GPS. Also their position towards power lines, gulley's, distinct changes in topography, outcrops, anthills (etc.) should be described for evaluation. When the topography difference is in the order of the minimum electrode distance or more it should be taken into account in the inversion.
5. ***Start the measurements with an electrode test***, with instrumentation like ABEM, both the electrode connection and electrode resistance, (which is the electric contact resistance with the ground), can be tested. When the electrode resistance is high (>>1 kΩ) not all the configurations can be executed and often only Wenner can be applied. Especially when using long profile lines.

   Electrode contacts can be improved by adding salt water around the electrode, bentonite or longer electrodes with larger diameter, or by using multiple electrodes at a single position close to each other and perpendicular to the profile. Electrodes should be made of stainless steel.
6. During the measurement, ***check the evolvement of the standard deviations***. In most instrumentation the maximum stack (amount of measurements at the same electrode position to be averaged) can be changed according the desired standard deviation.
7. ***Download the data and do a simple (robust) inversion in the field*** and check the 'fit': the error between the calculated apparent resistivity that belongs to the model and the measured apparent resistivity. Then decide to conduct a roll-along or change electrode configuration, adjust profile length (or both) or start a parallel profile etc.
8. While re-collecting, ***count and clean all equipment, electrodes, hammers, electrode connector, etc. after the survey***;
9. ***Interpretation of the data*** with the inversion software starts by exterminating bad data points and executing several inversions with different parameters. If necessary another session of forward modelling can be tried to support the hydro-geological interpretation. Other sources of data can be used. Inversions can be constraint with information (logging) form boreholes.

## 4.3 Application of ERT in Kajiado

In this fieldwork we used an ABEM LUND cable system with SAS 4000 Terrameter of KenGen, with 64 electrodes in use and with a total cable length of 800 meter divided over 4 cable reels. Each reel is 200 meter, on the 2 outer reels only half of the electrode positions were used and an extra electrode was added at the junction of the cables. De maximum possible distance between the electrodes was 10 meter with these cables. The expected exploration depth with the cables fully stretched is in the order of 130 – 140 meter. Of course the same cable can be used with smaller electrodes distances. In that case the cable is not fully stretched a measuring tape must be used for the correct electrodes distances. ABEM SAS 4000 is capable to measure 4 channels at the same time (4 potential electrode positions). ABEM LS is capable of 8 or 12 channels at the same time.

1. ***Pre-forward modelling.*** Forward modelling was applied on evaluation of the HEP profiles at Gully C (February 2017). See for the results Annex 2;

2. ***Exploration depth***. The exploration depth of ERT profiles is basically the same as in the conventional methods VES and HEP. As a rule of a thump, it is roughly 1/6 of the maximum AB length (maximum distance between the current electrodes or the dipole-dipole pairs). Nevertheless, it depends also on the used electrode configuration and the resistivity of the geological formations. Groundwater table (if any) in this area depends on the topography. It is encountered around 50 m. in the research area. The aquifer can, however, be confined, which means that the actual aquifer is deeper. In order to get information of the geometry and position of possible aquifers it is necessary to go far beyond the groundwater table. Therefore, ERT cables up to a length of 800 meter have been used. The 800-meter cables results in a maximum exploration depth of ~150 m. The direction of the profiles was based on an assessment of satellite images, existing boreholes (e.g. the HARAF trader's borehole) and the dendritic (rivers/gulleys) pattern. See Figure 18 below.

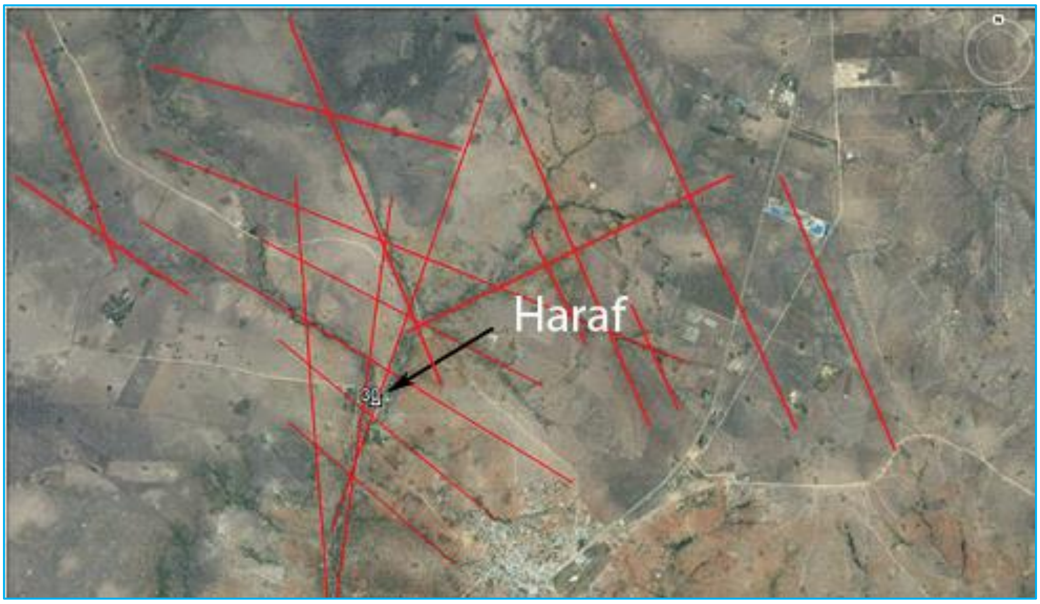

Figure 18. Lineaments from satellite images, with the location of Haraf borehole

3. ***Direction of the profile:*** Two transects were selected (Figure 14). One is perpendicular across Gully "C" to investigate the anomaly found in the first fieldwork period with VES and HEP. The second transect was perpendicular to the ephemeral Kajiado river system Northwest of Kaijado town to explore evidence of major fracture zones, as suspected from a high yielding commercial (Haraf Traders) borehole in this area (Figure 18). Since there was no documented information from existing surveys and boreholes, we assumed that the direction of geology change is perpendicular to the Gully/River. Because of the length of the profiles (800 m.) and the size of the gully system it was not necessary to "roll-along". We decided to do an additional ERT with a smaller electrode distance as well, in order to achieve a higher resolution (but smaller exploration depth);

4. ***Electrode configuration:*** The best possible electrode configuration depends on many things. Part of the project area was covered with a conductive topsoil (clay) which is favourable for the electric contact between electrodes and soil. Because both in resolution and exploration depth Wenner is less favorable, the Schlumberger[6] and Dipole-Dipole[7] configurations were selected. Also, a multi-channel Gradient protocol was conducted at the Gully "C" profile. A gradient protocol is based on Schlumberger, where not only the center potential but also 3 other offset

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[6] Manual ABEM SAS4000 manual, *http://www.guidelinegeo.com/wp-content/uploads/2016/03/Manual_Terrameter.pdf*

[7] USGS smooth sounding graph, *ftp://geom.geometrics.com/pub/GeoElectric/Drawings/Res2dinv.pdf*

potentials are measured at the same time. This will result in collecting more data points within the same time expand;

5. ***Electrode test***. Almost 60% of the electrode contact resistance was much lower than 1 kΩ. These locations with low resistance coincided with the clayey topsoil. The electrodes with a higher (but still acceptable) contact resistance could be related to the sandier soils. This was confirmed in the inversions. Because of these favorable conditions both the Schlumberger, Dipole-Dipole and Gradient configurations were applied. It was not necessary to reduce electrode resistance by adding salt water or extra electrodes. GPS points of each electrode position were taken as well as additional transect information on geology, hydrography, topography, vegetation, roads, houses, power lines etc. There was some confusion though on the GPS coordinate system to be used. KenGen is used to the ARC1960 system related to the Kenyan map system. It is advisable to move to WGS84 as standard, also for its direct application into Google Earth;

6. ***Standard deviation***. Due to the favorable conditions of the top soil, standard deviations could be kept well below 5% and most of the measurements even below 1% without additional stacking or averaging. For the calculation of standard deviation, two measurements at the same position are necessary. The new instrument of ABEM (Terrameter LS) is capable to calculate the standard deviation within one measuring cycle which reduces the total data acquisition time by at least 50%!

7. ***Data check.*** To check and evaluate the field data, the data was downloaded and simple robust inversions were done in the field in between each of the measurements;

8. ***Equipment check.*** All equipment was re-collected, counted and cleaned;

9. ***Interpretation of the data.*** Inversions were executed with the earlier mentioned RES2DINV and forward modelling with RES2DMOD software. After removing data outliers, a standard or robust inversion was calculated and several other inversion options were experimented. The more similar the results are, the more reliable the inversion model is. The amount of required iterations to reach a good fit is also indicative. In figure 4.6 (Schlumberger) and 4.7 (Dipole-Dipole), several inversions with different parameters on the same (Kajiado River) data set and the same electrode configuration are presented. The inversion with the best fit is at the top. The lower picture is an example of an inversion with extrapolation to the edges. This can lead to misinterpretations, especially with the Schlumberger configuration which has a much lower deep lateral data coverage than dipole-dipole. The fit is also misleading because the interpolated edges are not counting!

The next step is to compare the inversion results of different electrode configurations. In general, the results will be different, depending on the geometry of the resistivity distribution. The Dipole-Dipole configuration is more sensitive for relative small vertical conductors (e.g. in fractures); these conductors may be overseen in the Schlumberger configuration. This depends on the shape, location and resistivity contrast of such vertical anomalies. At the same time the Dipole configuration tends to exaggerate these vertical conductors. This is clearly illustrated in figure 20, especially in the lower picture, where at both ends of the profile, due to lack of data, vertical structures are generated in the model. In Figure 19 and Figure 20 on the next pages the inversion results of the different configurations are compared.

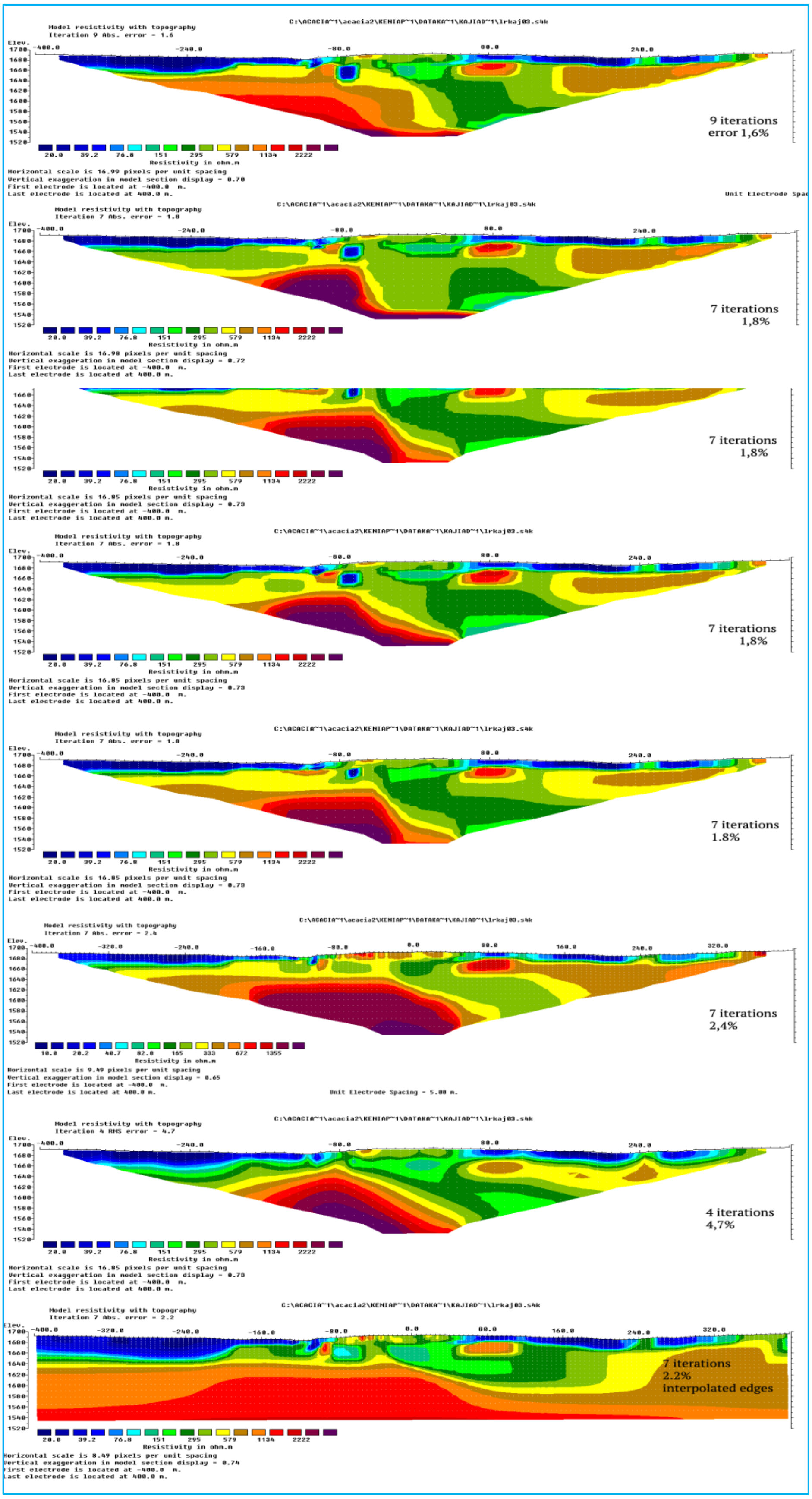
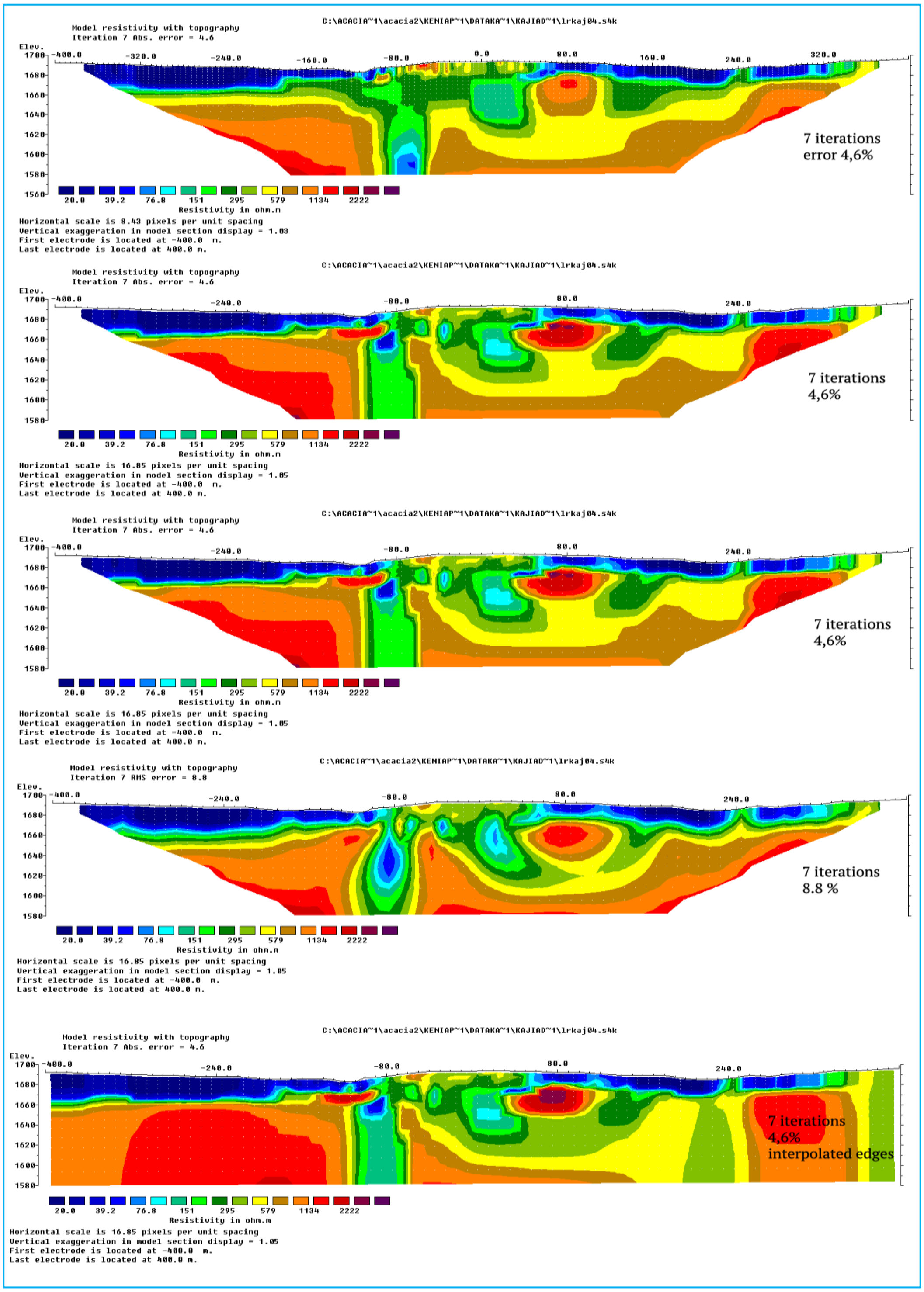


Figure 19. Several Schlumberger inversions of the Kaijado River data set, with different parameters on the same dataset ranked on their fit. Note that in the inversion with extrapolated edges (below) the fit does not count for the fit of these edges!



```
Model resistivity with topography
Iteration 7 Abs. error = 4.6
C:\ACACIA~1\acacia2\KENIAP~1\DATAKA~1\KAJIAD~1\lrkaj04.s4k
Horizontal scale is 8.43 pixels per unit spacing
Vertical exaggeration in model section display = 1.03
First electrode is located at -400.0  m.
Last electrode is located at 400.0 m.

Model resistivity with topography
Iteration 7 Abs. error = 4.6
C:\ACACIA~1\acacia2\KENIAP~1\DATAKA~1\KAJIAD~1\lrkaj04.s4k
Horizontal scale is 16.85 pixels per unit spacing
Vertical exaggeration in model section display = 1.05
First electrode is located at -400.0  m.
Last electrode is located at 400.0 m.

Model resistivity with topography
Iteration 7 Abs. error = 4.6
C:\ACACIA~1\acacia2\KENIAP~1\DATAKA~1\KAJIAD~1\lrkaj04.s4k
Horizontal scale is 16.85 pixels per unit spacing
Vertical exaggeration in model section display = 1.05
First electrode is located at -400.0  m.
Last electrode is located at 400.0 m.

Model resistivity with topography
Iteration 7 RMS error = 8.8
C:\ACACIA~1\acacia2\KENIAP~1\DATAKA~1\KAJIAD~1\lrkaj04.s4k
Horizontal scale is 16.85 pixels per unit spacing
Vertical exaggeration in model section display = 1.05
First electrode is located at -400.0  m.
Last electrode is located at 400.0 m.

Model resistivity with topography
Iteration 7 Abs. error = 4.6
C:\ACACIA~1\acacia2\KENIAP~1\DATAKA~1\KAJIAD~1\lrkaj04.s4k
Horizontal scale is 16.85 pixels per unit spacing
Vertical exaggeration in model section display = 1.05
First electrode is located at -400.0  m.
Last electrode is located at 400.0 m.
```

Figure 20. Several Dipole-Dipole inversion variants on the Kajiado River data set, with different parameters on the same dataset ranked on their fit. Note that in the inversion with extrapolated edges (below) the fit does not count for the fit of these edges!

As illustrated by Figure 19 and Figure 20 there are clear differences between the inversions within the same electrode configuration. And even more between the inversions with different electrode configurations. Additional forward modelling can help to find the most suitable inversion (see Annex 1).

In Figure 21 and Figure 22 the final inversions of the profile crossing the Kajiado River and Gully C are presented. In the River profile, Dipole-Dipole indicates a deep vertical anomaly. This could however be an amplification effect, caused by the presence of a local superficial low resistivity layer, a phenomenon that was already noted in the field. For this reason, a second profile on the same line with both Dipole-Dipole and Schlumberger was executed with a smaller electrode distance (5-meter, total length 400-meter, exploration depth 70 meter), giving a decreased exploration depth, but a higher resolution. This smaller profile confirms a distinct vertical anomaly, indicating a deep fractured zone. The shape and geometry of this fracture zone can be further verified by forward modelling.

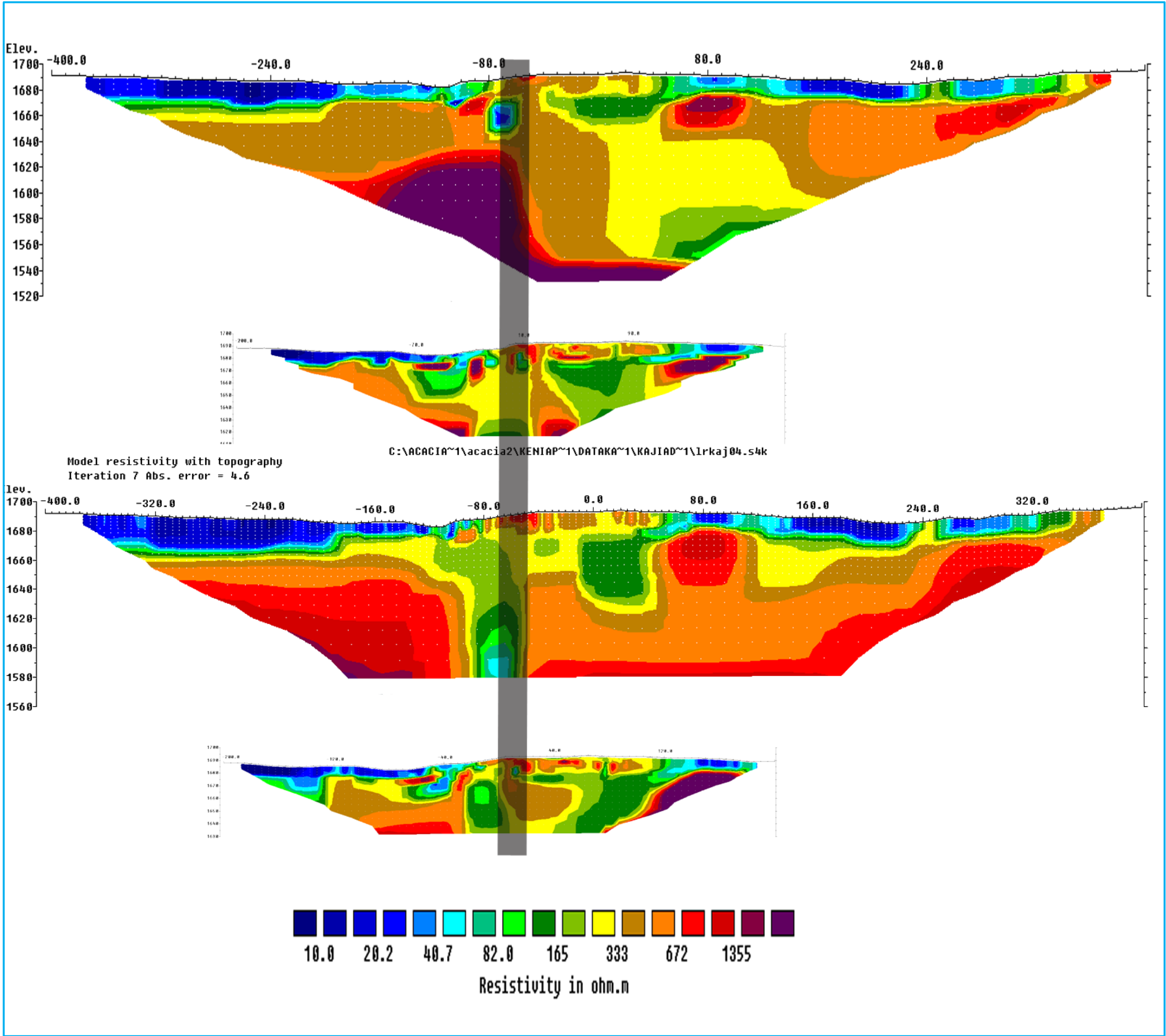


Figure 21. Overview of the different inversion results of the Kajiado River profile, above 800 and 400-meter Schlumberger inversions, below 800 and 400 meter inversion of the Dipole-dipole inversion variants.

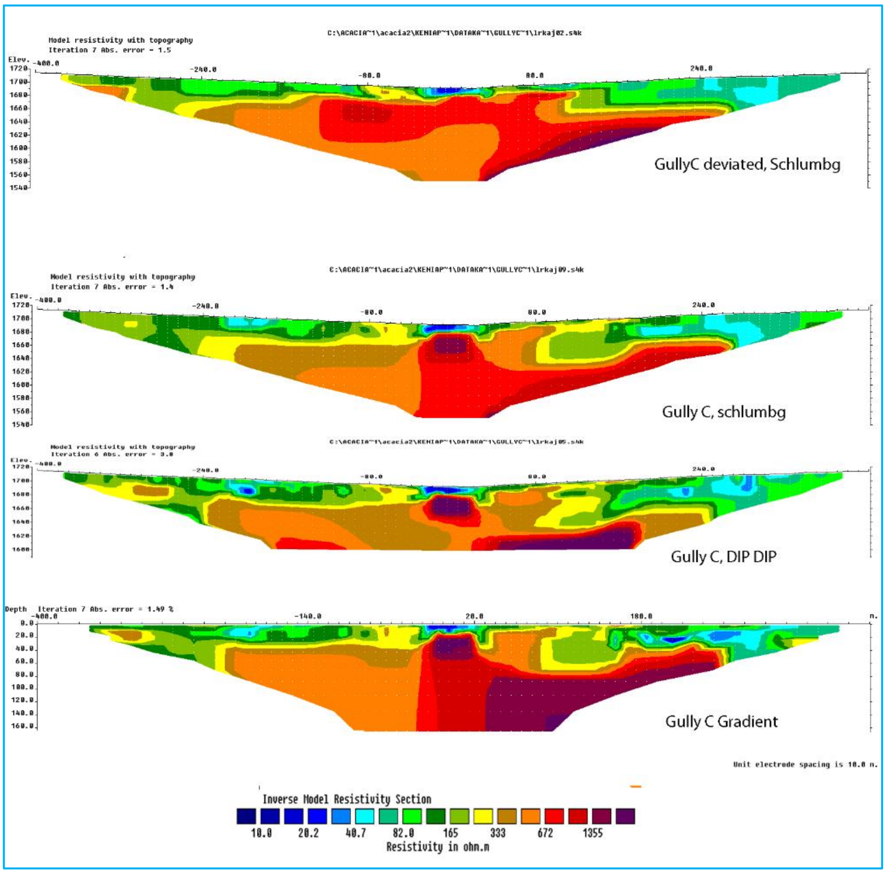


Figure 22. Overview of the different inversion results of the Gully C profile

The inversion results Gully "C" profile show less indications for a fracture. In the center, near the gully bed, a local clay layer is located directly on top of the bedrock (or hard cap, remnant of basalt outflow etc.). However, there is a distinct change in depth to the bedrock more north in the profile, which may coincident with paleo relief in the bedrock or deeper weathering due to different types of bedrock. The resistivity value >1000 OhmM experienced at depth is a clear indication of Fresh basement rock. It seems to be increasing with depth and there is a discontinuity towards the other side of the river (figure 22, see also paragraph 7 comparison of the methods).

In Figure 23 the Dipole-Dipole inversion of Kaijado River and the Gradient of the Gully "C" is projected into 3D picture at the location of the profiles, which is used for the hydrogeological interpretation.

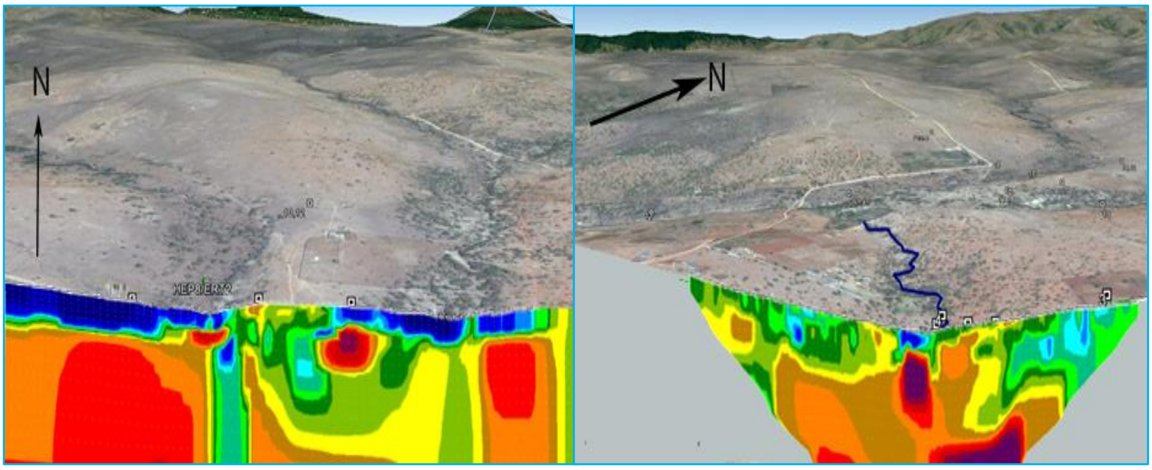


Figure 23. The projection of a Dipole-Dipole inversion of (left) Kajiado River (with interpolated edges) and (right) the Gradient inversion of Gully "C" into Google Earth 3D view.

At Gully C, two almost parallel ERT profiles were executed crossing each other at a small angle. This was to examine the effect of lateral change perpendicular to the profile (Figure 24).

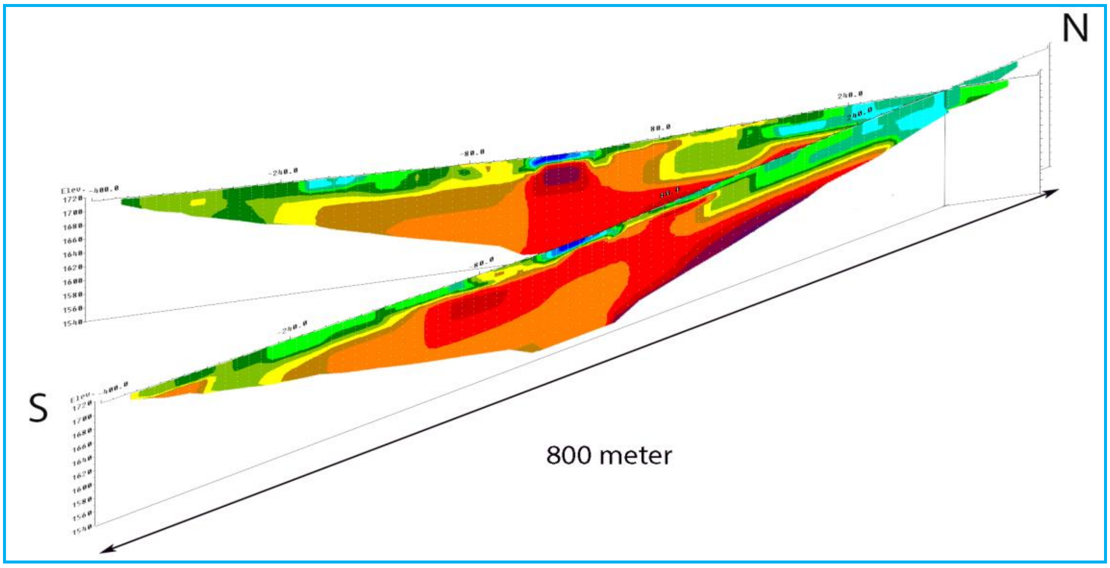


Figure 24. The two Gully "C" ERT profiles crossing each other at a small angle.

## 4.4 Conclusions

- Electric Resistivity Tomography is able to discriminate (vertical) anomalies, up to ~150 m depth with the equipment in use. Vertical anomalies within the initial spread (in Kajiado 800 m.) can be detected
- It is important to apply different electrode configurations if possible and carefully compare their inversion results.
- Though much less than in VES, equivalence (more models having the same fit on a single data set) is still an issue, also with ERT.
- The need for long ERT cables became clear. The ERT electrode distance should be related to the desired exploration depth. In this case the minimal distance between two electrodes was 10 meter which resulted in 800-meter profiles and an exploration depth up to 140 meters in the center of the profile. This is more or less 1/6 of the total profile length, which also applies to VES!
- Note that the exploration depth with this Dipole Dipole configuration extends over more than half of the profile length and its maximum exploration depth is (with the protocol used, 4channel protocols give a better later distribution of the exploration depth) less as compared to the Schlumberger configuration. This Schlumberger configuration reaches the maximum depth only in the center.
- Proper application of ERT is more than producing a nice color picture. The interpretation of ERT results towards the (hydro) geological concept needs professional care and verification by different geophysical methods, integration with all existing (and hopefully available) reported information and should finally be confirmed by test wells. Further discussion on the interpretation of the local hydrogeological concept is discussed in Chapter 9.

In Chapter 7 the ERT results are further compared with the results of other methods.
In Chapter 9 a concept of the hydrogeology is posed and discussed on its opportunities for sustainable water supply.

# 5 Application of Time Domain Electro-Magnetic (TDEM) Sounding

## 5.1 Introduction.

TDEM soundings have been applied to both ISGEAG research transects, crossing the Kajiado River and Gully C (see also Figure 2, Chapter 2). In this chapter a more profound introduction on the TDEM background, methodology and its application in Kajiado is presented.

In general, TDEM is used for (very deep) soundings, for instance it is used in Kenya by KenGen for hydrothermal energy (DOI >500 m.). Profiling can be achieved by the combination and joined interpretation of several soundings along a profile line. TDEM profiling based single soundings was the application that was used in Kajiado. In Kajiado we wanted to use, at least for TDEM, for relative shallow applications.

TDEM is not widely used in groundwater exploration in Africa. The reason might be the more complicated and expensive instrumentation, while interpretation is not as straight forward as the conventional VES method. However recent developments in instrumentation (like WALKTEM) end Software (like SPIA) overcomes this. In this field campaign we had, unfortunately due to unforeseen circumstances no possibility to use WALKTEM. However at the start of the second campaign we could use the WALKTEM instrumentation on the Kajiado river profile. See for these results chapter 7.
An advantage of TDEM is that a larger exploration depth is easier to achieve than VES, with a smaller spread (transmitter loop size). Because TDEM is based on induction, the method is particularly suitable for exploring deep conductors below high resistive top layers without using electrodes. The method is known to be less applicable in locations with high and increasing resistivity. The method is not suitable for very shallow investigation (10- 30m.) However with new instrumentation this is changing (like WalkTEM).

In the ISGEAG project the main reason for the choice of TDEM to test its applicability for groundwater exploration was because of its potentially large exploration depth compared to VES and ERT. Also the field lay out is less time consuming than VES. With TDEM, an exploration depth of 150 – 300 meter is relative easy to achieve depending transmitter loop and current in use. The exploration depth of VES soundings in the Kenyan consultancy practice is limited to roughly 100 m (with a current electrode distance of already 600 meter). Many Kenyan aquifers and groundwater levels are deeper. In many reports the exploration depth of VES is over-estimated (see paragraph ▯ on traditional methods).

More sophisticated systems for mapping lateral change (2D and 3 D) are airborne TDEM systems (like SKYTEM, Figure 25) [Pedersen e.a. 2017 and PWN, Artesia 2013]. These systems can map large areas with a relative high lateral resolution but are expensive to execute. This is why the applicability concerning exploration depth and resolution should be tested with single soundings at ground surface before the decision taken to apply airborne.

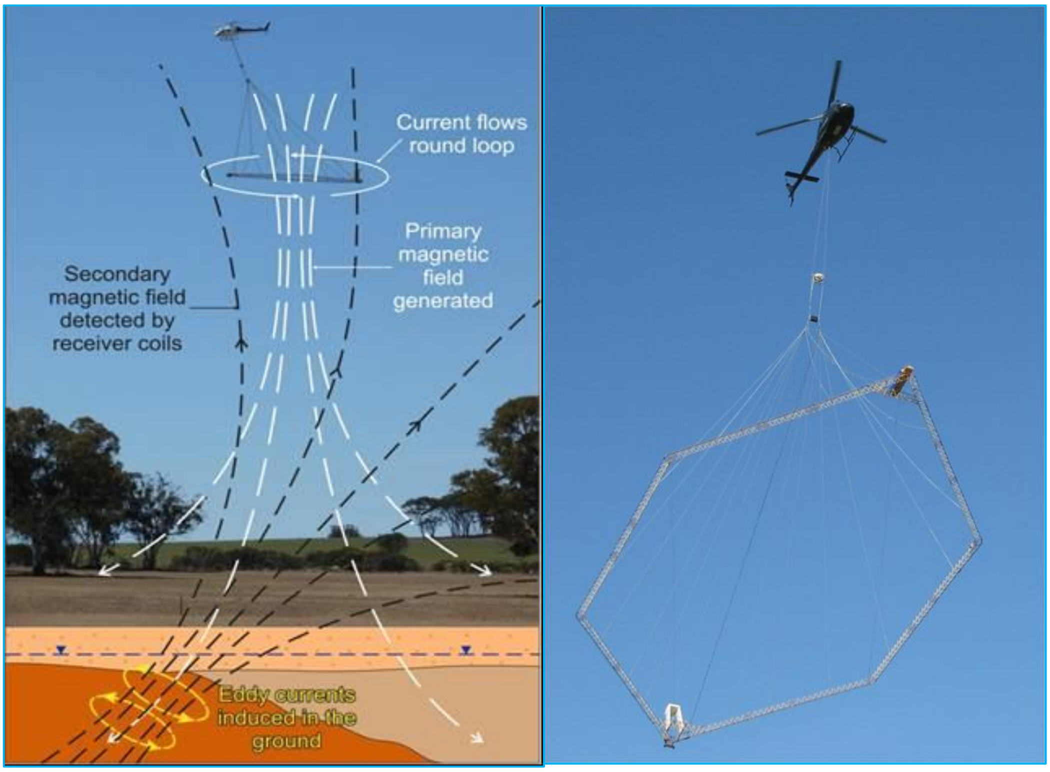


Figure 25. Airborne TDEM application (SkyTEM) in the Netherlands [PWN, 2013]. The basic principle is shown on the left, while the current transmitter coil below a helicopter is shown on the right.

## 5.2 Principles of TDEM

In general, electromagnetic (EM) methods are based on Maxwell's theory and equations: a changing electrical field in a transmitter antenna (or loop) generates an EM field. This so-called primary EM field passes through the subsurface and induces a secondary field ('eddy currents') in the more conductive layers. The strength of this secondary field increases with increasing conductivity of the subsurface. At the same time this signal decreases with depth because of the attenuation of the primary field. Two well-known systems used in groundwater exploration are TDEM (Time Domain EM) and FDEM (Frequency Domain EM). In this research only TDEM is applied because of the limitations of FDEM in its resistivity range and exploration depth.

In TDEM, the primary EM field is generated by a transmitter that is sending a low frequency switched current into a transmitter antenna or so called transmitter loop. This transmitter antenna can be typical an isolated single copper wire, laid down in a square on the earth surface ranging from 40 X 40 up to even 1000 X 1000 m side by side. The switching period can be arranged and runs typical from 2 Hz up to 100Hz or more depending instrumentation. Increasing the frequency will decrease the exploration depth but increases the resolution. This switched primary EM field induces eddy currents in the subsurface. The moment the transmitter is switched off, the receiver starts to measure the induction generated with this primary field in the subsurface in a receiver antenna with time. This antenna could be a simple isolated single wire loop or a more sophisticated multi coil receiver antenna. The change in strength of the induced EM field ('magnitude'), in the receiver antenna is measured with time (micro- and milliseconds) and in (Nano-micro) Volts (or amps). This time-magnitude decay curve is in fact a measure for the change in conductivity or resistivity with depth. The current due to induction of the primary field in the receiver antenna is measured in discrete time windows. The measurements in the first-time windows (first arrivals) come from layers closer to the surface and the later time windows hold information from deeper layers. The magnitude versus time graph can be calculated into an apparent resistivity versus time or depth graph. This graph can be inverted into a layer model (formation resistivity versus layer depth). As with VES there are more possible solutions for one single sounding graph (equivalence) and horizontal layering is assumed.

The receiver antenna can be located inside the transmitter loop (in loop), at the same location as the transmitter loop (coincidental loop) or outside the transmitter loop (external or moving loop either fixed or with an increasing receiver transmitter distance). See also Figure 26, Figure 27 and Figure 28.

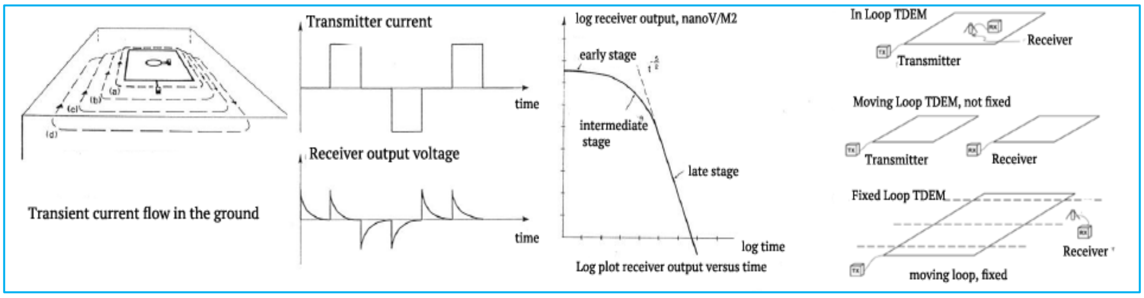


Figure 26. Left: primary field generates an EM field into the earth, center left: graphical presentation of alternating transmitting EM field and induced, secondary reaction in the receiver, center right: decay curve, right: various field set ups

Figure 27. Set up of TDEM system (KenGen), transmitter with car batteries at the corner of the Transmitter loop (100x100), the receiver and the multi coil receiver antenna are in the center (at distance).

Figure 28. Detail of the carefully oriented TDEM multi coil receiver antenna. In the back the (Zonge GDP32-II) receiving instrument, and further away (near the trees), the location of the (Zonge ZT30) transmitter at the corner of the insulated single copper wire transmitter antenna loop which is laid down in a square around the set up. The receiver antenna is located in the center of the transmitter loop.

EM systems measure the generated induction; this is the reason why they are especially sensitive to conductive layers and less sensitive to high resistivity's. This is a basic difference between DC (VES, ERT) and EM systems. TDEM, thus, is sensitive for the conductivity and the depth of a conductor, like a clay layer or saline groundwater and is less sensitive for changes in high resistivity or increasing resistivity with depth, like a bedrock basement (as in the Kajiado case).

One single TDEM measurement can be considered as a one-dimensional sounding. The TDEM inversion based on a single measurement assumes horizontal layering (same as VES). Multiple soundings along a profile line will give information on lateral change.
Both the lateral and vertical resolution of TDEM is in general less compared to tomography methods like ERT. However this is also depending the electrode distance in use of the ERT and the used protocol and the TDEM system in use. Nevertheless, TDEM systems can easily reach depths of hundreds of meters, without using electrodes through inductive coupling and with less lateral extend (and is therefore less influenced by the effects of lateral changes) if compared to conventional VES. Vertical conductors or strong conductive lateral changes will give anomalies in the sounding graph (compared with VES soundings) these graphs cannot be inverted into a (horizontal) layered model. This is the same as with VES when the sounding graph is not smooth due to lateral change, the inversion into a layered model is less reliable.

The TDEM method measures the decay of this secondary field in time (microseconds) after the “shut down” of the primary field, each time. The frequency of shutting down the primary field and recharging it is in fact the frequency of the measurement (repetitions). With the increasing time of the decay, also the exploration depth of the measurement will increase until the signal is lost in the background noise. The transmitter loop size (most systems use a transmitter loop as a single wire square), the amount of turns of the transmitter loop, the current of the transmitter, the frequency of the “shut down” pulse as well as the resistivity of the earth itself will influence the penetration depth and the depth from which the measurement starts. The first tenth of meters is lost due to the shut-off time (micro seconds) of the system, this starting depth is also depending on current and loop size. Very fast systems start earlier however they have a limited exploration depth. Increase of the loop size or current will increase this shut off time and therefore the starting depth of the sounding information. The more sophisticated the system is, the more (the faster) information you can get from the first layers and the better the penetration depth will be. The systems like WALKTEM (ABEM) are equipped with a so called dual moment option which will give both shallow as well as information from deeper layers at the same time, due to the application of two magnitudes of the transmitter current just after each other, within the same measurement. The data can be combined in a single sounding graph.

It depends on the size, depth and resistivity contrast of the target, how the operator should decide on loop size, amount of current, loop turns and other parameters for best resolution and optimum penetration depth.

Loop size can be used as an indication for the exploration depth, often 1,5 - 3 times of one side of a square loop is indicative but depends also on resistivity of the subsurface, transmitter current, transmitter turns and background noise. This exploration depth is roughly approached with the so-called diffusion depth and can be estimated according the time window which is still above the noise and the bulk earth resistivity:

$$D \text{ (diffusion depth)} = 40\sqrt{t/\sigma} \approx \text{equivalent depth of exploration, } D = 28\sqrt{\rho t} \text{ (meter)}$$

- $t$= *time milli-seconds (time window)*
- $\sigma$= *apparent conductivity (Siemens/m)*
- $\rho$= *apparent resistivity (Ohmm)*

The apparent resistivity can be calculated from the magnitude measured in the time windows which are still above background noise. Most of the instruments provide this calculation.
Due to equivalence (more solutions for one graph, as with VES) the exploration depth is not a fixed number and varies with interpretation of the model resistivity. For example, in Kajiado, for a homogeneous layer with resistivity of 400 Ohmmeter (weathered basement), measured at a time window of 1 millisecond, this diffusion depth could be over 500 meter, if the signal strength is still above noise. This depends on the chosen transmitter loop size and transmitter current. An uniform resistivity of 10 ohmmeter will result in a much lower equivalent depth of exploration, even less than 100 m.

### 5.2.1 Noise

Power-lines and metal fences should be at least at 100 meter distance or 1 - 4 times the distance of one side or radius of the loop. With increasing earth resistivity, the distance to these structures should also be increased. Inductive coupling with these manmade structures cannot be filtered.

Two types of coupling with manmade structures can be discriminated: galvanic coupling and capacitive coupling. Galvanic coupling, which can be caused due to coupling with overhead power lines, will cause a smooth change in magnitude over many data points, which is very difficult to recognize from single soundings. Capacitive coupling, due to conductors (grounded) in the sub surface (buried pipes, power lines, fences or natural conductors) will show a severe disturbance in the decay curve: both a smooth in magnitude (resulting in a lower calculated resistivity) over many data points and a sharp sinus shaped anomaly in several data points. (figure 29) These effects seem minimal in the log-log magnitude versus time graph however, the shift in the calculation of a layer model (inversion) will be severe. In this case the resistivity will be underestimated or the depth over estimated. It should be noted that the effect of coupling is not the same as the background noise.
Another type of disturbance is due to induced polarization (IP) caused by certain sediments like clay layers with minerals with a high magnetic susceptibility like magnetite. This can be recognized because IP effect will generate negative readings.

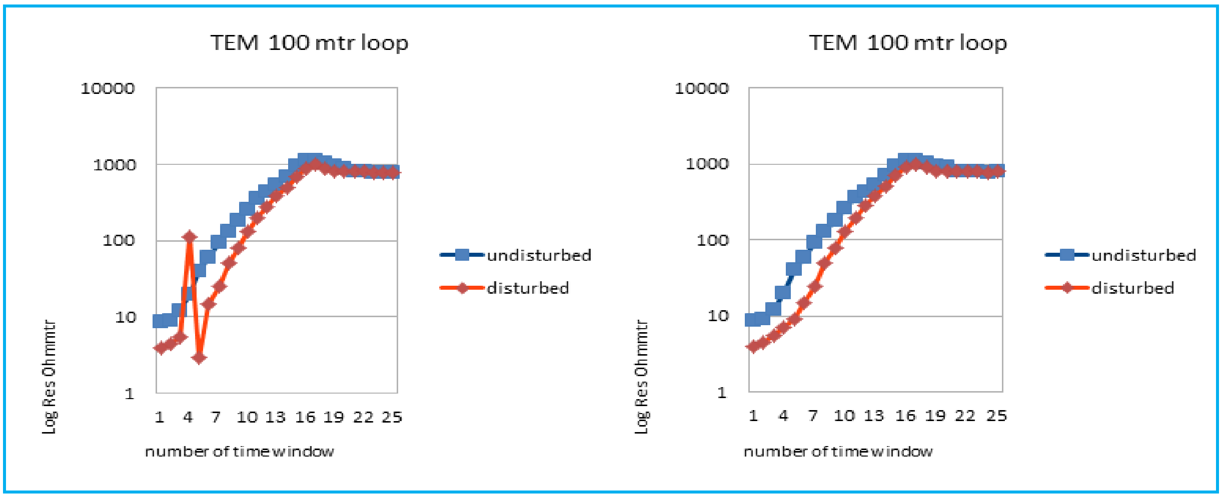


Figure 29. Synthetic examples based on field measurements of the effect of capacitive coupling (left) and galvanic coupling (right) on TDEM sounding graphs.

The central loop configuration is more sensitive for this IP effect. It will be visible in the early times, moves to later times with increasing transmitter coil size, but the effect will be diminished.

Offset configurations (receiver antenna is placed outside the transmitter loop) on the other hand are extremely sensitive to small variations in the resistivity of the near surface, which may influence the interpretability of the decay's. The in-loop configuration (receiver antenna is placed inside the transmitter loop) is far less sensitive for this. The offset configuration is also very sensitive for small deviations of the array. For hydro-geological profiling with multiple soundings, in-loop or coincidental configurations are therefore in most areas, preferable.

In loop configurations, while using high transmitter current may cause saturation of the receiver amplifiers and a distorted signal in early arrival times. Current should be kept relative low with small transmitter loops. Or a combination of increasing loop sizes and increasing current can be explored at the same station. The problem in this case can be that lateral change in geology will affect the transients resulting in decay's that cannot be combined. Instruments with a dual moment option (low current for early times) and high current for late arrivals can overcome this problem (ABEM, WALKTEM).

### 5.2.2 Methodology, general steps and field procedures of TDEM

The field described procedures depend also on the system and brand of instruments to be used.

1) ***Initial forward modelling.*** In general, forward modelling is advised to investigate if a proposed target is detectable. With forward modelling the sensitivity for changes in depth of a (weathered) basement or the detectability of low resistivity layers (conductors) can be tested. The resistivity's from existing VES's or borehole logs can be of use in the modelling. Most inversion programs support forward modelling. Actually, curve fitting, where the fit of a model is compared with the field data, is in fact a way of forward modelling. Freeware is available from Aarhus University, Denmark, the program is called EMMA[8]. With forward modelling equivalence can also be tested. Equivalence means that more than one-layer model has a good fit on the field data. Equivalence will always occur, as in VES and ERT (though in ERT much less). In TDEM, equivalence will be more severe in the high resistivity part of the sub surface. In general, TDEM is more sensitive on the resistivity of conductive layers and its thickness or depth but is less sensitive (more equivalence) in the less conductive (high resistivity) part of the subsurface. Which means that circumstances as expected and encountered in the Kajiado basement geology are less favorable for TDEM;

2) ***Optimum transmitter loop size and turns***. The next step is to perform a field test with the most favorable transmitter loop-size (if necessary multiple loop turns) depending on the desired exploration depth (and resolution). The test side should preferably have low background noise, away from power lines, metal fences and most favorable on a homogeneous but representative area of interest. Not too close to an expected (lateral) change in geology, like fractures. In this first test, all the important parameters can be examined; results can be compared and if necessary adjusted.
   The receiver antenna is in most cases a multi-coil receiver, (see figure 28. A single isolated copper wire can also be used as a receiver antenna. These simple single wired receiver antennas can be laid in a square at the same size (coincidental loop) or smaller than the transmitter loop (in loop) see figure 26;

3) After both the transmitter and receiver loop is laid down, the ***background noise*** should be recorded (with the transmitter turned off). This is the level were the signal of the sounding (transmitter on) in its corresponding time window will not be detectable;

4) At this stage several ***tests*** with different transmitter currents, delay times, measuring frequencies can be executed and the corresponding decay curves judged. Transmitter loop size or so-called transmitter moment (the moment is the surface of the transmitter loop times the amount of turns) will influence the exploration depth, resolution and the starting depth of the measurement. The bigger the transmitter loop, the higher the necessary transmitter current, the deeper the exploration depth will become, however resulting in a lower resolution and often missing more data of the first layers due to increased shut off times of the instrumentation. This is the so-called TX delay time and actually the time or moment the receiver can start to measure. For bigger loop sizes more current is required and the system in use must be able to generate this current.

   - Transmitter Loop turns: the amount of turns will also influence the transmitter moment (surface of the antenna loop) and therefore the Tx-delay (increase). The more turns the higher the moment, the longer the Tx-delay the deeper you will get, but at same time you will lose information of the top layers.
   - Receiver loop, which will result in the receiver moment, depends on the receiver in use: multi-coil or single wire. In the case of a single wire, the receiver moment is the surface of the receiver square. This value is necessary in the calculation of the resistivity's in the inversion software. Sometimes there is a magnifier taken in account depending the loop turns. Multi coil receivers will result in higher receiver moments keeping the loop surface small.
   - Transmitter delay time (Tx-delay): This is the delay time after the current shut-off and indicates the start of the measurement of the decaying field, thus influencing the depth from which information can be obtained. Some systems can measure the Tx delay time according to the loop size, loop turns and current in use. It can also be calculated. It will

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[8] *http://hgg.au.dk/software/emma/*

be in micro seconds. Wrong delay times will lead to missing data point at the beginning or end.

- EM-frequency: TDEM systems use fixed time windows at which the decay is measured. These windows depend on the chosen measuring frequencies. Therefore, resolution and depth also depends on the chosen frequency. With lower frequency's the windows become more distant and will shift to later times. The lower the frequency the longer the measuring time, which therefore will increase the exploration depth but at the same time will decrease the resolution (layer thickness versus resistivity contrast) and starting depth.
- Transmitter current: the current set in the transmitter will also influence exploration depth, the higher the current the longer the systems takes to shut of the power, this will increase the starting depth of the measurement and the exploration depth. With higher currents, the signal will be stronger and will be able to measure at later times above the background noise. There is a limit because at a certain moment the current will saturate the receiver amplifiers.
- Pre-Filtering, such as power line notch filters or low pass audio filters are possible in most systems. Filters might cause some extra delay, and therefore loss of information of the first layer(s).
- Gain settings, can be manually or fully automatic, gain is necessary to optimize the measuring scale of the input channels according to de strength of the signal. The process of gains depends on the type of instrument.

The combined effect of Tx delay, measurement frequency and current at a certain transmitter loop size are interacting each other and influencing the exploration depth, resolution and smoothness of the decay. They should be applied with care and judgement. When changing the transmitter loop or turns these parameters need also to change. The decay curve (time versus measured magnitude) should be a smooth descending graph. This graph can be calculated into smooth resistivity versus time or depth graph. This graph can be tested for inversions towards a layer model. Most of the instruments can perform a very rough inversion for a first judgement. The WALKTEM system of ABEM can perform a complete inversion on the instrument itself; also different measurement graphs at the same spot with other variables can easily be combined.
From the inversion also the exploration depth can then be observed. The measured magnitude in the decay curves should be well above the background noise for the measured time windows. During the measurement, data of a specific time window can be observed for its magnitude during and standard deviation in the averaging process (it should be stable and well above the background noise) In most cases some of the first data points and last data points (at background level) should be excluded for inversion. Out liners in the early arrivals could be because too short Tx delay time according to the first-time window(s) or conductive overburden and lateral inhomogeneity. Saturation due to high transmitter currents could also cause out liners;

5) ***Standard filtering*** can be applied:
Anti-Alias filter: the maximum frequency component a sampling data system can accurately handle is it's so called Nyquist limit. The sample rate must be greater than or equal to two times the highest frequency component in the input signal. When this rule is violated, unwanted or undesirable signals appear in the frequency band of interest. This is called "aliasing".
A power line notch filter is supposed to filter unwanted disturbance from 50Hz of 60Hz power line frequencies. Receiver gains settings are also an important issue in TDEM. Most of the equipment provides a fully automatic option;

6) ***Standard deviation*** could be optimized by data stacking. This can be the amount of data points measured and averaged within one acquisition, this is called stacks which are more sets of averaged decays at the same location. Note that this is not the same as stacking as meant in the data collection of seismic signals were the signal is added up (enhanced) every new measurement;

7) After this first field test, if decay curves are satisfying (smooth) with the corresponding loop size and current according to the desired exploration depth, the data can also be ***tested for***

***inversion***. For the inversion ‘non-fitting points should be disregarded. These points, as discussed, are in most cases (to) early arrivals and the late arrivals that disappear in the background noise;

8) When settings are satisfying, a profile with ***multiple soundings in the direction of the change in geology*** can be executed. The distance between the soundings (stations) could be in the order of ½ - 2 times the size of the loop side. This depends on the local geology (expected lateral change) and size of the area to be investigated. Individual soundings should be checked. If necessary in between 2 stations, when an abrupt change is visible, another sounding can be added in between;

9) Inversions can be done on the single sounding curves or with software that combines and integrate the soundings into a profile. The first step in interpretation (at each sounding location) is to select and combine and average the best stacks (decays with the same loop size, frequency and current) rule out the out liners and check the smooth inversions to judge the number of layers and tendency of the curve. This type of smooth inversion is based on a multilayer inversion with fixed depths from which the resistivity is calculated. The result of this inversion is not the true resistivity distribution of the subsurface but helps to judge the tendency of the sounding when layers our not clear.

Based on this information, a layer model can be tried. With trial and error, a best fit can be achieved, or more data points can be skipped. After selecting the part of the graph that can be used for inversion, it is also possible to combine decays of different frequency’s and currents into one resistivity graph. After this, the measurements can be selected for an integrated 2D inversion along the profile.

The fit of the model with the actual field data is called residual, this fit should be below say 5%, better is below 1%. It is important to realize that the more data points are skipped the better the residual of fit will be, but the model might be less representative for that specific location. If any information of other methods, like VES soundings are available, this can be used for the interpretation of the first layers. Inversion software that is used in this project is SPIA (Aarhus GeoSoftware, Aarhus, Denmark) and Zonge inversion software, distributed by the manufacturer of the equipment. With this software sounding graphs of different instruments or settings on the same spot can be combined or compared.

## 5.3 Application of TDEM in Kajiado

See for the location of the measurements Figure 30. During this field work period we were able to work with Zonge instruments, a GDP32-II receiver and a ZT30 transmitter (KenGen), see Figure 31.

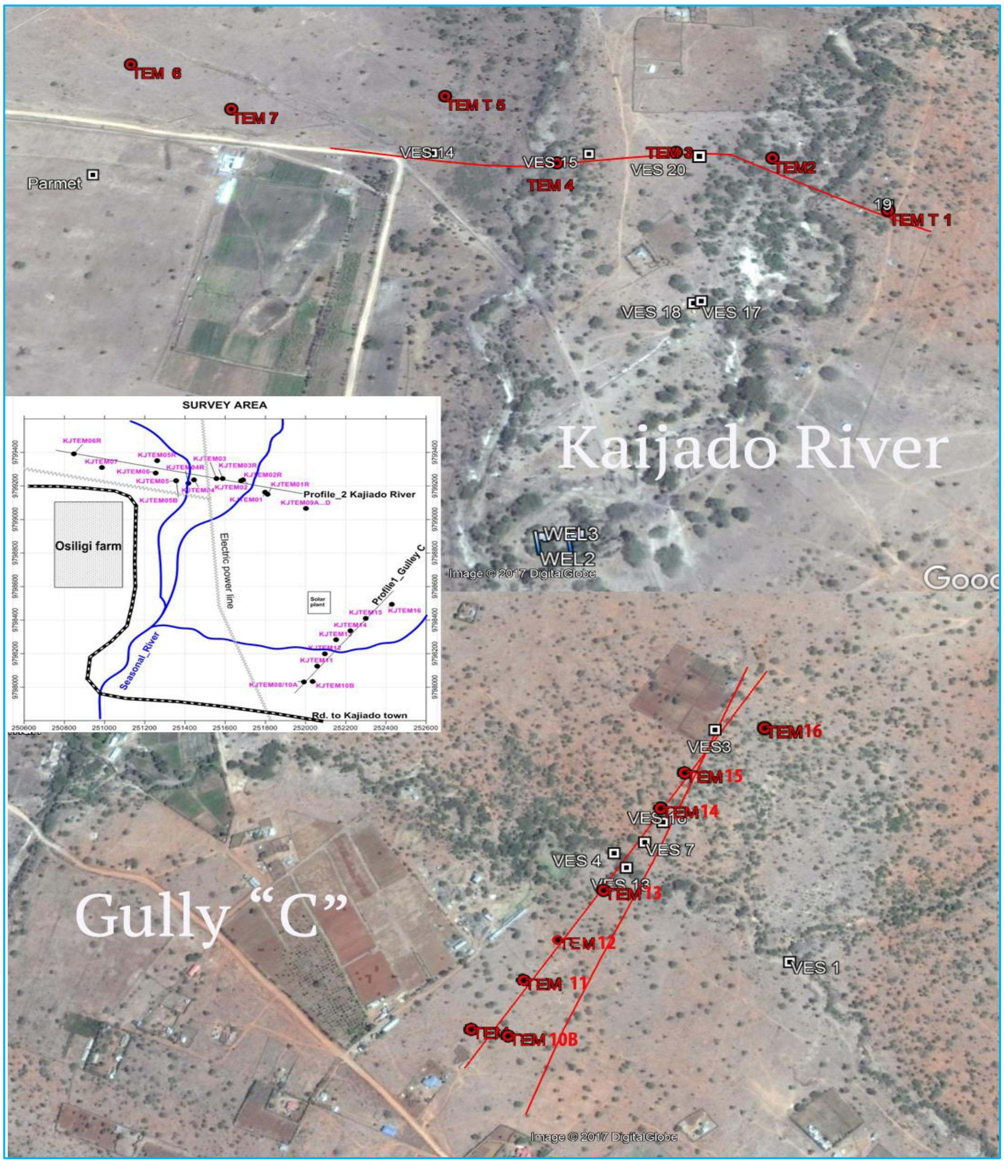

Figure 30. Overview of the TDEM sounding locations (KenGen). This google earth image only presents the soundings that are actually used for inversion. VES sounding locations are presented as squares.

In the Zonge equipment this type of transmitter and receiver are not connected by a (optical-fiber) wire. Therefore it needs to be synchronized in time, in a way that when the current is abruptly turned off, the timing of this moment is exact the same at the transmitter and the receiver. This is achieved with the XMT16 (transmitter controller). The equipment is therefore also suitable for deep soundings with extensive transmitter loops. In the case were the coincidental loop is used, the receiver and transmitter are close and could be connected with a wire for direct timing.

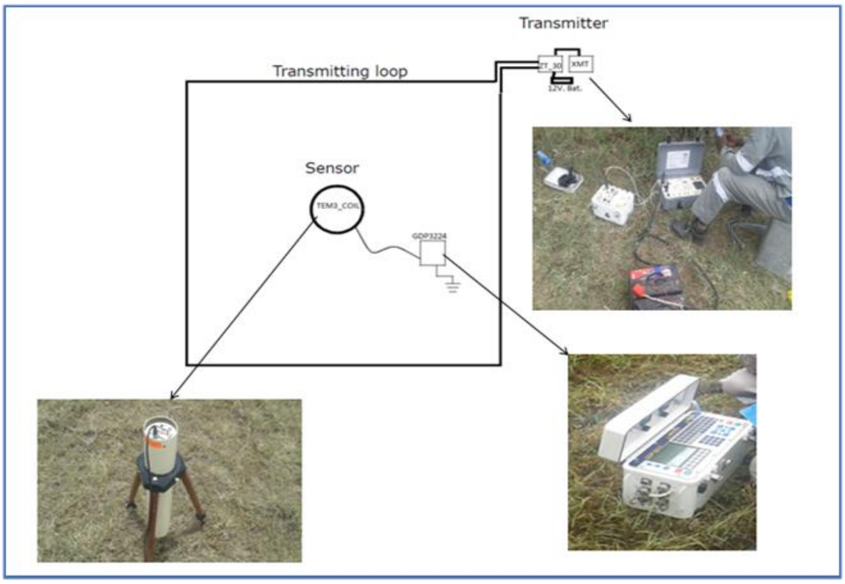

Figure 31. Overview of the setup of the Zonge TDEM equipment.

1. Forward modelling was applied to test the TDEM sensitivity for changes in the depth to basement. Information from VES or ERT can be used for this.
   It was to be expected and confirmed by the forward modelling that the benefit of the use of TDEM in this type of geology is limited due to the basic principle of the EM method, it responds basically to good conductors, especially with high resistivity contrasts. Forward modelling (figure 3.5) indicated high equivalence, (more possible layer models) when resistivity increases with depth and even worse when the resistivity increases with depth below a conductive clay layer. Which makes it difficult to indicate the exact depth were the weathered bedrock changes into the fresh bedrock. Of course, in reality this is not a sharp change. However, comparing single soundings, inverted with the same constraints can indicate changes in the depth to the fresh bedrock without pinpointing the exact depths. This is the same for VES: if the apparent resistivity graph increases with 45 degrees, the start of this increase can give an indication of the depth to the fresh bedrock.

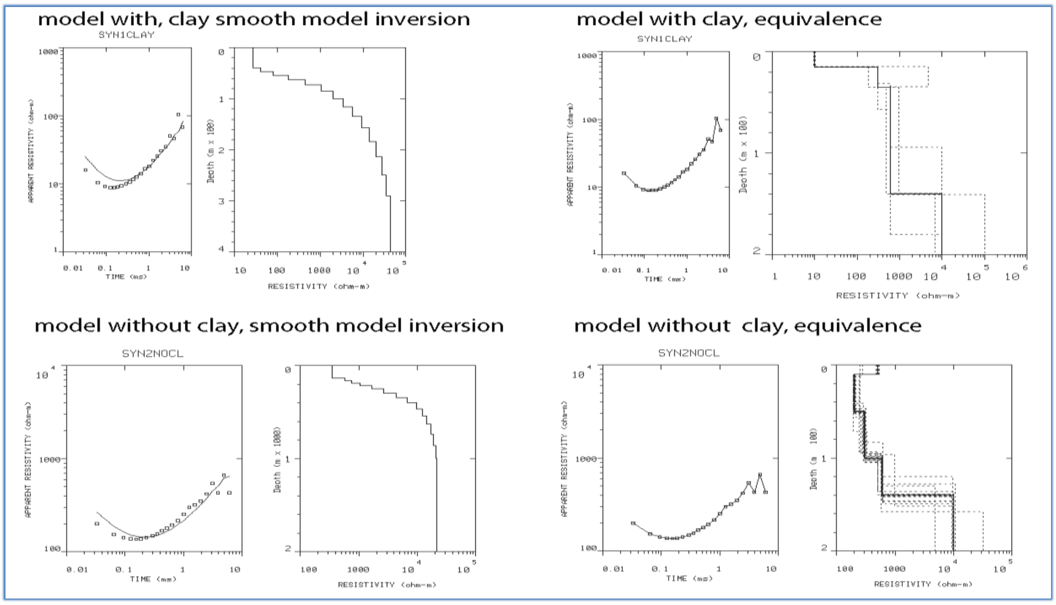

Figure 32. Forward modelling with 100 x 100m loop and 10-amp Tx current, the model was with (top) and without (below) a 20m top layer of low resistivity clay.

2. In Kajiado, the main purpose was to compare TDEM with AMT, VES's and with the ERT tomography profiles. The first TDEM soundings were executed on the west end of the Kajiado profile. At this location loop sizes of 100x100 m. and 50 x 50 m. were tested with various transmitter currents and frequencies.
3. Background noise was monitored by shutting off the transmitter, leaving only the receiver on. With (automatic) gain settings the scale was adjusted to a low input signal. Due to the increasing resistivity with depth, lots of data in the late times had to be skipped due to the effect that no induction is inferred in these high resistive layers. The signal disappears faster into the background noise under these circumstances.
4. Loop sizes of 100 x100 and 50 x 50 were executed with different currents (3-10-20 amp). Transmitter loops (with only 1 turn) and frequencies of 4, 8, 16, 32 Hz were applied 2 Hz was not applied because of possible interference with the 50Hz power system in Kenya. As standard both 16 and 32 Hz were selected to use at each station. Many decay's showed disturbances in the early and intermediate time gates. Because we could compare the TDEM soundings with the results of the ERT it seemed that these disturbances were not due to the top layer of clay. The disturbances were somewhat similar of what can be expected from 'capacitive coupling'. However, at locations where the issue was more severe no fences or buried pipes were encountered. Lateral change due to irregularities in weathering and erosion in the subsurface seemed to be the most logical explanation.

   In Figure 33 the averaged decay data of a field test is presented, in which various Resistivity – Time curves for different loop sizes, frequency's and current were measured at the same location. From this it was concluded that a 100m x 100m loop with a current in-between 5 and 20 amps gave the best results, in generating a smooth decay curve for most of the time windows.

   It is also shown in this figure that a lot of early times gates and late time gates have to be skipped. Small loop sizes clearly show that more data is lost in the background noise, and at the same loop size higher currents seem to lead to saturation of the receiver amplifiers. 32 Hz measuring frequency seemed to be more stable than 16 Hz. Other stations were regularly checked with different settings and showed similar or more severe effects.

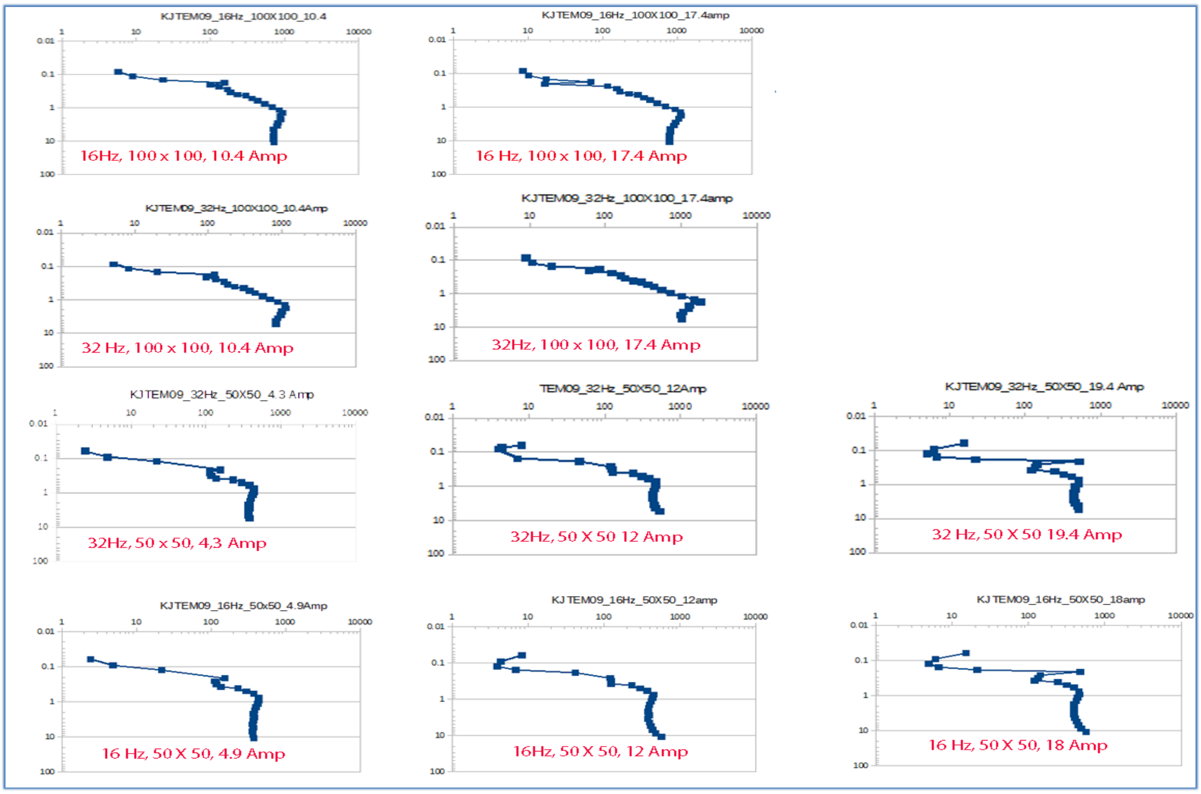

Figure 33. Decay curves (time, micro seconds versus resistivityin ohmmeter from field test with different loop sizes, frequencies and current)

5. Standard filtering was also applied, like anti Alias filter and a Power line notch filter. Gains were set in the fully automatic option of the Zonge instrumentation, which gave the best results.
6. During acquisition standard deviations of both decay and resistivity of a single (mid) time window was monitored. Both 32 Hz and, (8192 measurements or cycles) and16 Hz, (4096 measurements) were sampled and averaged. During measurement the standard deviation was observed of the averaging process of a single time window of these measurements. This is an indication for the quality and repeatability of the data. See Figure 34 for example of a raw data file.
7. First smooth inversions were, after removing outliers, reasonable and made sense indicating increasing resistivity with depth. It should be kept in mind that a smooth layer model is not a true resistivity model because the amount and depth of the layers is fixed and resistivity's are calculated based on these layers. Both a smooth and a layered model inversion (as with VES under these circumstances) with a good fit were difficult to achieve even with deleting more data points.
8. After these tests both 100 X 100 and 50 X 50 transmitter loops at the River profile were executed. The 100 x 100 loops gave the best results. The Gully C profile soundings were done with 100 x 100 transmitter loops and current between 10 and 20 amps at 32 and 16 Hz frequencies. Smooth inversions and layered inversions were applied to 100 x 100 transmitter loop data sets. Layered inversion failed for some of the soundings. Interpretation of the single soundings has been executed with SPIA software. If more soundings are compared along a profile line it can give an indication of lateral change in resistivity. A semi (semi) 2D interpolated cross section is done with Zonge software (see Annex 1).

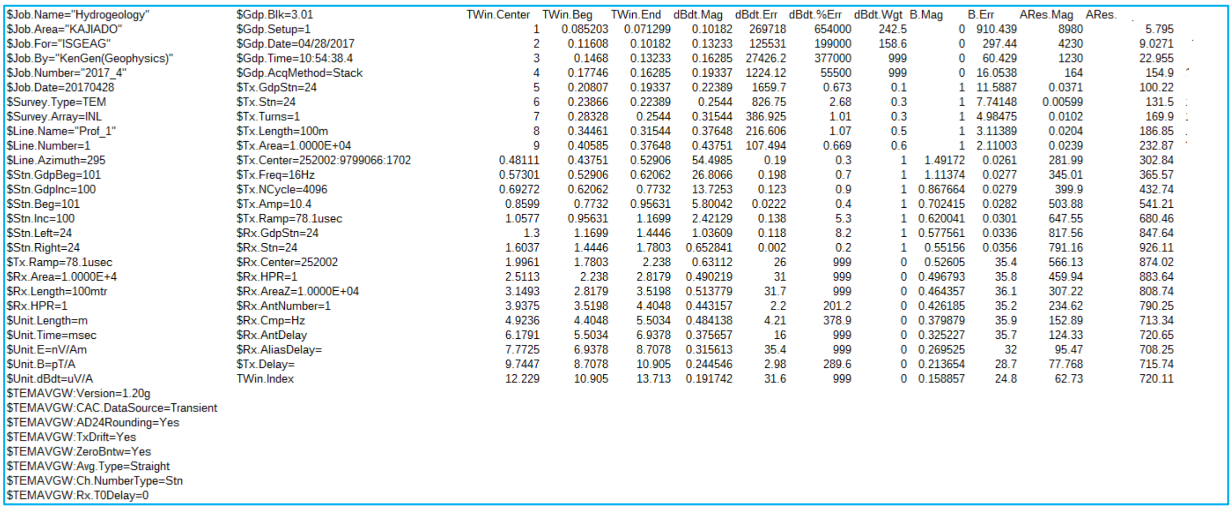

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Figure 34. Tem.avg file, a typical example of a raw (but averaged) data table of Zonge GDP32-2 receiver: 16Hz, 100 X 100, 10.4 Amp, Delay 78, 1 microsecond, average is taken from 4096 transients.

9. The general process of interpretation of single soundings.
Figure 5.9, example of a first but very simple visual qualitative smooth model interpretation based on a multilayer inversion with fixed depth's which can help to discriminate the layers in cases where they are not clear. Depth and resistivity may not be representative for the actual situation because of this smooth model inversion, were the resistivity is calculated from a fixed number of layers with a fixed thickness. However, it can help in selecting a layered model as a trial in the layered inversion in cases were the layers are not clearly recognized in the resistivity versus depth sounding graph's. This is often the case in areas with increasing resistivity's with depth. In Figure 35, in the part of the data were the resistivity is increasing, 3 different layers towards the bedrock are visible. The interpretation is based on the change in gradient of the smooth model layers of a single sounding.

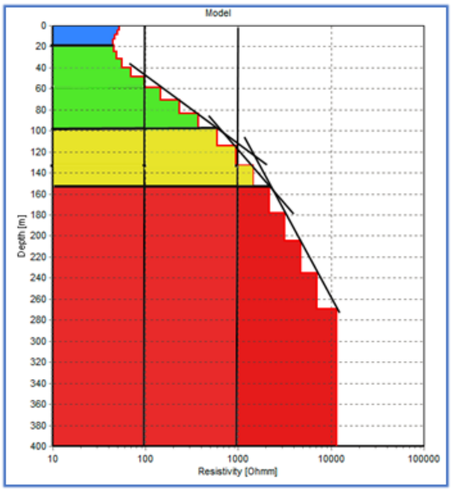


Figure 35. Example of a first but very simple visual qualitative smooth model.

The different steps of interpretation of a selected single TDEM sounding on the Kajiado river profile is presented in Figure 36a, b and c.

In Figure 36a, both de averaged raw data (decay graph, magnitude versus time) and the calculated apparent resistivity versus time is represented. The red dots indicate the data points used for the inversion. Note the difference in scale and the error bars in the resistivity graph. In Figure 36b the inversion steps in the decay (magnitude versus time) graph are represented: 1) free smooth inversion, 2) layered inversion based on the smooth inversion, 3) manually graphically manipulated layered inversion. Figure 36c shows the same process again but in the resistivity versus time graph, which is in a different scale. Note the change in fit or residual of each step. The fit is in fact how the graph fits the averaged measurement points. It can also be expressed in a number, the so-called residual, which is in %.

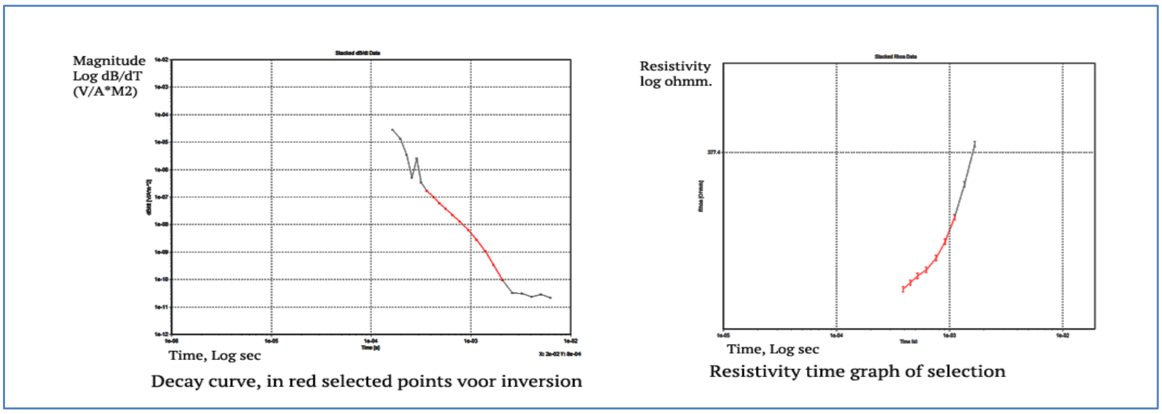
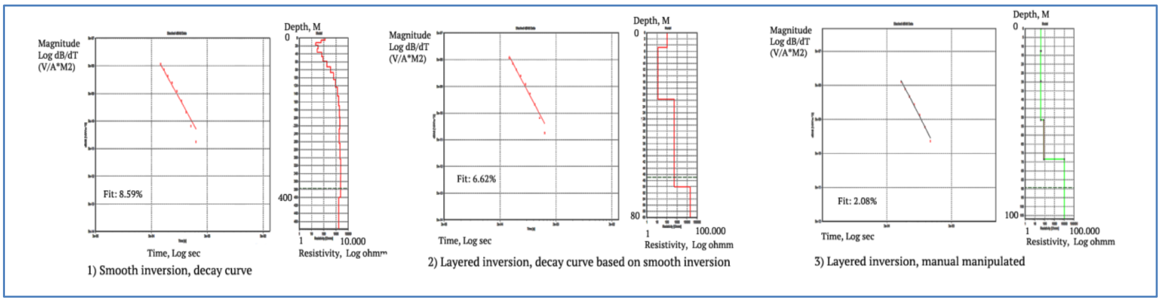
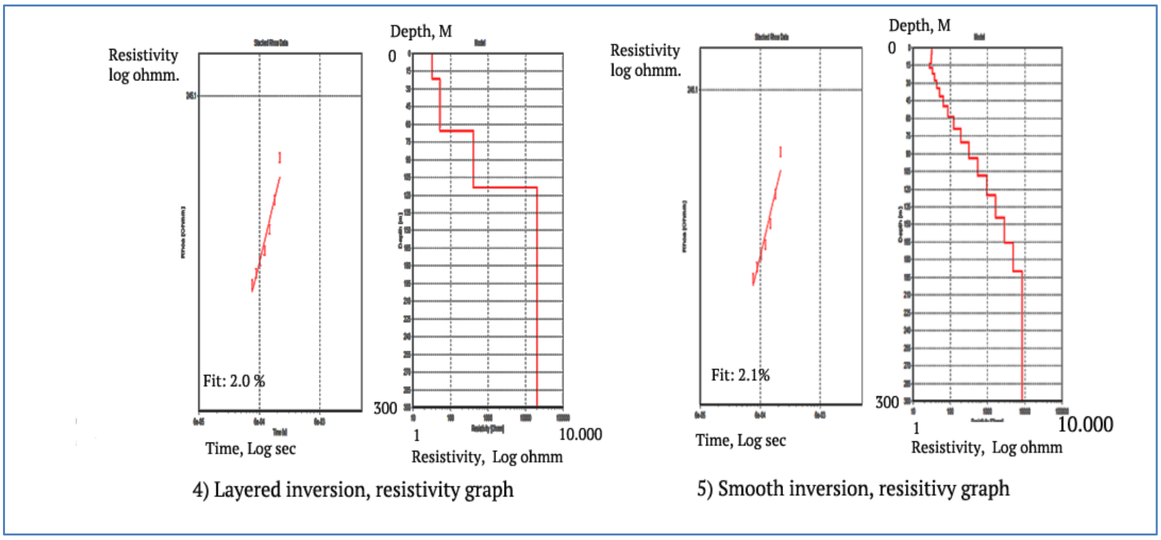


Figure 36a



Figuur 36b



Figuur 36c

The next step is to combine the soundings and inversion along the profile. In Figure 37, the first (top picture) averaged raw data decay curves (32 Hz) are presented with the preliminary selected data points from (32 Hz) decay curves for inversion, visible in red.

In the second-row results of the smooth inversion are shown. Similar resistivity classes are lateral connected. Because this smooth model calculates depth and resistivity automatically, it may not represent true depth and resistivity'. Note that the difference in depth scale. Only the trend in resistivity's should be compared. In the third row the layered inversion is presented, and layers are lateral connected into a profile. Note that more models are possible due to equivalence (more models will have the same fit in a single sounding). The trend in the change off the depth to bedrock is (and should be) similar for both the smooth and layered inversions. It is expected that the weathered layer will gradually change into bedrock with depth; however the smooth inversions show the change in 3 different layers (figure 5.9). In figure 5.11 below, a picture of a profile interpolation based on 1D smooth inversions (with Zonge software) is represented. The Zonge smooth inversion differs from the smooth inversion with fixed number of layers and fixed thickness. This Zonge inversion can be compared with the ERT (smooth inversion) were the change between layers is smooth and the number of layers and thickness is not fixed.

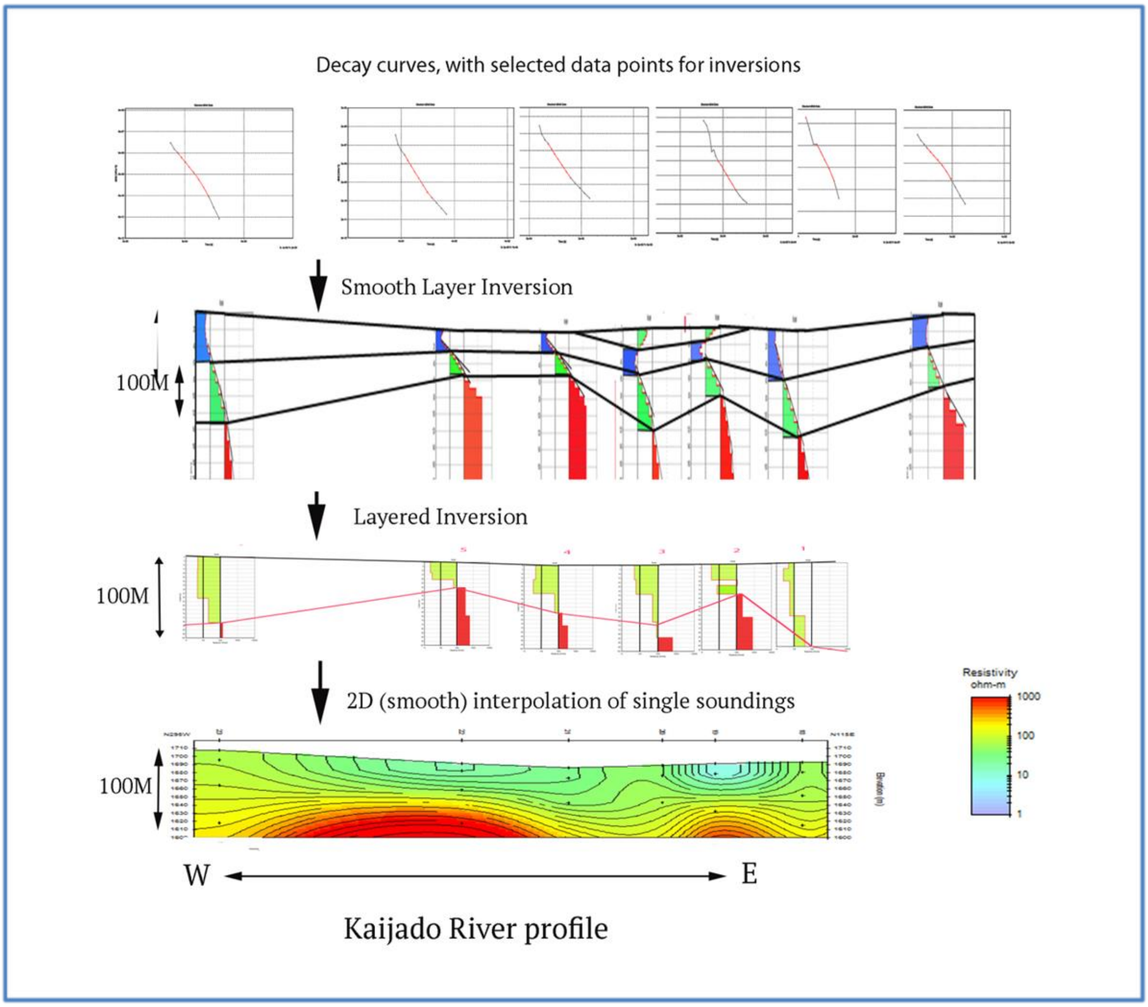


Figure 37. Example of interpretation steps of the Kajiado River profile.

In Figure 38 the results of the River and Gully profiles are displayed. They are based on interpretation of single soundings, both smooth inversion based on fixed number of 25 layers and a layered inversion with SPIA software. Below a 1D smooth modelled inversion based on Zonge software

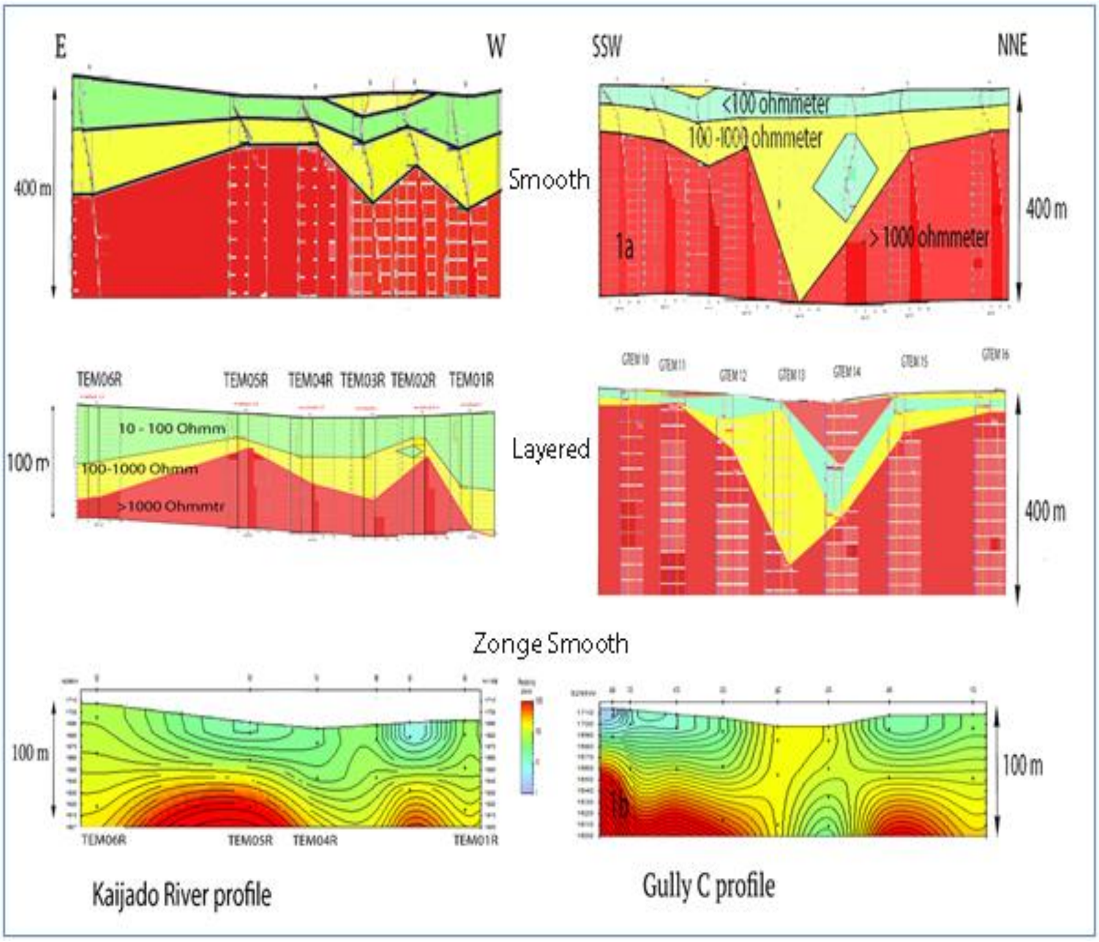


Figure 38. TDEM results of both of the profiles (Kajiado River and Gully C)

## 5.4 Conclusions

- At the start of the fieldwork, it took a lot of effort to test the many settings and configuration set ups in order to get satisfying sounding graphs with the Zonge instrumentation. The inversion into reasonable resistivity layer models was not always straight forward, lot of data points had to be left out to get a reasonable fit. The reason for this is probably due to the lateral change caused by severe irregularities in basement weathering and fracturing, these seem to affect more the early and middle time arrivals. These irregularities seem to be on a scale that they interfere with the single soundings and contribute to the outliners in the sounding graphs. The discarded data points in the late arrivals is due to the increasing resistivity with depth resulting in late arrivals disappearing in the background noise due to lack of induction;
- Inversion of TDEM assumes horizontal layering. See also chapter 7 in which the VES and TDEM soundings are compared. Disturbed graphs, due to anomalies within the spread, are difficult to invert and if many points need to be discarded and the layer model is less representative for the resistivity distribution of the sub surface;
- The final profiles are based on 1D smooth inversion and a 1D layered inversion of single soundings (SPIA software). A semi 2D interpolation based on the 1 D inversions was executed with Zonge software. They all give comparable results but lack in lateral resolution at the necessary scale. From all these profiles it was only possible to interpolate the change in depth to bedrock not the actual depth. It was not possible to locate or discriminate fracture zones or pinpoint the thickness of the weathered basement (saprolite);
- Remarkably, the locations with deepest basement (>1000 Ωm) or thickest weathered zone according to these soundings, are found at the western and eastern ends of the Kajiado profile line. Unfortunately, these were beyond the stretch of the ERT profile.
- The TDEM soundings at Gully C clearly indicate, however based on a single sounding, a deeper basement close to the gully, confirming a lateral discontinuity;
- The difference between Zonge smooth semi 2D inversion and the 1D layered inversion is due to differences in deleted data points of individual soundings
- Unfortunately, it was not possible the use the WalkTEM in Kajiado at the same time we used the Zonge instrumentation, due to delays related to transportation and custom facilities. WalkTEM is a more recently developed TDEM instrument. This instrument induces two different currents (dual moment) and can be used with smaller transmitter loop sizes. It will be less sensitive for lateral changes which might result in soundings from which less data points have to be discarded. This may lead to a better resolution of the soundings and profiles. In the next ISGEAG fieldwork the WalkTEM instrument additional WalkTEM measurements have been made on the Kajiado River profile. See chapter 7 for the results.
- In short, TDEM, with the instrumentation we used in this fieldwork, is a relative fast method, with satisfying exploration depths; however its relative low resolution in areas with increasing resistivity with depth, combined with a more complex instrumentation and interpretation makes this method less appropriate especially under the Kajiado conditions. Soundings in areas with lateral change within the scale of the spread are difficult to invert.

In Chapter 7 (method comparison) this will be discussed in more detail.

# 6 Application of Audiomagneto-telluric (AMT) Soundings

## 6.1 Introduction of Audiomagnetotellurics (AMT) method

- ***What is the Source of the MT Signal?*** In the lower frequencies (generally less than 1Hertz, or 1 cycle per second), the source of the signal is interaction of the solar wind with the earth's magnetic field. The higher frequency signal (greater than 1 Hertz) is created by world-wide thunderstorms, usually near the equator.
- ***What is a telluric signal?*** Also called Earth Current, natural electric current flowing on and beneath the surface of the Earth generally following a direction parallel to the Earth's surface;
- ***What does the AMT field layout look like?*** The AMT field layout should be exact according the true magnetic north. See also Figure 40 below.

Figure 39. The Phoenix AMT/MTU-5A unit

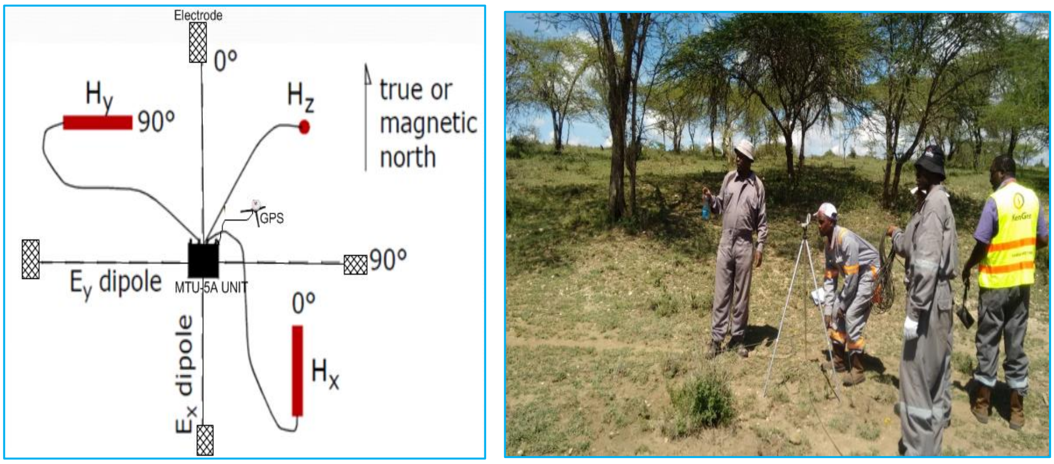


Figure 40. AMT field layout and the process of carefully establishing the true magnetic north.

## 6.2 AMT coils & electrodes

- The 3 directions of the magnetic fields are measured with special designed magnetic field antennas, basically an iron-cored coil with over thousands of turns of wire.
- The coils are extremely sensitive to noise from wind, walking or trucks, and are buried in soil or under rocks to prevent movement due to wind.
- The electric fields are measured with long “antennae or dipoles – usually coaxial wires about 60-100 meters long. The ends of the wires are connected to potential electrode “pots”: – sealed containers a few inches in diameter and about six inches high, (filled with an electrolyte) with a ceramic permeable bottom for the slow release of the electrolyte. On the bottom left-AMT Electrode; referred to pots.

AMT coil

Electrode

Figure 41. electrode in position

Figure 42. Vertical oriented Magnetic coil

## 6.3 Data acquisition

- The coils and electric-field dipoles are all connected to “sensor” boxes (MTU-5A) where filtering and amplification of the signals take place and finally stored in a compact flash.
- The data is then transferred to a laptop /computer where they are digitized and recorded on digital media.
- This is where the new 24-bit Analog to Digital (AD) systems comes in. These new systems allow for a much larger amount of data (in amplitude) to be transferred from analog to digital.
- The electric and magnetic fields are measured as a function of time.

### Acquisition channels

- At each AMT station, five measurements (channels) are recorded;
- Magnetic field in two horizontal directions (*Hx* and *Hy*), and in the vertical direction (*Hz*).
- Electric field in two horizontal directions (*Ex* and *Ey*).
- Recording the time series; processing will convert data to frequency domain.
- Best if x and y directions are orthogonal.
- Orientation does not usually matter - x and y can be any direction as long as they are perpendicular.
- Best orientation if x is along strike of a target conductor.

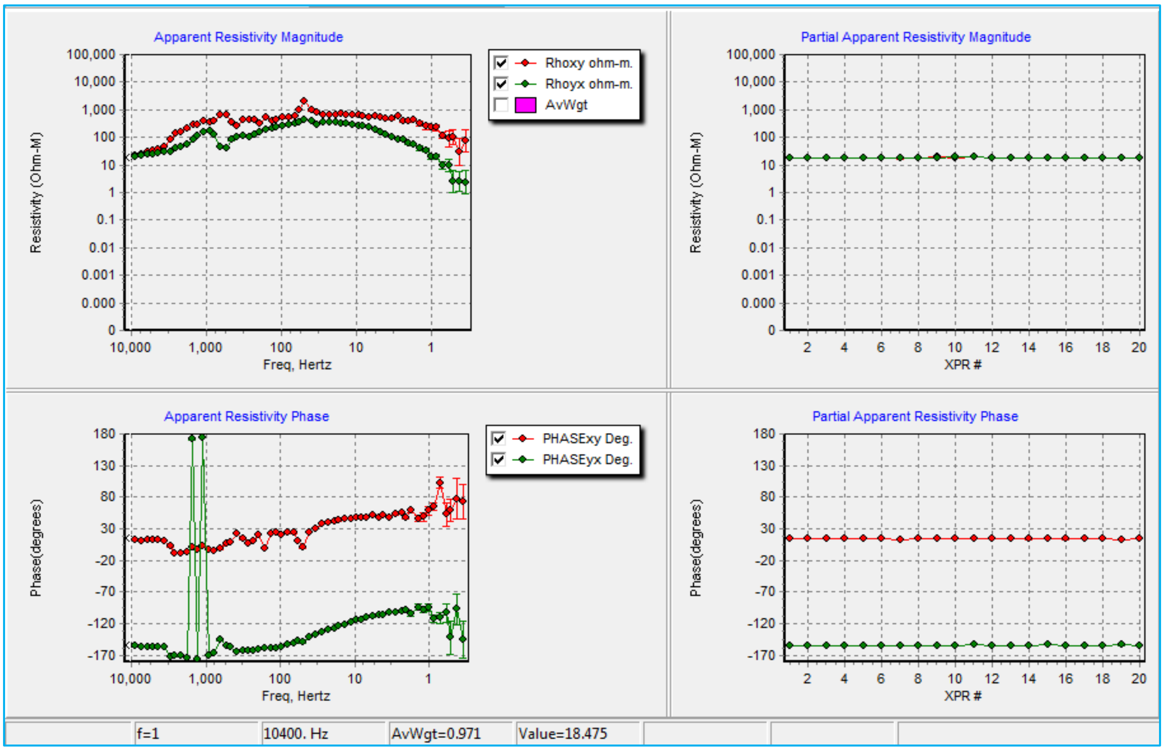
### Time series data

The time series data is processed to Fourier transformation before running the robust process where incoherency noisy data is clipped off before editing in MT-editor program. Clean data is exported to EDI file. Below is a sample from KJAMT04.LE/LH data which will be exported to *WinGLink SOFTWARE* for static shift correction & 1DInversion modeling.

## 6.4 Static shift correction on AMT data with TDEM curve

The TDEM and AMT/MT methods are measured at the same site because TDEM is used for *static shift* correction of the AMT/MT data. TDEM data depends on secondary magnetic field hence is not affected by near surface inhomogeneity. This effect is caused by shallow resistivity and is commonly seen in AMT/MT data that causes shift in the apparent resistivity curve. Therefore, Central Loop TDEM is used because it is less sensitive to lateral resistivity variations and the strength of the induced signal is highest at the center of loop.

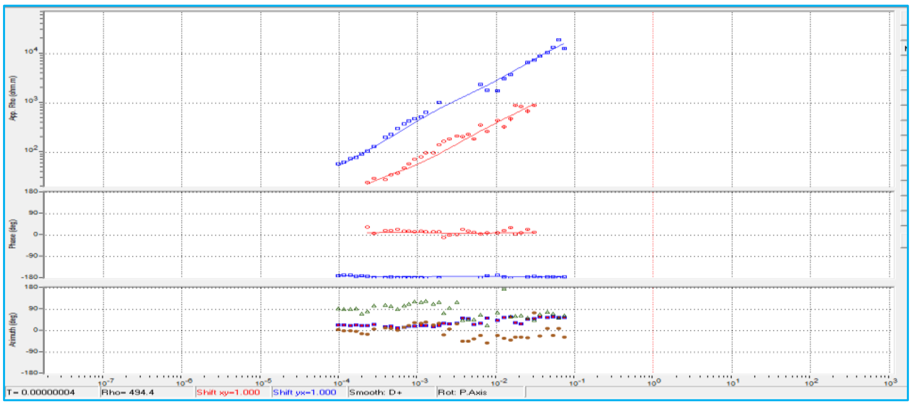
The correction is done by a joint interpretation (inversion) of the TDEM and the AMT/MT data where the AMT/MT shift parameter is one of the solved parameters. If no correction is done; Static shift due to near surface inhomogeneity’s can have a severe influence on the interpretation, $\rho a$-curves are shifted upward or downward giving a wrong resistivity model.



f=1 | 10400. Hz | AvWgt=0.971 | Value=18.475

Figure 43, time based raw data output of 3 direction of the magnetic field and 2 directions of the electrical field

The AMT data is imported to WinGLink (figure 45 a), combined with the nearest TDEM data, which correlates well in between the two AMT curves, yx & xy (figure 45b). Both xy & yx AMT curves are manipulated manually towards the TEM curve, till both graphs fit into TEM curve (figure 46). After this the corrected AMT data can be inverted into (figure 47).



T= 0.00000004 | Rho= 494.4 | Shift xy=1.000 | Shift yx=1.000 | Smooth: D+ | Rot: P.Axis

Figure 44. Correcting the AMT time series data and calculation of the apparent resistivity

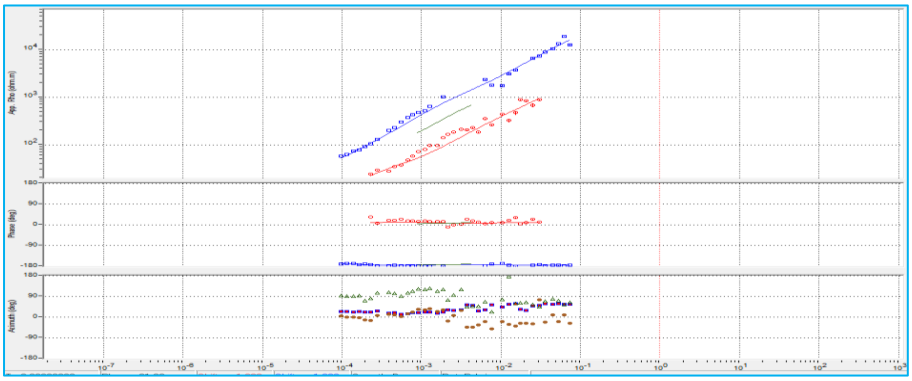
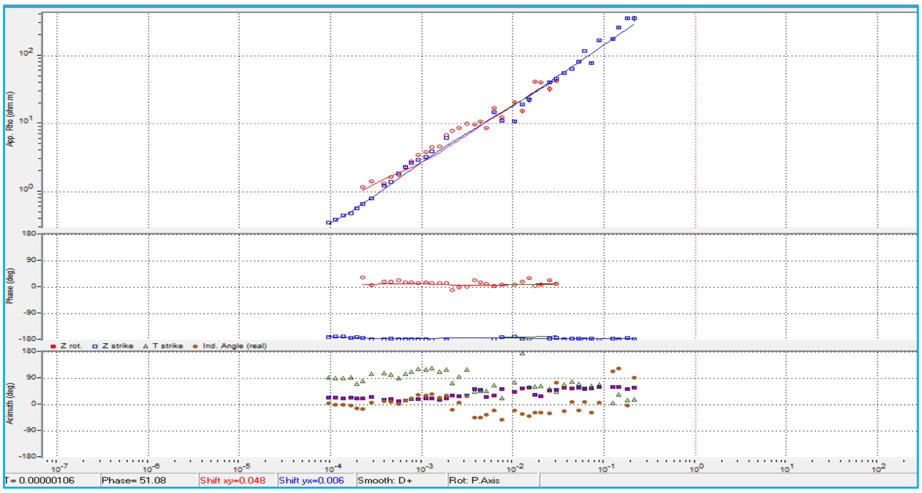
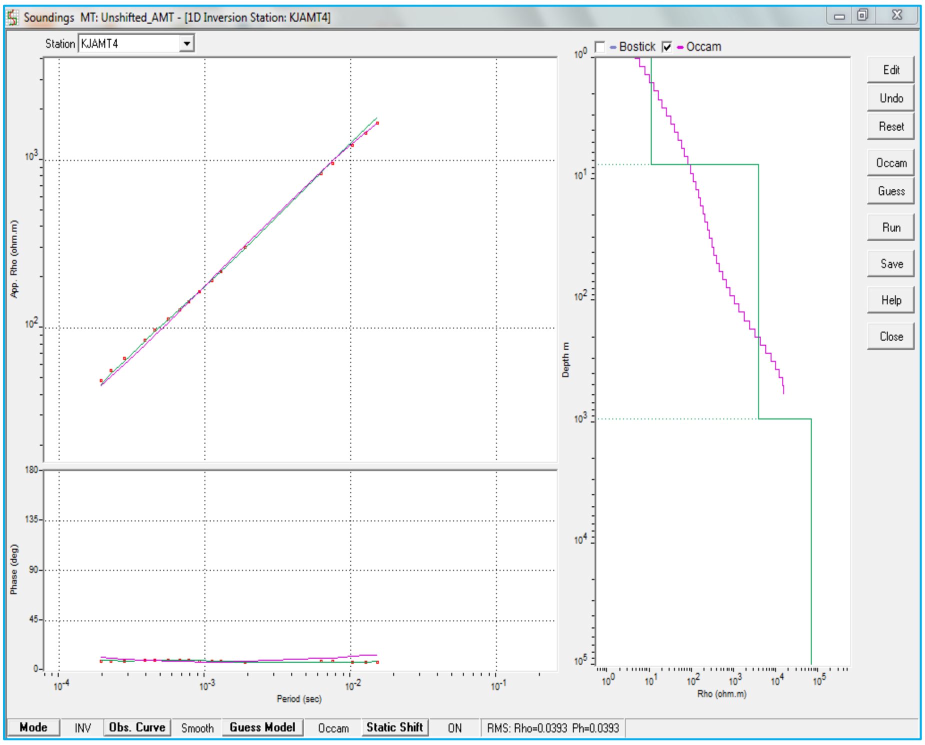


Figure 41a (above), b (below). Process of manual static shift correction of KJAMT4.



T= 0.00000106 Phase= 51.08 Shift xy=0.048 Shift yx=0.006 Smooth: D+ Rot: P.Axis

Figure 42. AMT sounding KJAMT4. after static shift correction with TEM


Soundings MT: Unshifted_AMT - [1D Inversion Station: KJAMT4]

Station KJAMT4

☐ Bostick ☑ Occam

Mode INV Obs. Curve Smooth Guess Model Occam Static Shift ON RMS: Rho=0.0393 Ph=0.0393

Figure 43. 1D-inversion in WinGLink software after static shift of AMT sounding KJAMT4 .

The shifted AMT soundings (taken along a transect) can be combined in a profile, for a combined inversion calculation with WinGlink. This will result in a 2D smooth inversion, see figure 48.

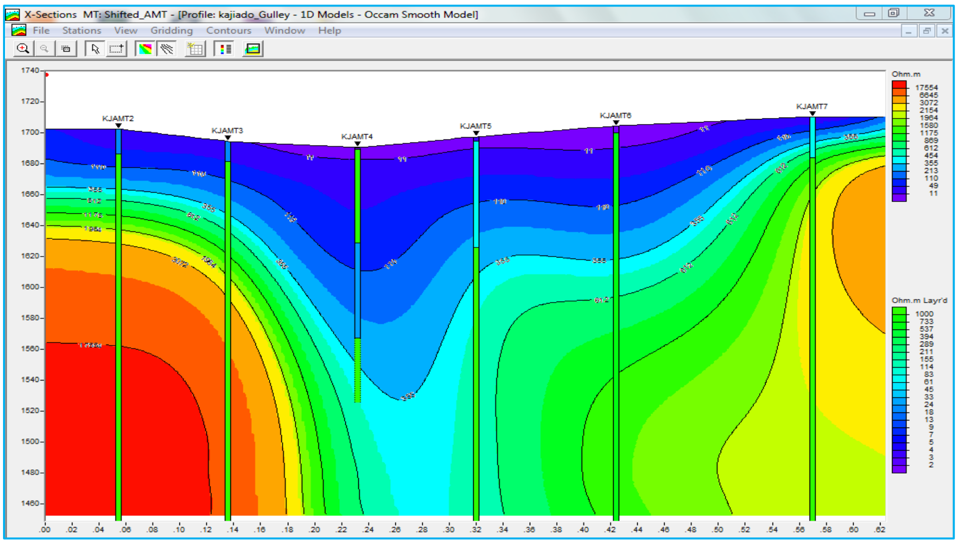


Figure 44. Smooth inversion, based on shifted AMT data on the Gully C profile up to 250 m. depth

## 6.5 Inversion results of the Kajiado River and Gully C profile

In figure 49 an overview is given form the profile lines and the location of the AMT soundings. In figure 50 and 51 the results of the shifted and un-shifted data are shown of the Kajiado river profile and the Gully C profile.

In figure 50b, at the most eastern AMT sounding, missing data of TDEM with depth is clearly showing the effect on the (wrongly) calculated resistivity in this part of the profile!

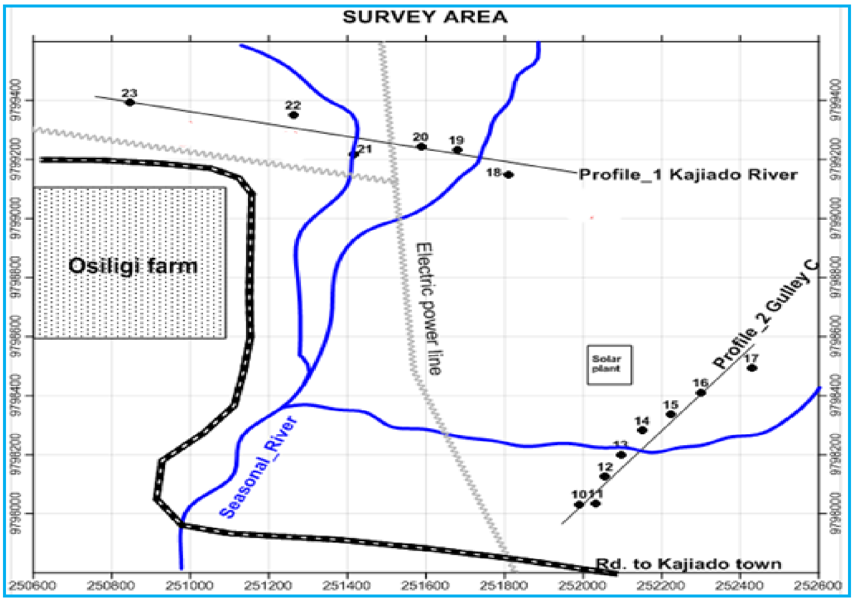


Figure 45. Locations of the AMT soundings.

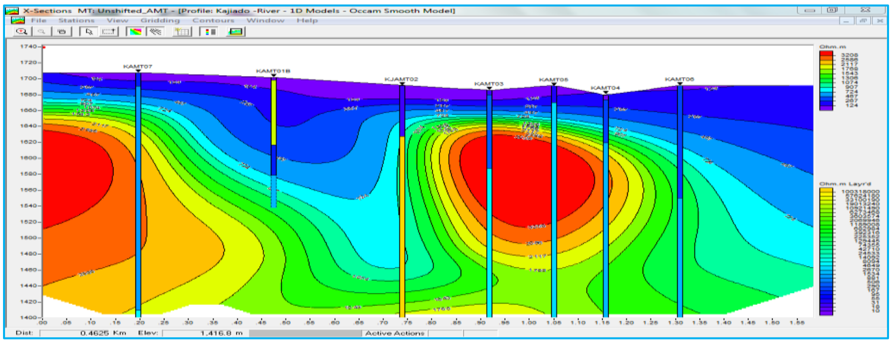


Figure50a. AMT inversion unshifted, Kajiado River.

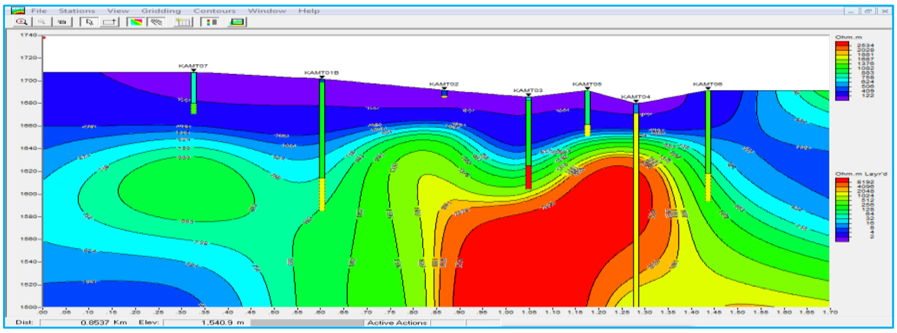


Figure 46b. AMT inversion shifted, Kajiado River.

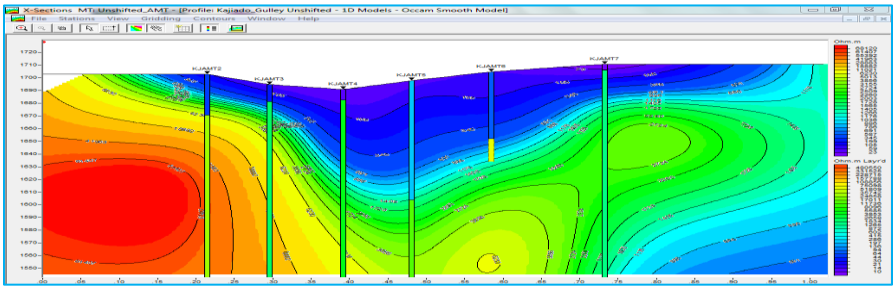


Figure 47a. AMT inversion unshifted, Gully "C".

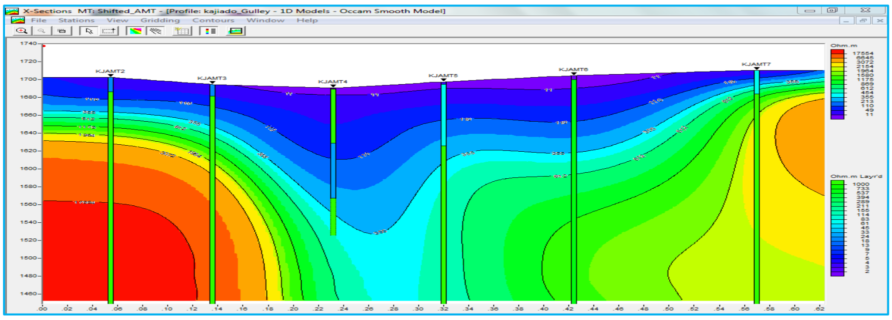


Figure 51a. AMT inversion shifted, Gully "C".

# 7 Comparison of the resistivity methods

## 7.1 Introduction

The aim of the ISGEAG project is to introduce ‘new’ geophysical methods for groundwater exploration and compare them with the more conventional methods and to discriminate the advantages and limitations of each method.

In Kajiado, VES soundings, HEP profiling, ERT tomography, TDEM and AMT soundings were applied on 2 transects. The location of the transects was based on a first reconnaissance field campaign [Rolf, 2017], which was focused on the conventional VES and HEP methods. During the second campaign, the main focus was on ERT, TDEM and AMT.

The two transects are once more shown in Figure 48, one crossing the two branches of the Kajiado River and one profile crossing the so-called Gully “C”. Kajiado town is situated to the southeast.

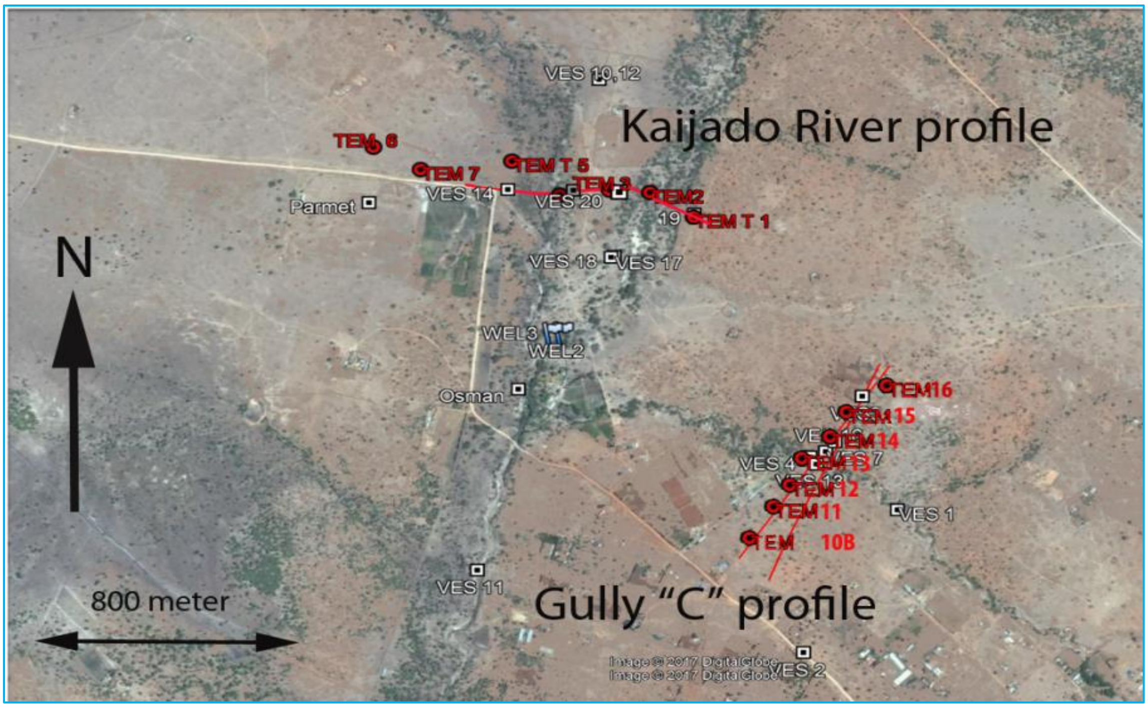


Figure 48. Google Earth overview of the locations of the measurements

The Kajiado River transect was selected on several criteria:

- potential recharge from the existing river;
- the river might indicate major fracture zone(s);
- location of existing high yielding boreholes;
- Lineaments visible on satellite images.

Gully "C" was selected because:

- the gully discharges most of the excess of rain water from Kajiado town;
- direction of the gully corresponds with certain lineaments;
- the gully discharges into the Kajiado River;

## 7.2 Comparison of the resistivity profiles

### 7.2.1 Kajiado River profile

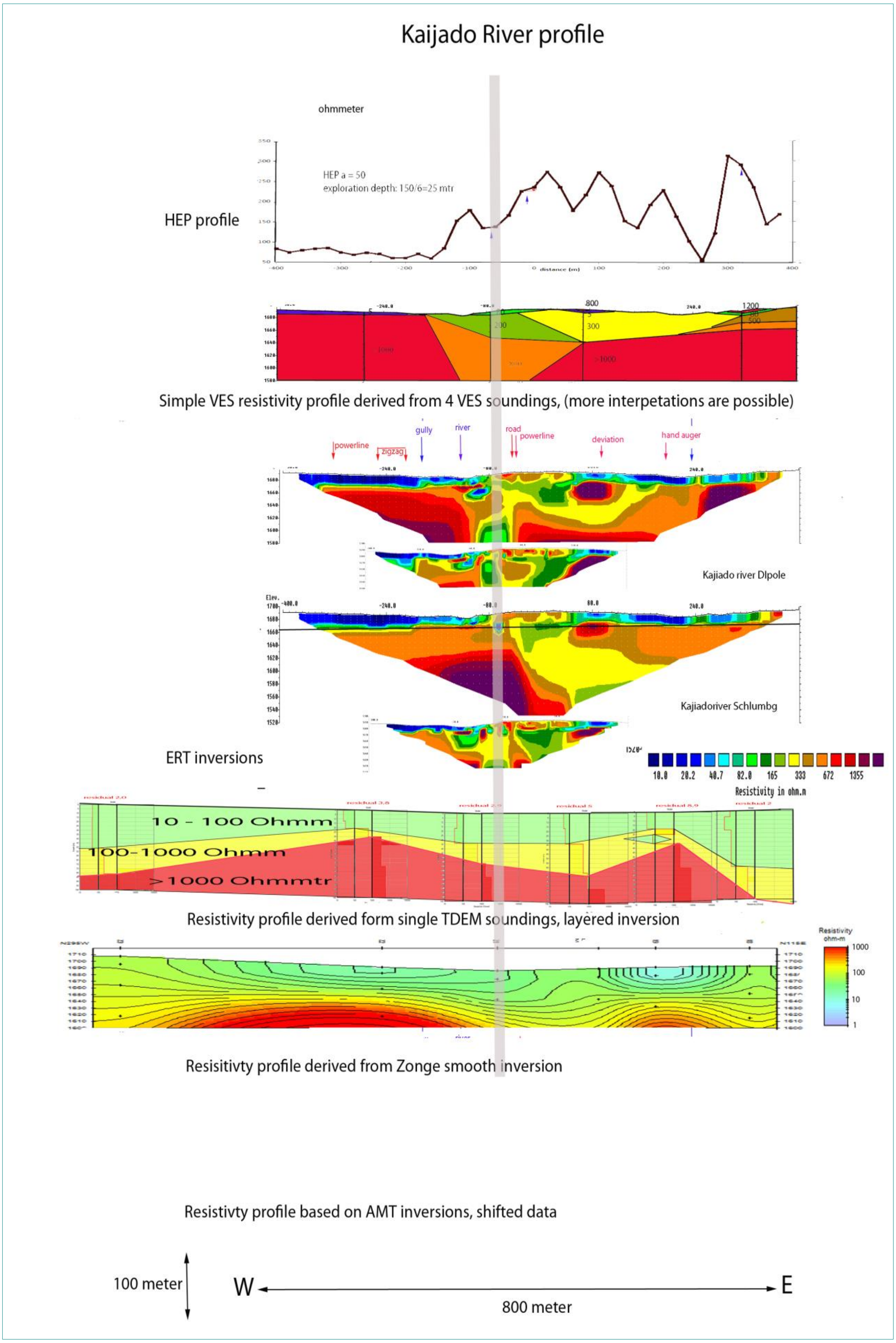
The location of the Kajiado River measurements are given in Figure 49 An overview of the results of HEP, VES, ERT and TDEM (except AMT) measurements is presented in Figure 50.

From Figure 50 it can be concluded that all the methods indicate similar layering and resistivity distribution, with large difference in resolution. From this figure one can observe how VES, TDEM and AMT mainly indicate the change in depth to the basement and do not give direct information on locations of fractures.
VES soundings give more details on the shallow layers. TDEM and AMT do not show detailed information on the superficial (clay) layers. The change in depth to the basement is similar in VES, ERT, TDEM (and AMT). The best vertical and lateral resolution is however observed in the ERT profiles.

In the ERT profile with the Dipole-Dipole configuration the location of a possible fracture becomes most clear. A profile with a smaller electrode distance (5 m., 400-meter profile length, exploration depth 70 m.) was executed to achieve a higher resolution close to the surface.

The directions of the VES soundings are all perpendicular to the profile and might be influenced by lateral changes not visible in the ERT. Also, the difference in initial electrode spacing of the VES soundings compared with the spacing's in the ERT will result in different results. The resolution of TDEM and AMT is much lower than the ERT and VES. The effect of equivalence is most severe in the VES and in the high resistivity layers of TDEM and AMT soundings.

Figure 49 Location of Kajiado river profile on a North-up Google Earth overview, the red line is the ERT profile; this was also the HEP profile. Red dots indicate locations of the TDEM (and AMT) stations used in inversions. The white boxes are the VES locations



Kaijado River profile

HEP profile

Simple VES resistivity profile derived from 4 VES soundings, (more interpetations are possible)

ERT inversions

Resistivity profile derived form single TDEM soundings, layered inversion

Resisitivty profile derived from Zonge smooth inversion

Resistivty profile based on AMT inversions, shifted data

Figure 50. Comparison of HEP, VES, ERT, TDEM and AMT of the Kajiado River profile. AMT is missing in this profile.

### Comparison of HEP with ERT of the Kajiado River profile

When comparing the HEP results (Wenner with a AB=150 meter, a=50 meter) with the corresponding ERT profile (see Figure 52) it becomes clear that HEP sounding values correspond with the resistivity variations of the top 20 – 25m subsurface only. This corresponds with the exploration depth (DOE) of the HEP profile: AB of the HEP is 150 m and thus the DOE is in the order of 25 m (being 150/6).

This implicates that even with a relatively long 150 m AB; a HEP profile only measures the apparent resistivity changes of the top 20 – 25m. The HEP anomalies just reflect the lateral changes in the first 25 meter, mainly representing the changes from clays to river sediments and do not show the deeper changes in resistivity.

The lowest resistivity values in the HEP profile (Figure 52) clearly correspond with the superficial clay layers showing up in the ERT. It is very important to realize that these HEP anomalies do not give any direct information on the change in depth of e.g. basement or location of fractures and deep aquifers!

Figure 51. Location of the ERT /HEP profile (green line) and the VES sounding locations (boxes) at Kajiado River profile

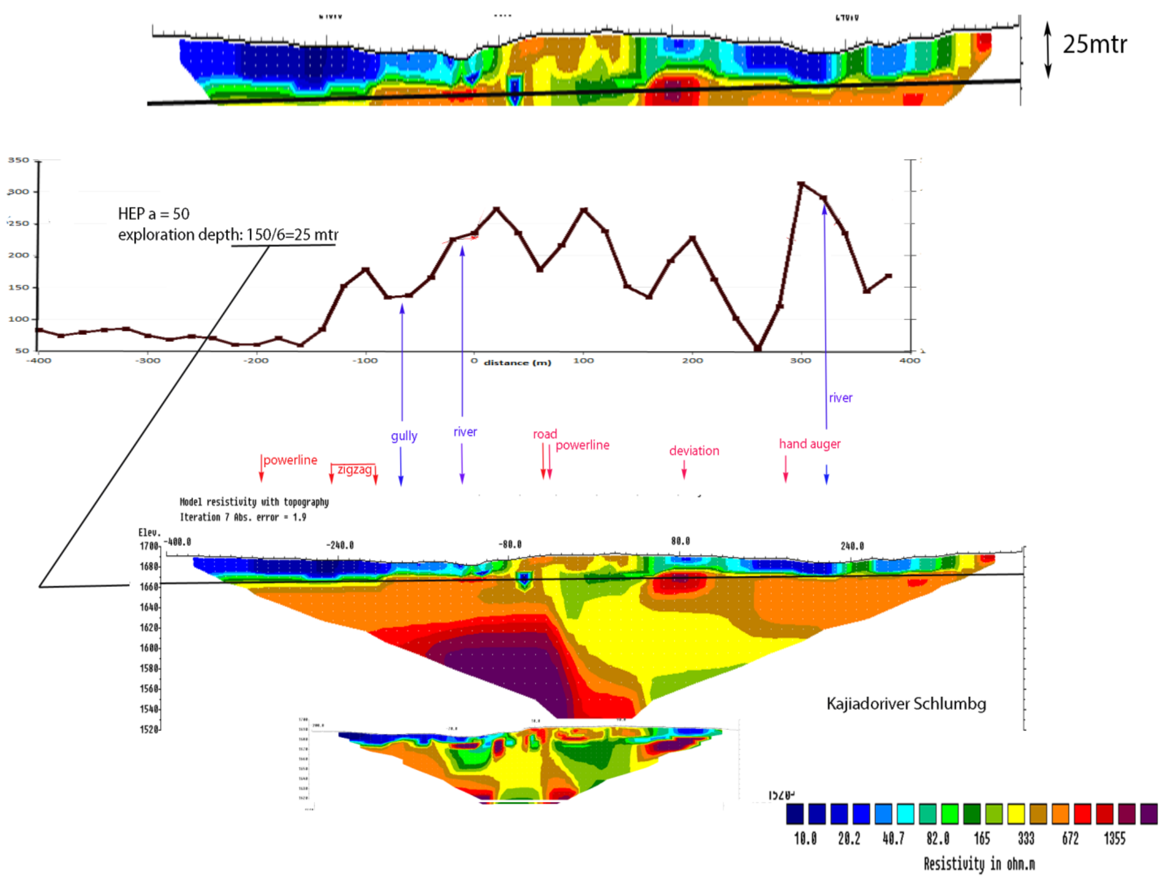


Figure 52. Comparison of HEP and ERT profile results

### Comparison of VES soundings and ERT of the Kajiado profile

All VES soundings were done perpendicular to the profile line, see for their locations Figure 49 (paragraph 7.2) and the results in Figure 53.

- VES 14 corresponds well with ERT: clay layer at surface, directly on high resistive rock. The thickness of the clay in the VES is however small as compared to the clay thickness in the ERT profile. This could be due to lateral change effects in the VES sounding;
- VES 15 at least confirms deep basement at that location but it does not give the resistivity variations in the top 50 m that are shown in the ERT profile. Differences are due to VES inversions assuming horizontal layering and equivalence;
- VES20 was conducted with a relatively short electrode range (AB=500 m). The uncertainty is large. Due to equivalence, and lateral discontinuity, it was not possible to invert the sounding to a similar model as seen in ERT: lower resistivity beneath the high resistivity layer at approx. 25m. Basement depth is very uncertain, it can be “anywhere deeper than 45 m”;
- VES19 is slightly beyond the very (east) end of the ERT line. It confirms that there is no clay on top. Due to major lateral changes the depth to the basement in the VES is extremely uncertain (“at least deeper than 25m”).

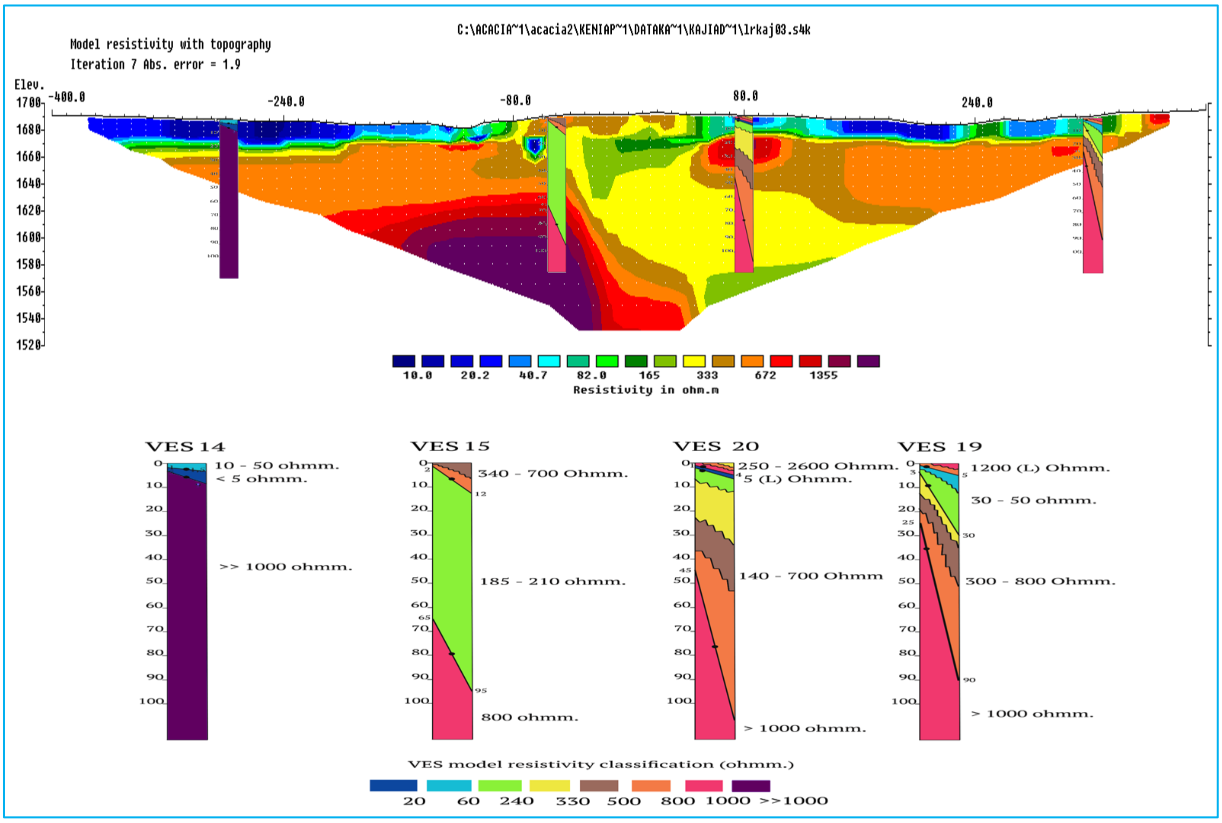


Figure 53. VES inversion results in ERT

### 7.2.2 Gully C-profile

See Figure 54 for the locations of the HEP profile, ERT (two parallel 800m lines), AMT lines, TDEM and VES stations. In Figure 56 the comparison between HEP, ERT, TDEM and AMT results is given. Comparing the superficial clays in the ERT with the HEP measurements, the figure again shows that the anomaly in the HEP profile is mainly caused by the presence of superficial clay, including the clay in the gulley itself.

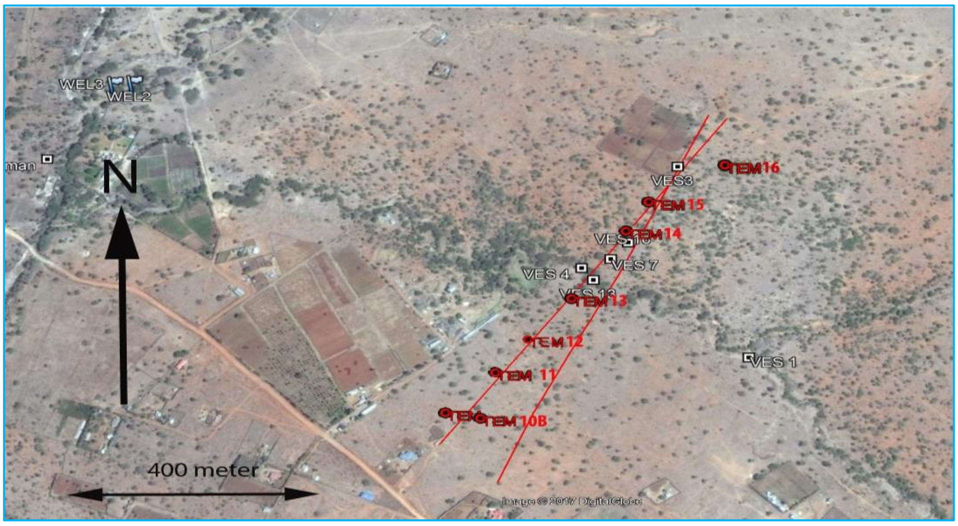


Figure 54. Google Earth overview over Gully C, with the 2 ERT profiles and TDEM/AMT stations plus VES locations. The HEP profiles were taken over the eastern profile line

In the ERT profile in Figure 56 the depth to bedrock in the northern part (at right side in the picture) compared to the southern part is not clear in resistivity. There is a difference in resistivity between North and South side of the gully. The reason is unclear and could be due to a change in basement rock type.

ERT, TDEM and AMT resistivity anomalies give an indication for a geological unconformity in the subsurface near the gully. However, as compared to the Kajiado River profile, it seems less evident that this unconformity is due to a fracture, it could also be due to a change of the bedrock composition (a 'dyke') related to a deeper or different weathering profile. In the field, coarse, angular quartzite grains were observed, particularly on the south side of the gully. From field observations (e.g. from water level logger data) it became clear that rain water easily infiltrates in the underground in this section of the gully.

The exploration depth of AMT and TDEM is larger than the ERT; their results indicate a deeper low resistivity zone beyond the exploration depth of ERT (140 m.). In fact these results are not in a good agreement. The best agreement of TDEM interpretation with ERT was with the 1D layered inversions. These differences in agreement are due to the increasing of the equivalence caused by the need to delete data points for obtaining smooth sounding graphs for inversion. Both the Zonge and AMT inversions seem to suffer from this. As has been explained before, the inversion result is very much deepening the data points you choose to use for the inversion and picking too many or leaving out to much points can result into misleading results. More forward modelling with ERT could help to solve which model is most convenient.  In ERT the influence of the superficial clay layer and high resistivity right beneath still relative close to the surface could shield the information of the deeper layers.

### Comparison of the HEP and ERT results of the Gully C-profile

When comparing the HEP results of the Gulley C profile with the ERT profile (Figure 57) it becomes clear again that HEP measurements basically represent the apparent resistivity variations of the upper part of the subsurface, the shallow part in the ERT. Visual comparison of the ERT and the HEP indicates that the HEP variance roughly compares to the top 25m in the ERT.

The latter finding is clearly illustrated near the gulley, where the ERT profile shows low resistivity (clays) directly on top of a very high resistivity zone, which may indicate a hard cap due to chemical weathering processes or a basaltic remand if it fits with the geology and its topographical elevation. Both with the short AB, (a=30m, Wenner, marked with the red line in Figure 57) and in the long Wenner and Schlumberger (AB=150m, the green and blue lines in Figure 57) HEP profiles, the measured apparent resistivity is dominated by the shallow clay layer. In the long HEP the resistivity values are higher because it is also influenced by the high resistivity (the top of the 'hard cap') underneath. The influence of the clay is still larger than the hard cap.

Figure 55. Location of the Gully C HEP profile and VES locations

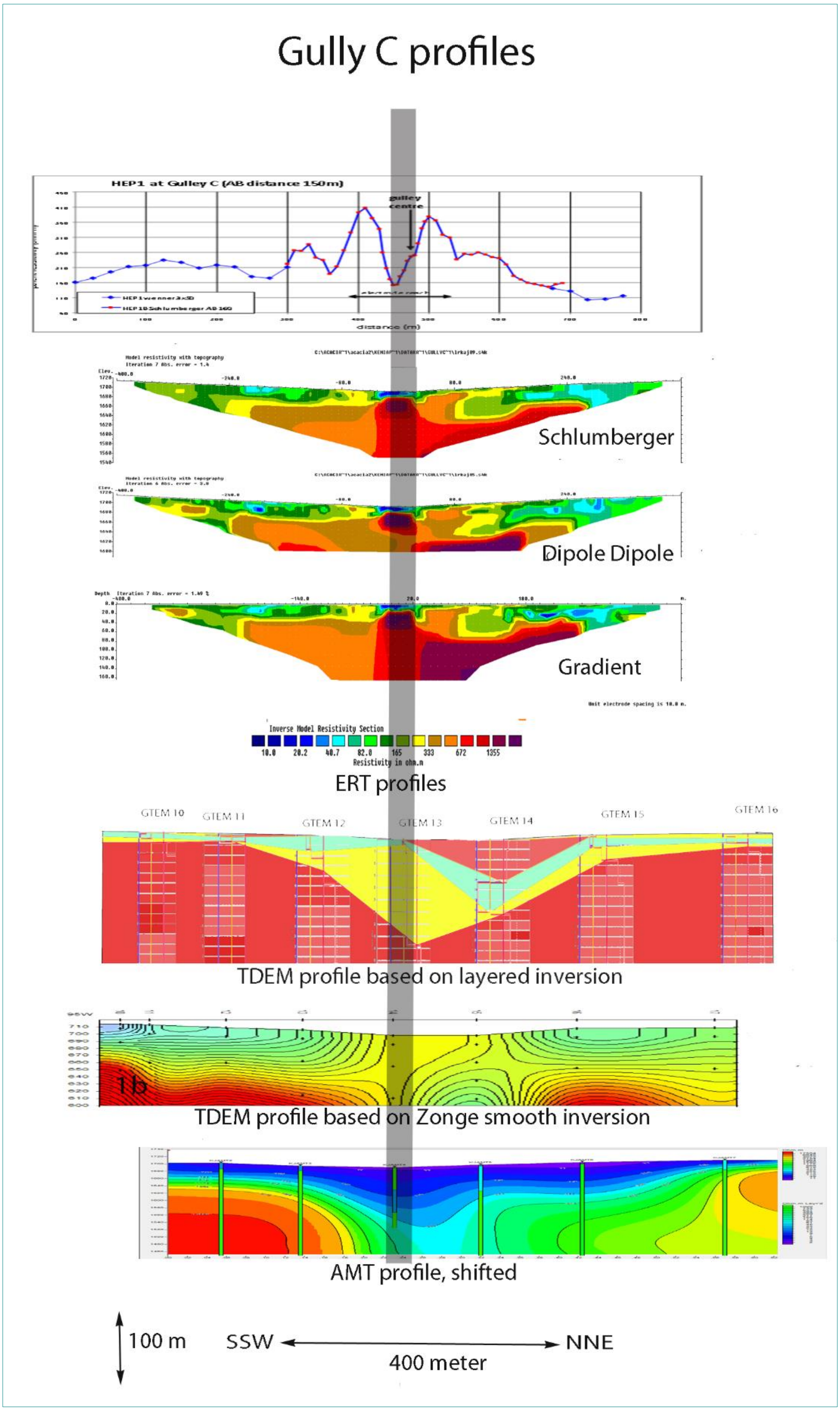


Figure 56. Gully C profile: comparison of HEP, ERT, TDEM and AMT results.

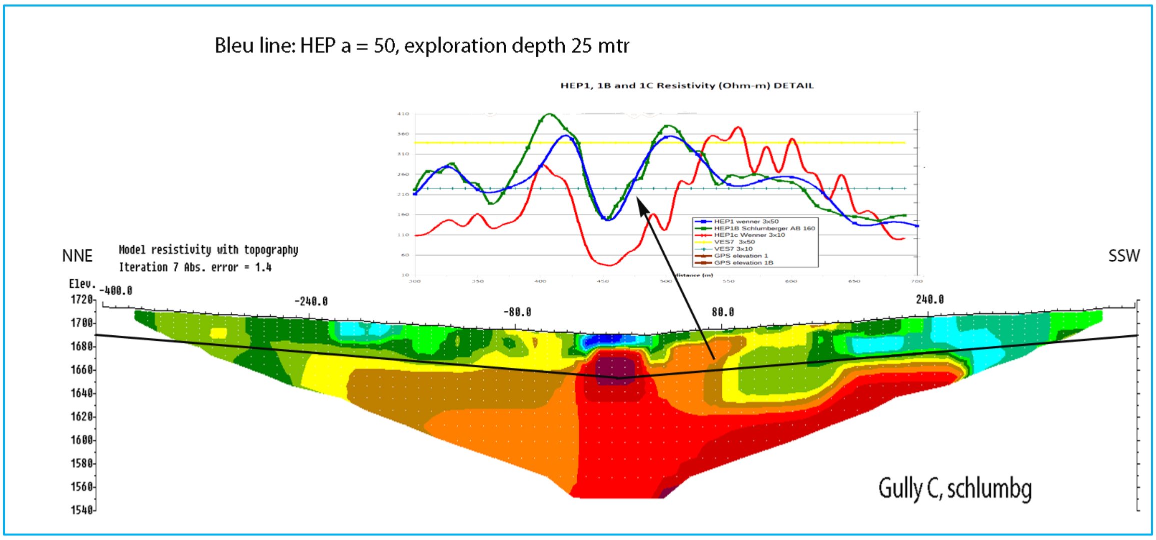


Figure 57. Comparison of HEP and ERT results at Gully C-profile

In Figure 58 the apparent resistivity of the data set and inversion of the ERT profile (deviated profile that crosses the main profile) at Gulley C is shown without topographical correction and no constraints in the inversion calculation. In this figure the effect of shallow clay layers on the apparent resistivity is clearly visible in the center of the profile. The influence of the top (clay) layer on the apparent resistivity 'goes all the way down', this is meaning that its effect is measured even at the largest electrode distances. In the inversion (lower picture) it is clear that this effect is solely caused by the strong contrast of a low resistive clay layer on top of high resistive rock. The apparent resistivity is the same as what is measured with HEP. Even in a long range HEP (large a's) this effect will show up as an anomaly and might be confusing if it is not realized that the effect is caused just by shallow layers. Only from the inversions the irregular subsurface of the weathered basement is visible and only looking at apparent resistivity's as in HEP can be misleading!

Synthetic HEP values can be derived from forward modelling with ERT data to explore the effect of different targets, see annex 2.

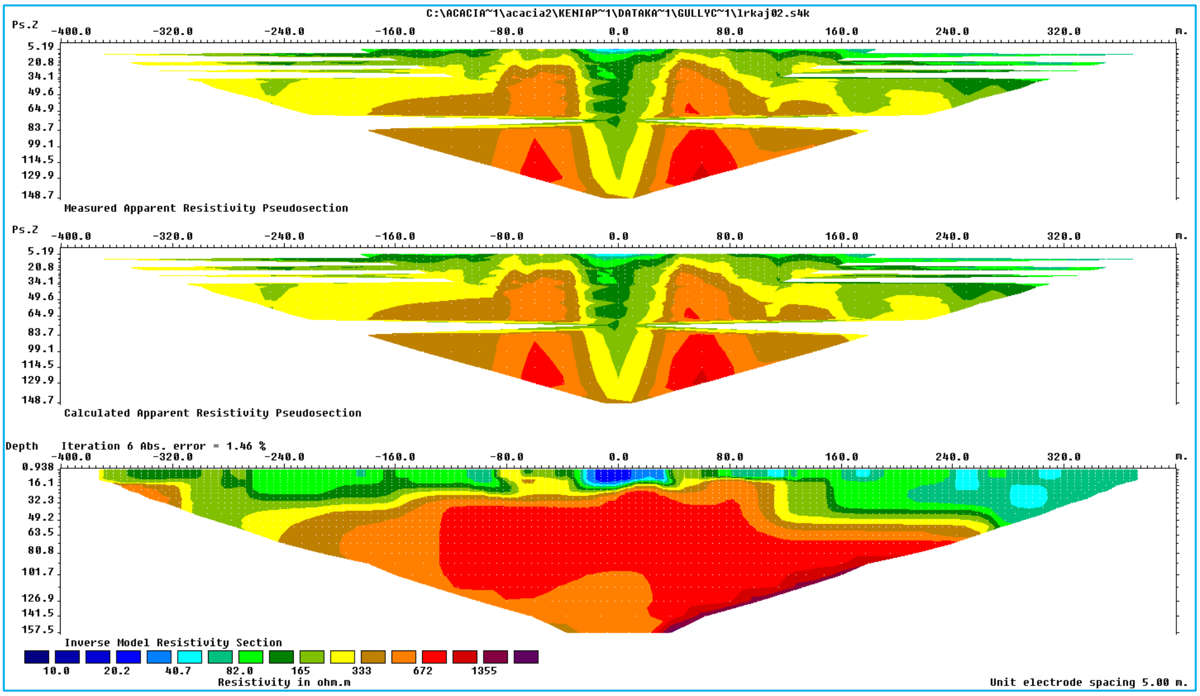


Figure 58. Inversion results of profile A at Gully C

### Comparison of VES soundings and ERT of the Gully C profile

All presented VES soundings were done perpendicular to the profile line; see for their locations Figure 3. Some other soundings were done in the profile line direction, these are not included here.

- The high resistivity the gulley is confirmed by VES13.
- VES 7 confirms relative deep basement right to the North of the gully
- The depth to basement in VES16 is uncertain and difficult to compare with the ERT result.

One should bear in mind that the VES sounding directions are perpendicular to the profile line and may be influenced by lateral geology changes in that direction.
In general, it is concluded that the resolution of the VES models is (of course) less than the ERT, meaning that the equivalency is much better solved in the ERT than in VES.

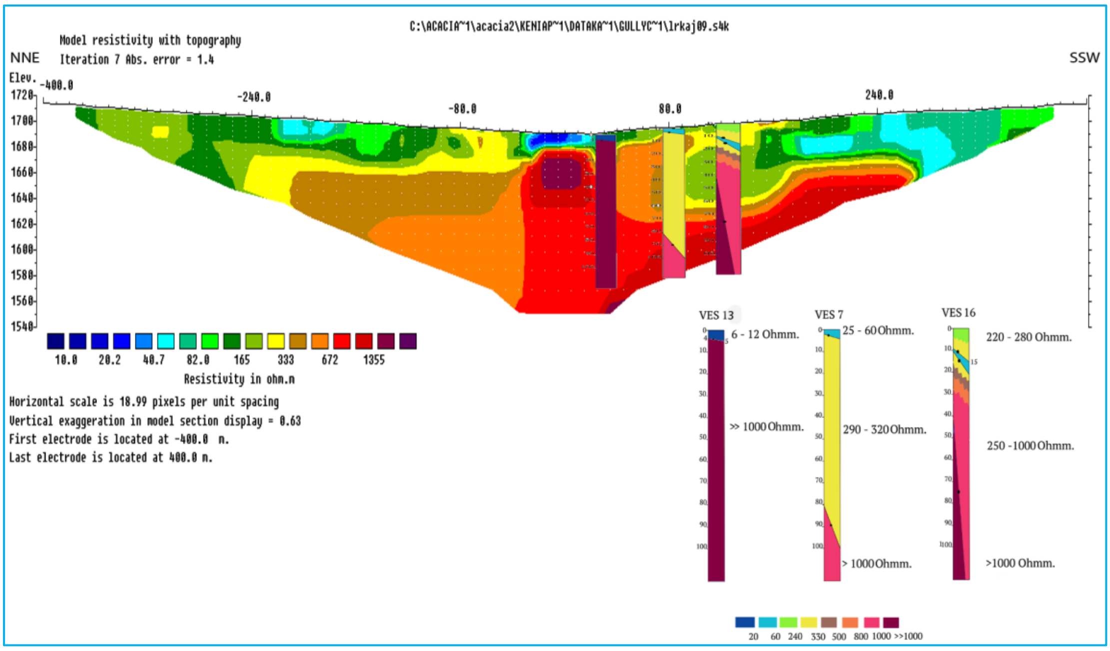


Figure 59. VES inversions compared with ERT

## 7.2.3 Comparison of WalkTEM soundings with ERT on the Kajiado River profile

In the 2nd ISGEAG campaign, on the way to Kwale, it was possible to conduct 4 additional TDEM soundings in Kajiado with the new ABEM WalkTem equipment. See for the results figure 65 below.
The two soundings on the left (WalkTEM nrs. 7 and 8) were done in the fracture zone and confirm low resistivity up to 200mbgl!. WalkTEM nr. 5 was done in the 'buried river valley' showing basement at 80 m and WalkTEM nr. 6 shows shallow basement. It should be noted that the locations of the Walktem soundings were based on the ERT results and the existing location of the Zonge soundings. All the (smooth) inversions both Zonge and WalkTEM are without constraints.

The WalkTEM results are consistent with the ERT results (in figure 65 below the WalkTem soundings). The measurements were done with a transmitter loop size of 40 X 40, dual moment and standard tuning. Important differences with Zonge are the loop size, resolution and estimated depth to basement. The loops size could be kept much smaller which made is less vulnerable for lateral change. The WalkTEM system measures more time windows, resulting in more data points from which less points needed to be discarded. This results in a significant increase of the vertical resolution. The small loop size made it possible that 2 soundings (nr 7 and nr 8) are within the unconformity.

In figure 65, the differences between Zonge and WalkTEM become more evident:

- The positive effect of smaller loopsize (WalkTEM) on the influence of lateral change;
- The effect of increase of resolution, because more datapoints are available for inversion with WalkTEM (less points needed to be skipped and more time are windows measured);
- A better estimation of the depth to the basement (based on smooth inversions without any constraints);

- A better location of the anomaly, a more precise measure of the lateral extend, and a better indication of depth of the fracture.

In W5 the effect of lateral change becomes clear, because the lateral change was within the transmitter loop, more datapoints needed to be skipped for the inversion. The depth to the bedrock in the Zonge smooth inversion are underestimated, the clay layer in Zonge sounding Z2 seems to be exaggerated in thickness. If more Walktem soundings would have been executed allong the transect and a contraint 2D inversion was possible to conduct, the resolution of the 2D results will become close to the ERT resolution with a increase of DOI (over the total profile length). ERT in Kajiado because of the favourable circumstances will take 4 ours (with at least 4 persons). Walktem every 40 mtr over 800 mtr (20 soundings) will take 2,5 days with at least 2 persons. Because inversions can be done in the field, the measuring strategy could be optimized which will reduce the amount of soundings and measuring time. When the DOI of the ERT will be also kept at maximum at the edges of the profile the ERT should be extended 5 times which will increase the measuring time with at least 1 day.

WalkTEM proves to be the next generation in TDEM sounding but also in 2D imaging. The system is very easy to apply and can be used at several levels. A preset standard operation makes it very easy to measure with a high resolution both at shallow depth and deep (150 – 200 mtr). It is also possible to design you own “sounding” according to desired target depth and resolution at greater depth’s. The instrument measures with a dual moment (two different currents) combined in one sounding. It is possible to see the sounding graph during the measurement. The combined graphs can be inverted directly after the measurement has been taken, on the screen almost automatically!). The quality of the automatic inversion is execptional thanks to special filtering of the data points to be used for inversion. This makes it possible to adjust the measuring strategy (i.e. sounding station interval, repetitions, transmiter loop) at once. In the next report (Kwale) the WalkTEM system will be evaluated more in detail.

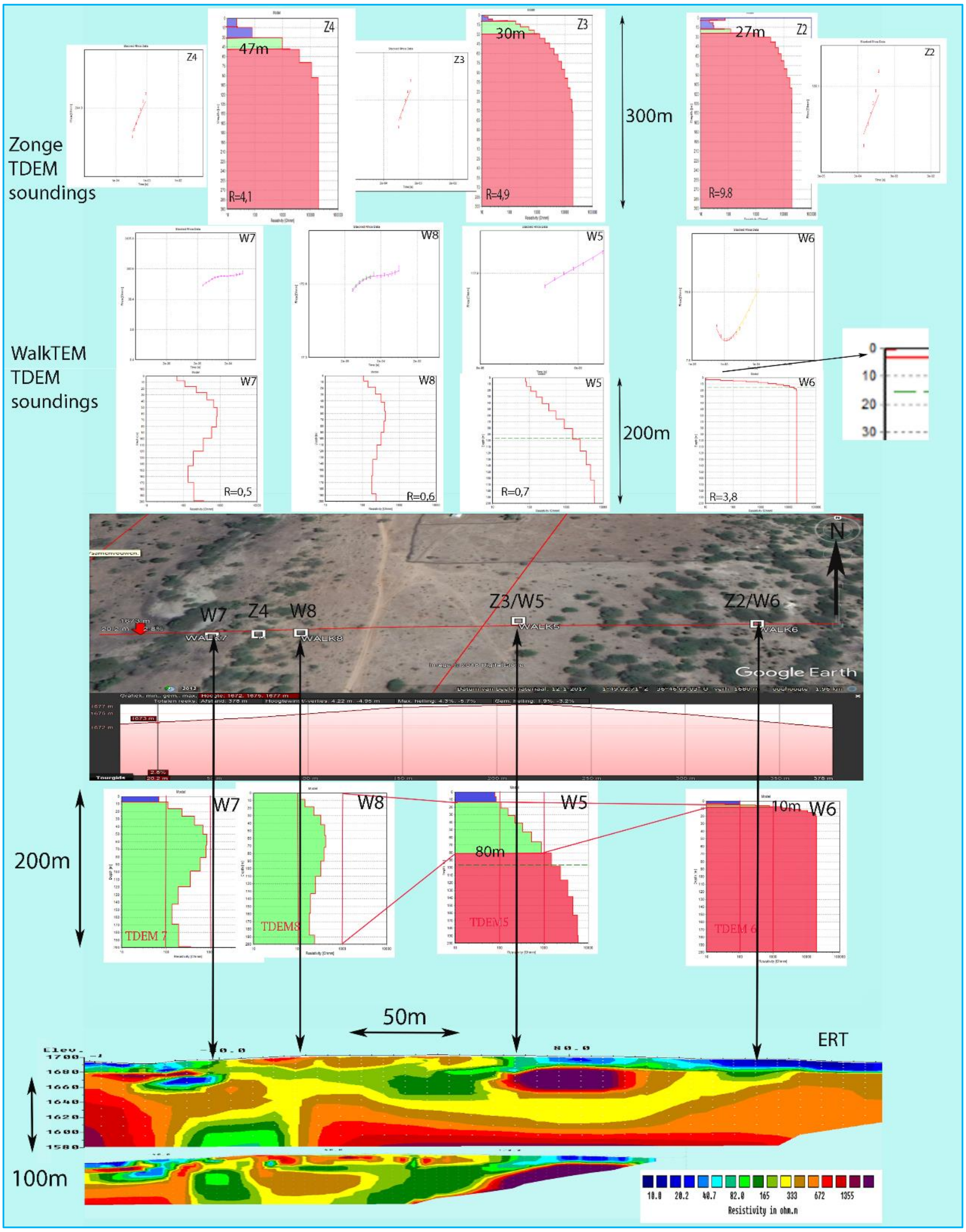


Figure 65. ABEM WalkTEM inversions compared with ERT (Kajiado River profile)

# 8 Conclusions and lessons learned

This Kajiado experiment shows how skilled applications and integrated interpretation of multiple soundings and methods can help to a better insight in the groundwater system, leading to an increased borehole drilling success rate. Lack of documented information from existing boreholes and previous surveys and the quality of survey reports is a main hinderance to fully understand the system. This is why we urgently advise to pay more attention to the quality and availability of consultant survey and borehole completion reports. These technical documents should be easy to acquire, while the information of the reports should be complete, correct and reproducible in a way that the data can be of use in future programs and help to get more insight in the hydrogeology of a certain area. This ongoing process of gaining and increasing knowledge is fundamental for the way forward to a sustainable groundwater exploration.

## 8.1 Overall conclusions

The main conclusions of the Kajiado geophysical fieldwork are can be summarized as follow:

1) In Kajiado, it became clear that the ERT gave the best results in resolution. An important issue is that the cable length and the accessory electrode distance should be according the desired exploration depth. The exploration depth, the extension of this depth over the profile length and the lateral as well as the vertical resolution very much also depends on the used protocol (e.g. Dipole Dipole, Wenner, Schlumberger).

2) HEP anomalies with the electrode distances normally used in Kenya groundwater prospecting (a =50 and L=3x50m), give only superficial information on the lateral changes within the first tenth of meters. In the Kajiado case the HEP anomalies where dominated by the presence or absence of low resistive, superficial clay layers. These HEP profiles gave no secure or direct indication of depth to bedrock or location of fractures.

3) Both TDEM and AMT are poor in resolution especially when lateral changes are within the spread (the ‘loop size’) and the resistivity increases with depth. More data points need to be excluded under these circumstances and this will lead to a decrease in resolution. The soundings are also lacking information of the first layers. Exploration depth is larger compared to ERT with the same spread. New instrumentation like WalkTem show much more promising results.

4) The quality of the inversion of AMT (resistivity) is strongly depending on the quality of the TDEM data.

5) For TDEM and AMT less labor is required when compared with VES soundings, however the interpretation of the data is less straightforward and instrumentation is (especially the older generations of instruments) more complex and expensive. Interpretation based on individual soundings (VES, TDEM, AMT) assume horizontal layering and therefore detailed information on location and geometry of faults cannot be obtained in this complex type of geology.

6) The application and interpretation of all the methods should be used with skills; conclusions should be based on multiple soundings and profiles. Inversion results should be combined with extra information to reach a conceptual conclusion. The use of HEP and VES is relative cheap, easy to use, simple and straight forward however with a limited resolution, exploration depth and usefulness to understand the hydrogeological system.

7) Survey reports needed for the permission for boreholes often lack essential information, sometimes contain even mis interpretations and assumptions, are difficult to obtain and do not contribute in understanding the (local) hydrogeological concept, which is needed to achieve sustainable groundwater exploration.

Chapter 3: Conventional methods (VES and HEP)

- The applicability of one dimensional methods as VES soundings and HEP profiling is limited, because of inherent limitation of the long AB electrode distance, compared to its exploration depth;
- Due to lateral changes in geology within the long AB electrode reach, a reliable horizontal layer interpretation is often challenging. Also, the non-uniqueness or equivalence (several layer models can fit to one sounding) of interpretation is a limitation, especially when the VES graph is increasing with an angle 45 degrees indicating increasing resistivity. This makes it difficult to discriminate the weathered zone.
- This study clearly demonstrated the validity of the 'rule of thumb' on the exploration depth of these resistivity methods, saying that the DOI is roughly 1/6 of the electrode distance AB. According this this ' rule of thumb', VES soundings with an AB up to 600 meters (AB/2=300 can give an indication of subsurface resistivity distribution up to roughly 100m;
- VES soundings can be helpful in finding rough indications and directions of major lateral changes in geology by applying soundings in various compass directions and by using multiple potential (MN) electrode spacing's at the same AB distance (to be further tested in the next ISGEAG campaign);
- In areas with a high resistive top layer, smooth VES soundings are difficult to conduct.
- Single and isolated VES measurements do not give the required insight for prospecting drilling locations when the geophysics is not compared to borehole logs and not guided by wider hydro-geological insights from existing information;
- Survey 'borehole siting' reports encountered in Kenya often lack essential information: location and the direction of the measurements, raw measured data, inversion program used, accuracy of the fit of the model etc. Often only 3 VES sounding (sometimes even only 1) are executed at apparent arbitrary locations without explanation. The exploration depth is in most cases over-estimated which results in (deep) drilling depth without argumentation. The results of different VES soundings are not compared and the line of reasoning for choosing the drilling location as well as a deduced hydro-geological concept is often missing;
- HEP profiling may give misleading results when the HEP exploration depth is not properly understood. The exploration depth is very limited (20-25 m with AB=150m). With larger electrode distance the resolution decreases rapidly and potential fractures based on the standard Wenner configuration will not be detected. In most cases HEP anomalies just represent lateral changes in the shallow subsoil;
- A common misunderstanding is that a HEP profile measures the resistivity changes at one specific 'probing depth'. This is not the case: each HEP measurement gives a weighted average of the resistivity of a subsurface 'block' (the so called apparent resistivity) of roughly 1/6 of the AB in use;
- The execution of HEP profiling is questionable if one is looking for (deep) groundwater aquifers of -say- 100mbgl.
- If one is interested in shallow groundwater, it is advisable to at least conduct a second HEP with smaller electrode distance to check on the variability of these shallow (clay) layers and to conduct VES soundings on these anomaly's perpendicular and parallel of the HEP profile and compare the results.

## Chapter 4: Application of Electrical Resistivity Tomography (ERT)

- ERT is an integrated combination of multiple VES's (and therefore a much better alternative for HEP) along a profile line and will give 2D results. In this way it largely overcomes the problem of equivalence, especially when using different electrode configurations at the same line and also smaller electrode distances (shorter profile lines with a higher resolution but with a decrease of the exploration depth). ERT tomography (resistivity imaging) is for this specific type of basement geology the best choice when it fits within the desired exploration depth (max ≈ 140 m);

- The ERT system in use must have the desired cable length related to the electrode distance, enough power for deeper measurements and the possibility to change electrode configurations. Not every brand or system can reach these requirements;
- Multi-channel instruments (Like ABEM SAS 4000 or ABEM LS) can speed up the measurement and increase the amount of measurements.
- Because of its excellent lateral resolution, when choosing the right combinations of electrode configurations (e.g. Dipole, Gradient, Schlumberger, Wenner) , it can give insight in the change of depth to basement and the location of potential fractured zones;
- In regions with very high resistivity at the top (i.e. dune sands) the application of this method can be difficult due to poor electrode contacts, especially with long cables and electrode distances. In these area's often Wenner is the only configuration that is applicable, this configuration is less good in resolution and less sensitive to lateral changes;
- Coupling with powerlines and galvanic protected buried iron pipes can influence the quality of the data especially when the profiles are oriented parallel.
- ERT generates nice coloured pictures, this is not were interpretation ends….actually it is where it starts, a process of trial and error with different inversion constraints alternating with forward modelling in order to let it fit into a hydro geological concept.

## Chapter 5: Application of Time Domain Electro-Magnetic (TDEM)

- In areas with basement geology, as met in Kajiado, where resistivity increases with depth the application of TDEM was expected to be limited because these EM systems are more sensitive to conductors (low resistive layers). Lack of resistivity contrast, equivalence and lack of resolution is limiting the results. This is also observed in the Kajiado case. The optimum resistivity range in which the system operates is restricted as compared to DC systems in a way that TDEM systems can find very secure low resistivity zones (high contrast) beneath high resistivity. The method is limited in its capability to distinguish layering within a higher resistivity zones, equivalence is limiting a reliable layered model;
- Relative narrow spaced lateral variation (within the spread) is affecting the sounding curves and is limiting the (horizontal layered) inversion due to a limited amount of data points that can be used for inversion;
- As with VES, the interpretation is assuming horizontal layering. Lateral change (vertical contrasts in resistivity) in near vicinity of a TDEM sounding will give disturbances. This effect has been observed in both of the profiles. The spread (radius of influence) increases with depth but is much better - even at larger depths - as compared to VES;
- In areas were the exploration depth of VES and ERT is limiting, the system can be useful in exploring the variation of the depth to the basement which can be indication for fractures and fault zones. Exact location of fractures is difficult to determine when they are within the radius of influence of the measurement (spread); However new developments in instrumentations, like WalkTEM can overcome this;
- Compared to VES and ERT, The TDEM method, potentially has a better exploration depth when exploring low resistivity zones below high resistivity overburden (e.g. salt and fresh groundwater interfaces). Even at hundreds of meters of depth it can find low resistivity layers within an accuracy of less than 5 m. The lower the resistivity (the higher the contrast) the better the depth resolution. The resolution becomes poor in high resistive area's especially when resistivity is increasing with depth;
- In TDEM systems, the first tenth of meters is not measured due to delay times needed to shut of the transmitter;
- For a proper application of TDEM, good skills and experience in interpretation are needed; a standard operation protocol with instrument settings like VES is not straight forward. Useful soundings are not always directly recognized from decay curves. For very deep soundings stronger transmitters are needed.
- Instrumentation is more sensitive, expensive and complicated to control;
- Inversion, and inversion software is more complicated than with VES;
- Higher resolution 2D profiling can be done by conducting multiple soundings along a profile line with airborne TDEM especially when used with helicopters, like the SKYTEM system. SKYTEM is an airborne system that generates 2D (or 3D) profiles, more complex software is needed for inversions;

- TDEM is an EM method. Galvanic coupling with metal (fences, pipelines, powerlines) can be severe, however no electrodes are needed which makes it very suitable in area's with a high resistive top layer;
- In Kajiado, at this campaign we did not had the opportunity to test the new WalkTEM TDEM system (ABEM, Sweden) using a so-called 'dual moment'. With this system two soundings are executed at the same time with 2 different currents. This will result in both superficial and deeper resistivity information with the same transmitter antenna loop. In this way the resolution will increase. We did test the WalkTEM in Kajiado on our way to Kwale (second campaign), and the results show that this system overcome the limitations encountered with the Zonge system.

### Chapter 6: Application of Audiomagneto-telluric (AMT) Soundings

- The AMT method is less labor intensive than VES or ERT. However, the setup should be done with great care. Adjusting the system and taking measurements as well as data validation has to be done with professional judgement. At the location of the fieldwork a calibration should be executed for the magnetic sensors in a magnetic relatively noise-clean area;
- Because AMT is a passive system that uses natural sources (thunderstorms, solar winds), no transmitter is required which makes the instrumentation relative light and compact, compared to TDEM and ERT. There are also systems that use their own transmitter (Controlled Source AMT);
- Applications in noisy area's (power lines, urbanization etc.) is very limited and relative long data sampling is required;
- In Kajiado, the application of AMT combined with TDEM showed that the system is sensitive to vertical anomalies due to the extra (magnetic) component that is measured. AMT is (as TDEM) more useful for deeper exploration because of the low frequencies it measures. For a reliable layered resistivity inversion from AMT, information from TDEM soundings has to be combined with AMT in a joined inversion, especially in cases with near surface in homogeneities. (Shifted AMT). It is advised to apply them both if (true) resistivity information is needed; The quality of the TDEM soundings influence the reliability of AMT sounding (with shifting, calculation of the resistivity)
- The resolution of AMT is comparable to TDEM. The AMT data also approves the TDEM data and vice versa.

## 8.2 Lessons learned

Some other lessons that are learned from this fieldwork:

- It is important to get the Kenya Water Resources Authority (WRA) more involved into the project, being 'game changers' in groundwater exploration and exploitation; the project plan should have incorporated WRA involvement from the beginning. It has been difficult to contact WRA officials and get the right persons involved.
- The same goes for University of Nairobi, they could play a important role in the dissemination of the newly gained knowledge;
- Memorandums of Understanding (MOUs) with project and involved partners should be signed well in advance of starting the fieldwork mission;
- The project plan does unfortunately not allow the required time for mutual interpretation and reporting, in particular between KenGen and Dutch experts. Mission time is mainly spent on measuring in the field, logistics, data quality analysis and building a database. For combining inversions and mutual interpretation of all the data into a hydrogeological concept really lacked time. Afterwards email communication proves not to be effective. There should be ample time for mutual interpretation, comparison, discussion. Realize this process together in Kenya will improve the results and the reporting and it will enforce the role and knowledge of the local partners.
- File names, stations names and numbers should be unambiguous;
- GPS coordinates should be from the start according to international standards and reciprocal with Google-Earth;

- Before the start of the fieldwork, the field location should be visited for reconnaissance and social grounding by a field hydrologist and local community leaders;
- ABEM WALKTEM should have been send to Amsterdam and consequently brought with us in the plane to Nairobi instead of directly to Nairobi. It was really a pity that we could not use the ABEM WalkTEM in Kajiado. With the WalkTEM system it is proved that a higher resolution can be achieved. We used the system in Kajiado on our way to Kwale.
- It should be noted that in the next location the geology is completely different and a different approach might be needed.
- The ABEM WalkTEM system proved to be very successful, especially in Kwale but also in Kajiado, it is an easy to use sounding system with a very high resolution combined with a relative small transmitter loop (spread). This system should also be available in Naivasha.

# 9

# Hydro-geological interpretation of Kajiado River

A hydro-geological concept for the Kajiado river investigated area is evaluated based on these results. The concept is hypothetical, since no specific more detailed geological information for this area could be found. At least some test wells would be required to verify this concept because no other information (like reliable drilling logs or test wells) was available.
In Figure 9.1 a 3D view of the conceptual interpretation is presented: a low resistivity anomaly that is related to a fracture zone in the Kajiado River profile. The unconformity in the Gulley C profile shows less evidence for a fault system, but from this section of the gully we at least observed that rainwater infiltrates fast down, recharging to the underground.

A buried river channel seems to be related to the fracture zone observed in the River profile, this may correlate with another geological period and climate, after a period of sedimentation and less rain the main river has been split and diverted into two separate branches. The isolated high resistivity 'hard cap' found both in the buried river channel and in Gully C might be from (Pleistocene) inflow of volcanic material (basalt) this should be verified with geological map and the topography.

The equivalence in resistivity of the weathered basement and buried river sediment is visible and its interpretation is also based on other arguments.
Productive boreholes like the HARAF borehole are obviously located in the sediment of this buried channel and in, or close to, the presumed fractured zone.
Although the concept has to be verified by test wells, it indicates excellent potential for sustainable groundwater exploitation. Based on this hydro-geological concept a sustainable groundwater exploration plan can be derived.

The potential aquifers contain several elements:

- Weathered basement with relative small fractures
- Main fractured zone
- Buried river channel

Direct recharge of the weathered basement and its small fractures can take place if soils and vegetation are in equilibrium and if there is no thick clay layer on top unless the clay is cracked in the dry season. With a good developed vegetation cover even superficial clay layers can contribute to recharge due to secondary permeability related to plant roots. Indirect recharge of the main fractured zone will also take place via infiltration at the surface were the buried river channel is exposed and at locations were the seasonal rivers are in contact with this sediment.

Major recharge can also be indirect, through the deep fractured zone, transporting groundwater from the Northern Oloyiangalani volcanic hills.
Access of rain water from urbanized areas (Kajiado town) may also contribute if it is channeled towards the buried river channel sediment. Gulley C is a main channel for the excess of rain from Kajiado town.

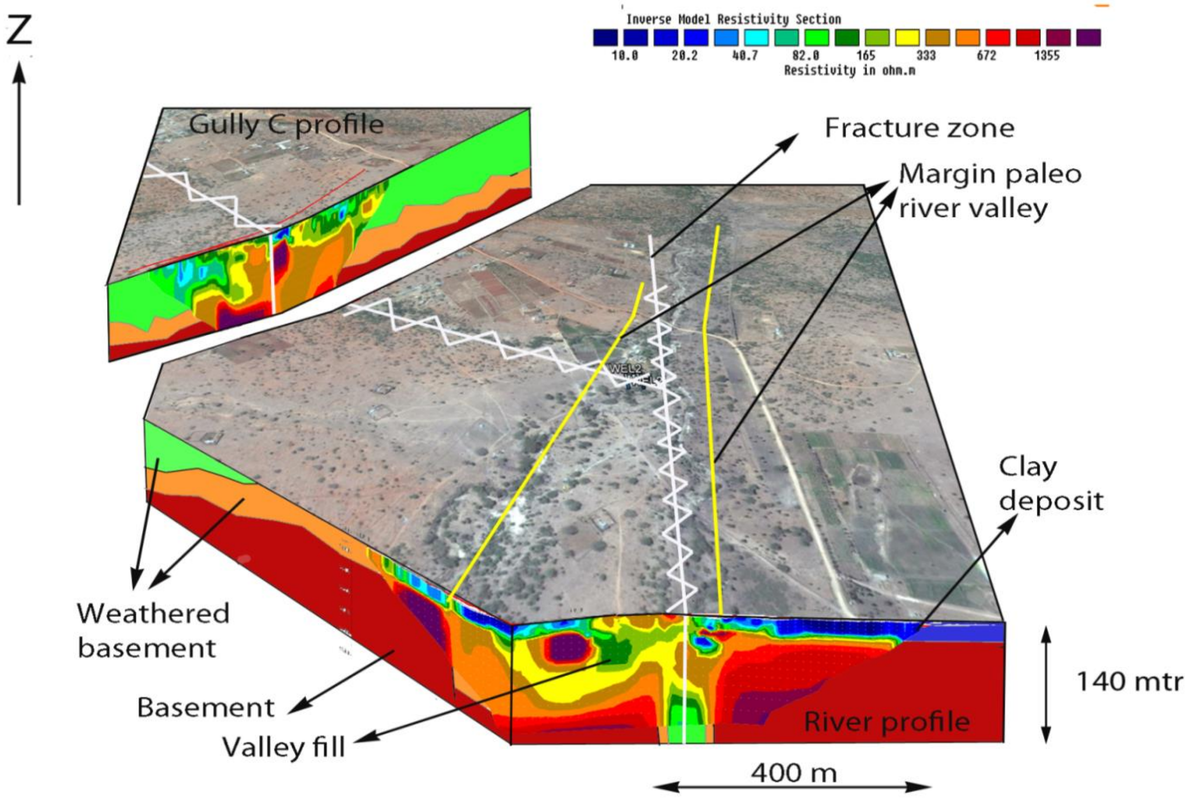


Figure 66. Hydrogeological concept of Kajiado River

A potential danger for the (natural) recharge system is soil erosion (figure 9.2), especially in areas with clay layers on top. If the clay is not protected by a healthy soil plant cover, clay will be eroded, transported and sedimentation will take place in the potential recharge area's preventing recharge. In areas without clay and lack of soils, on basement rocks, the weathered layer will be gradually eroded until the bare rock is exposed, and also the recharge of this zone will rapidly decrease. Soil protection is very important and very urgent for future water supply.

Figure 67. Soil erosion, starting in small gullies, resulting in deep canyons when not interfered

For this reason (ground) water protection by preventing soil erosion should start by a groundwater protection program. This will increase and preserve the groundwater potential and at the same time agriculture can be developed if done with care (permaculture/agroforestry) and in equilibrium with groundwater potential and the local socio-economic situation. The landscape will be restored, soil erosion decreased, attractive again (also for animals) and the local people will, by seeing the results be stimulated to maintain and even enjoy.

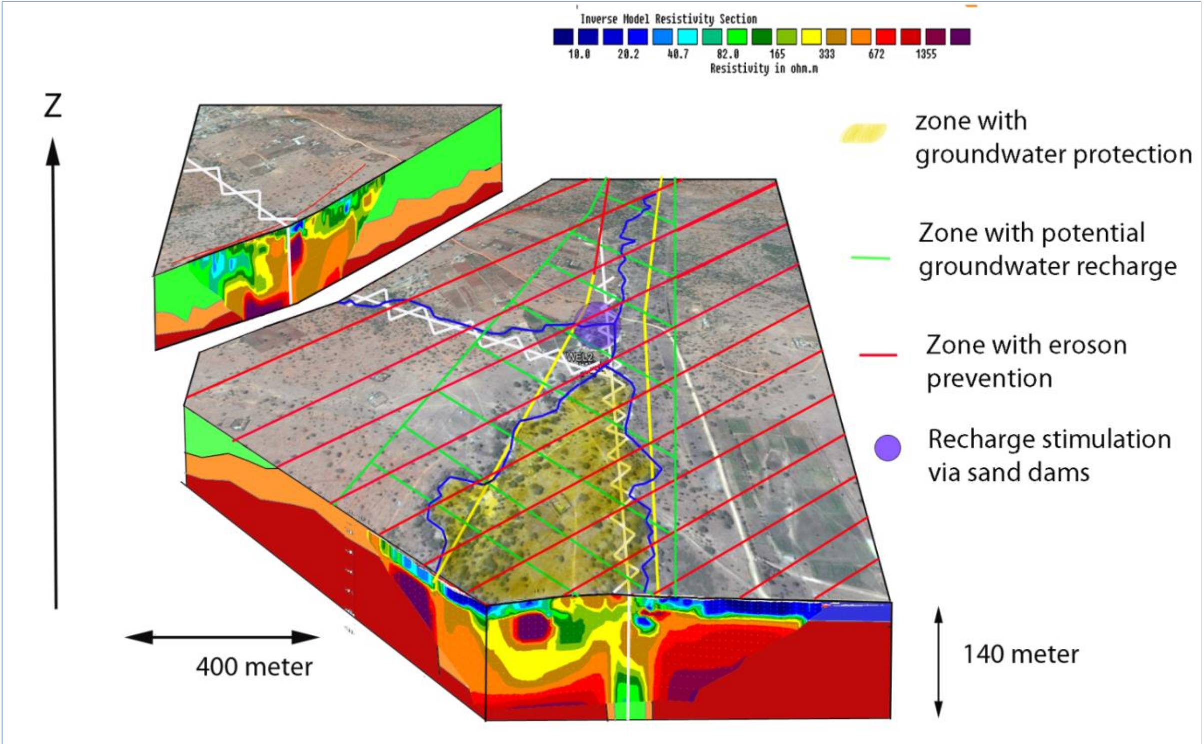


Figure 68. Intervention suggestions for groundwater recharge at Kajiado River

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# Annexes

# ANNEX 1: ZONGE data processing

Data processing with dedicated ZONGE software:

1. Raw data is downloaded from Zonge GDP3224 multifunction receiver to a laptop pc, pre-installed with ***TEMAVGW*** software. The ***TEMAVGW*** software is used to average the transient decays.
2. Using the ***temavgw*** command, each sounding is opened systematically along each profile and the decays averaged independently. The software automatically generates two data sets with extension names; (*.avg & * .zdb), both have the same formats.
3. Using the command ***temtrim*** to open the averaged data sets (*.avg or *.zdb) one after the other along a profile e.g, sounding no. 13 (KJTEM12.avg), for editing & skipping noisy sections. Ref. to fig3.bellow;

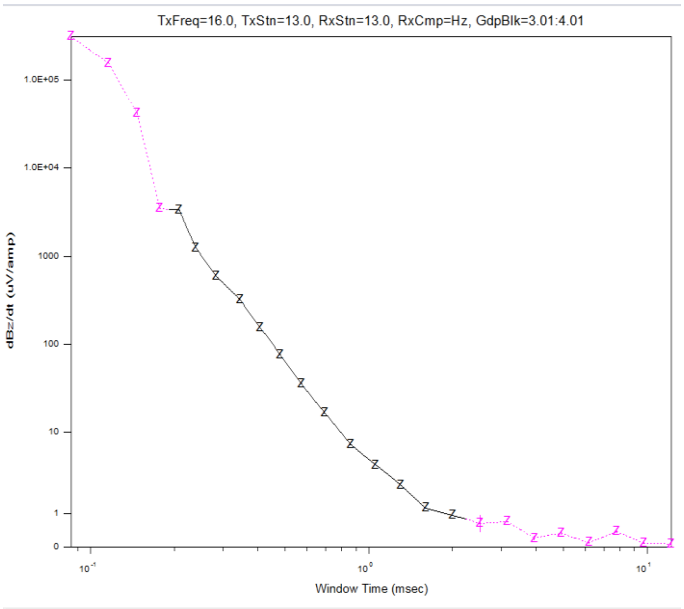


***Fig3; above:*** From the curve; (upper section;-first, intermediate, late arrivals) & (lower last data points) purple in color has been skipped. The smooth black curve saved as KJTEM12.avgo is the one to be used for *1dinversion*.

4. Using the command steminv (Smooth TEM Inversion) prompts for an avg file to be opened e.g KJTEM12.avgo. The result is saved as *.m1d.

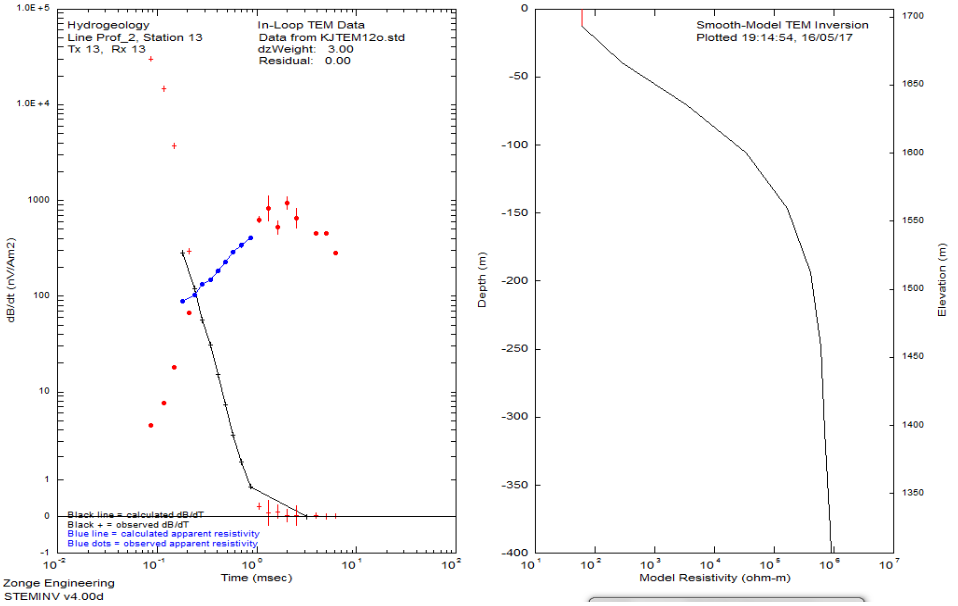
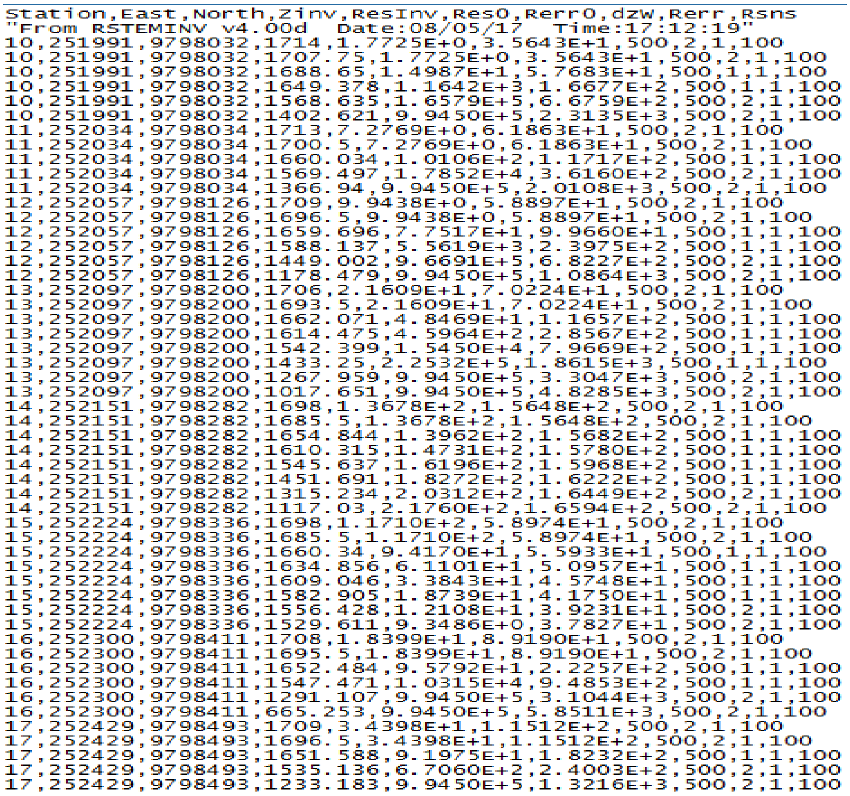


***FIG.4*** left:-. The black plots are the voltage decay and blue the apparent resistivity as a function of time after switching off the primary field. Points represent measured values; the continuous curve is the model response. The red plots are noisy data that has been skipped.
Right: - smooth 1D model result.

***Table -1*** bellow: a sample m1d file combined data sets for ***Kajiado Gulley C*** soundings for cross-section plotting; first column on the left is the sounding number which is plotted on the cross section map bellow. Second, third & fourth columns are the station locations followed by resistivity values, &; inversion residuals.



```
Station,East,North,Zinv,ResInv,Res0,Rerr0,dzW,Rerr,Rsns
"From RSTEMINV v4.00d  Date:08/05/17  Time:17:12:19"
10,251991,9798032,1714,1.7725E+0,3.5643E+1,500,2,1,100
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```
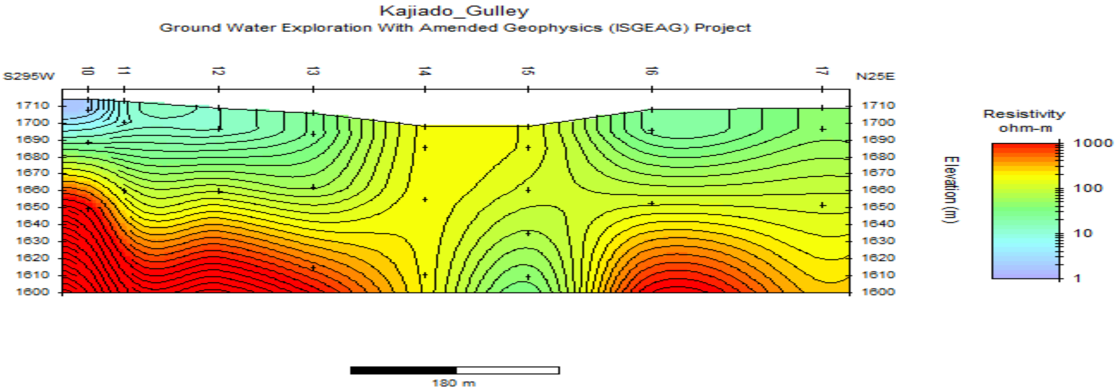
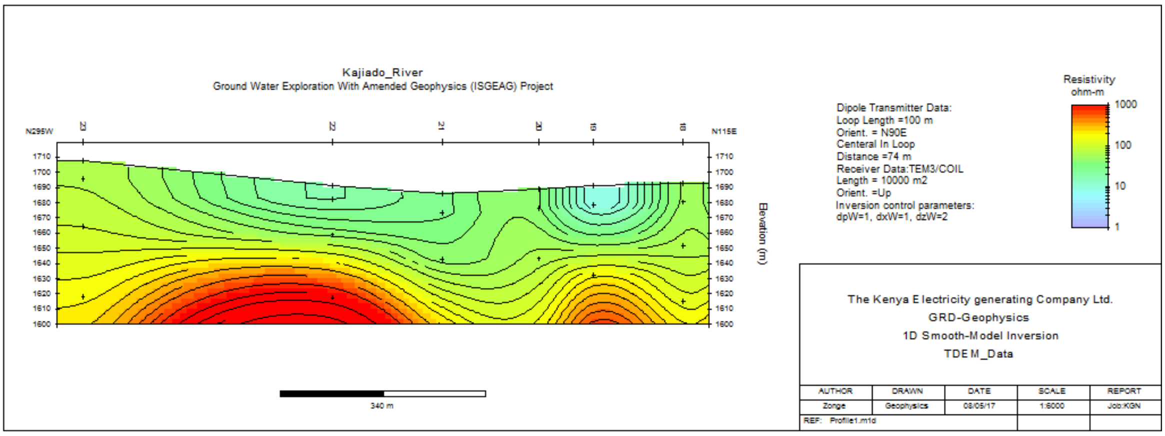

The command***, modsect*** will prompt for an ***(*.M1D***) file to be opened for plotting in pseudo section plot. Table1 above has generated the plot bellow;





Dipole Transmitter Data:
Loop Length =100 m
Orient. = N90E
Centeral In Loop
Distance =74 m
Receiver Data:TEM3/COIL
Length = 10000 m2
Orient. =Up
Inversion control parameters:
dpW=1, dxW=1, dzW=2

The Kenya Electricity generating Company Ltd.
GRD-Geophysics
1D Smooth-Model Inversion
TDEM_Data

| AUTHOR | DRAWN | DATE | SCALE | REPORT |
|---|---|---|---|---|
| Zonge | Geophysics | 08/05/17 | 1:6000 | Job:KGN |
| REF: Profile1.m1d | | | | |

# ANNEX 2: FORWARD MODELLING

### *Forward modelling*

Forward modelling is a technique that can be used to test different resistivity distribution concepts based on an assumed geology concept and other measurements (borehole logs) or field observations, before even going into the field. In fact curve fitting with the VES of TDEM inversion program is a forward modelling process: a synthetic graph based on a model that is compared with the field data.

With forward modelling synthetic data can be generated from a (resistivity) model and it can applied to all the geophysical methods used. With this technique the sensitivity of a method can be tested for detecting layers with different resistivity contrasts (both in layer thickness and in resistivity). The exploration depth of the method can also be tested.

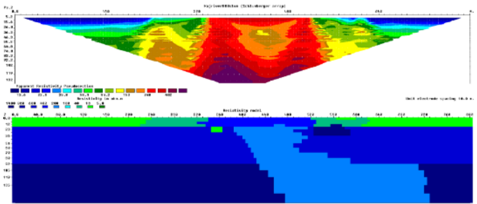
Forward modelling for ERT was done with the program RES2DMOD (Loke). With this program it is possible to generate from a hypothetic (on a geological concept based) resistivity model, its synthetic apparent resistivity distribution (in fact what you expect to measure in the field). From this hypothetic model, the apparent resistivity distribution can be calculated. This is the synthetic apparent resistivity of the given conceptual model. This synthetic apparent resistivity data set can be inverted, the same as with normal field data. This inverted synthetic dataset can be compared to a real dataset or used to test sensitivity for certain targets.

Also the sensitivity of different electrode configurations can be tested for a future survey or testing if the expected contrast is enough to “see “ the target in the inversion. The influence of different shapes of the expected target or depth on the inversion can also be studied.

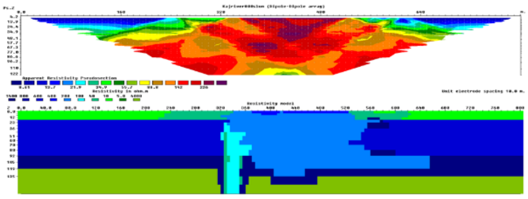
From the synthetic apparent resistivity data it is also possible to derive the (synthetic) 1D Wenner or Schlumberger profiles, comparable to a HEP profile. With these derived 1D profiles it is possible to see the influence of superficial clay layers or deeper lateral changes on the anomalies of these 1D profiles.

### *Forward modelling to compare with existing ERT profiles.*

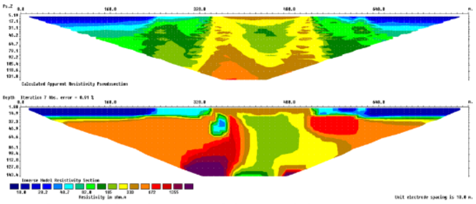
Due to some remaining uncertainties in the interpretation of the ERT profile, like the precise location of the possible fracture zone and influence of superficial layers on this anomaly and the difference between the results of different electrode configurations, a sensitivity analyses was performed by forward modelling (see figure 1).



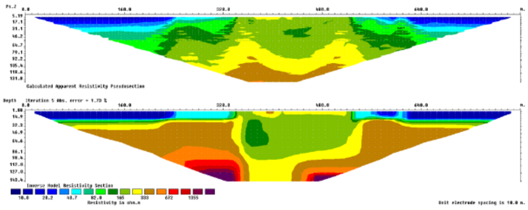
Forwardmodel without fault



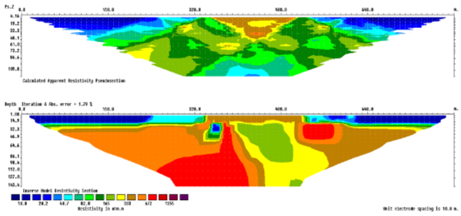
Forward model with fault



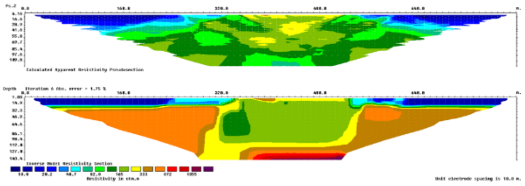
Synthetic schlumberger of this model,
apparent resisitivty (above), and inversion (under)



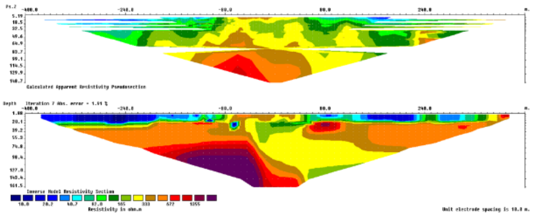
Synthetic schlumberger of this model,
apparent resisitivty (above), and inversion (under)



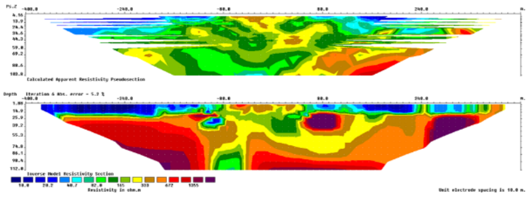
Synthetic DIPDIP (a=max 10 ,n=4) of this model,
Apparent resisitivty (above), and inversion (under)



Synthetic DIPDIP (a=max 10 ,n=4) of this model,
Apparent resisitivty (above), and inversion (under)



Real data, Schlumberger



Real data, dip dip

***Figure 1, forward modelling with 2 different models.***

According to these analyses a relative broad fracture zone (or high a resistivity contrast) is needed to make it visible in the inversion of both the Dipole-Dipole and Schlumberger configuration. The superficial low resistivity zone just above this main anomaly seems not to be the cause of the deeper anomaly in the Dipole. Schlumberger can give misleading results for the location of the fracture but also for the depth to the bedrock, it depend the electrode distances used. However Schlumberger also shows a major unconformity. More forward modelling could be applied to get more proof of the dimensions and location of the vertical anomaly if required for selecting the best drilling locations. In this case a parallel ERT profile at some distance (>100 m.) is also recommended

### *Constructing synthetic HEP profile from synthetic ERT data with forward modelling*

During and after the first campaign forward ERT modelling has been exercised to evaluate the influence of the superficial clay layers on HEP anomalies compared to deeper structures at the gully C profile (figure 4.2).

From the calculated apparent resistivity data, theoretical HEP profiles of different “a” distances can be derived and compared with HEP field data to verify the type of geological unconformity that causes the HEP anomaly’s. It is in this way possible to test what sort of lateral change at what depth caused a specific HEP anomaly.

The HEP profiling in February at Gulley C showed a remarkable anomaly near the crossing of the Gulley. Shallow drilling and VES13 showed that subsurface consisted of a relative thick clay layer (low resistivity) right on top of high resistive rock. The question was whether the HEP anomaly is caused by the local clay or by changes in the shallow basement rock.

ERT ‘forward modelling’ has been applied to evaluate the influence of the superficial clay layers on HEP anomalies compared to deeper structures (figure 4.1).

Different conceptual models were tried (figure 4.1 left to right):

- Fracture with lateral change
- Only lateral change
- Only shallow clay on top
- Low resistivity fracture with lateral change

The modelling indicates that the anomaly produced in this HEP profile (Gulley C) was mainly due to superficial clay layer, represented by the 3rd model in the figure.

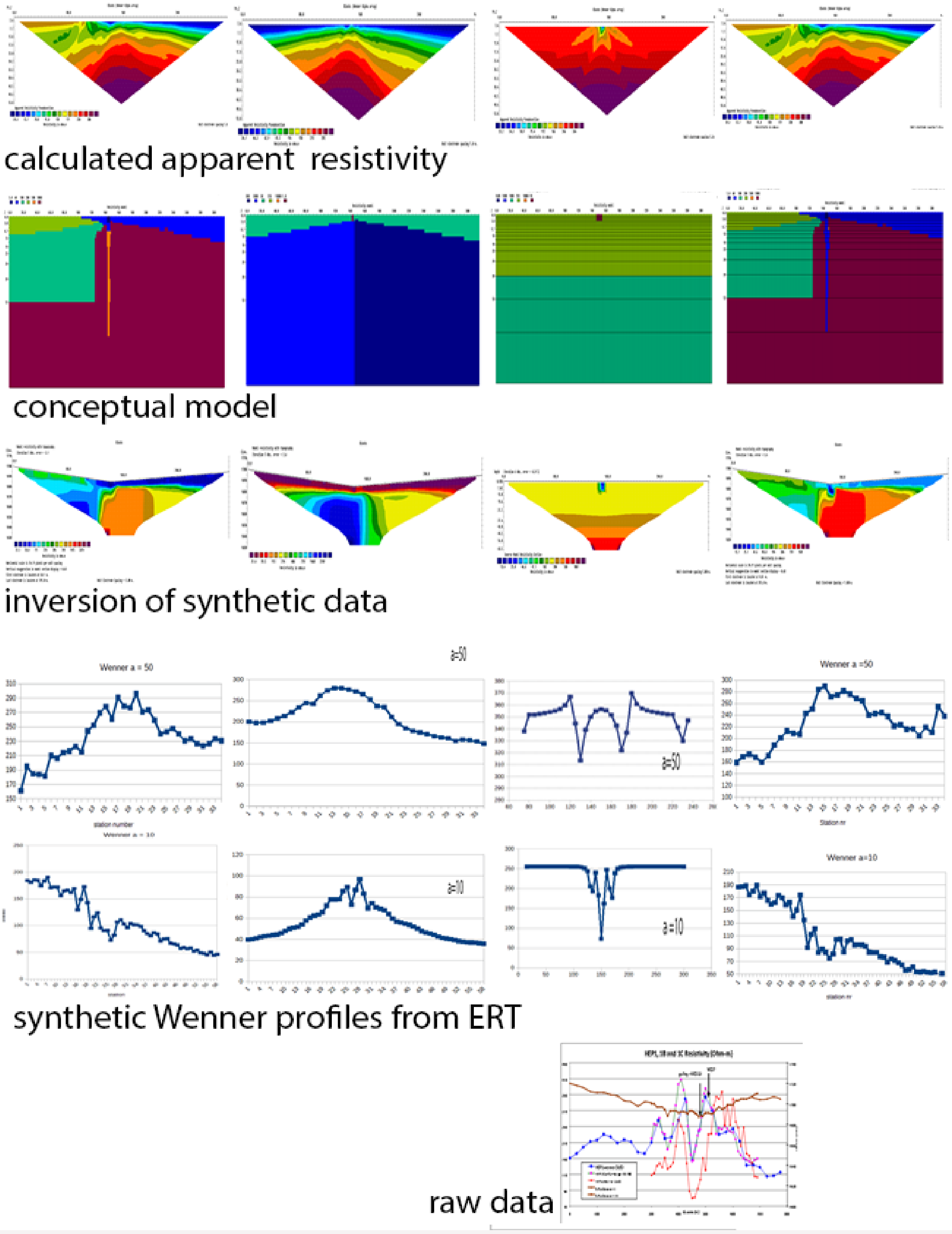


*Figure 2, forward modelling with ERT, different ERT models based on different geological concepts with different resistivity contrasts, resulting in different HEP anomalies. (The actual field measurements are below the third model).*

# ANNEX 3: RESISTIVITY PROFILES

### *Resistivity profiles*

To develop a geological concept it is helpful to sketch resistivity profiles along a profile line with the depths corrected on topography. As an example, based on the VES results of this first campaign, a preliminary conceptual NW – SE profile was drawn over the area to get a general impression on the resistivity's distribution (figure 4.3) in the area.

The topography of the profile was taken from google earth; the locations of the VES's were projected on this profile.  Layers with similar resistivities were connected. This method will give a very rough and theoretical impression, however combined with the topography, rivers and lineaments it can be helpful to develop a hydro geological concept.

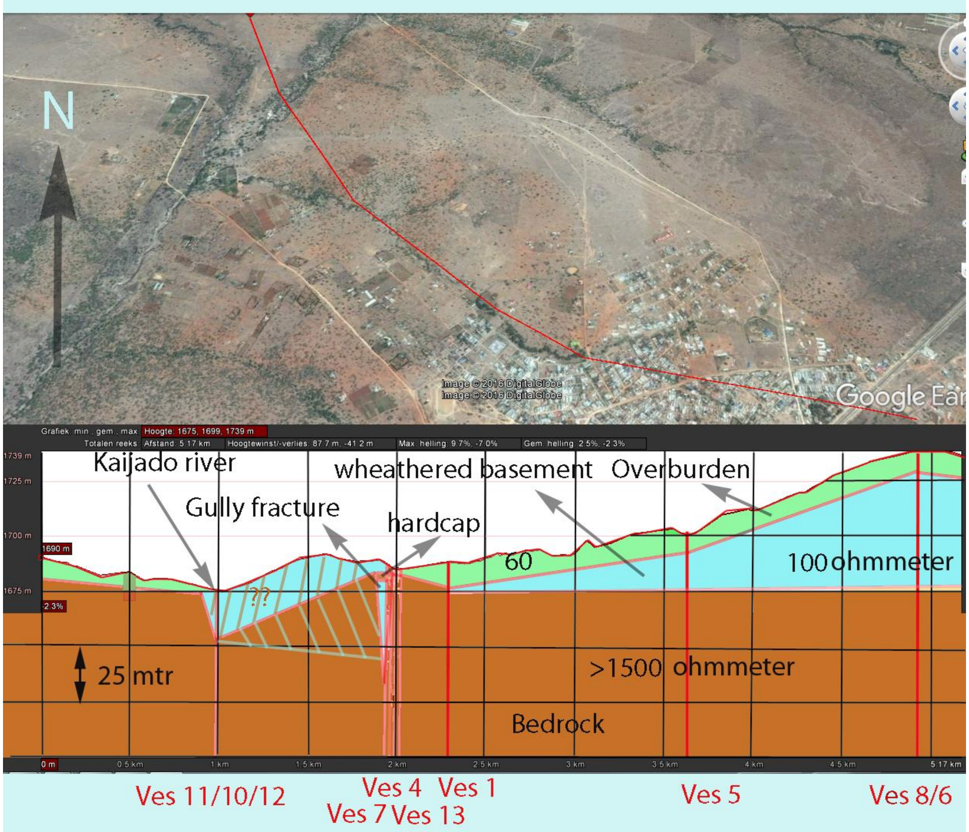
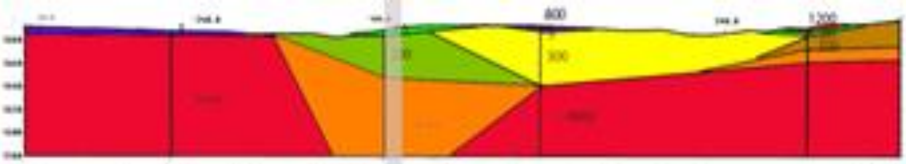


*figure 1, preliminary conceptual and schematic cross section only based on VES-soundings.*



Simple VES resistivity profile derived from 4 VES soundings, (more interpetations are possible)

*Figure 2, possible VES interpretation, also based information from ERT, Kajiado River profile.*

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