

Mar 31, 2019

Amended Geophysics for Groundwater Exploration: the coastal pilot in Kwale County, Kenya

2nd Technical report within the ISGEAG VIA Water project

Final Report

VIA Water







KenGen
Energy for the nation

SamSam WATER

ACACIA WATER

amref health africa

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, SamSamWater Foundation and Wiertsema & Partner. Important relevant stakeholders included: Base Titanium, Rural Focus/Gro for gooD, Earth Water Ltd., Jos Hansen & Soehne Ltd, ABEM/Guideline Geo Sweden, Manken Geohydrotech Consultants Ltd, and students & trainees 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 the second field campaign conducted in the typical coastal geology of Kwale County near the Base Titanium wellfield in Gongoni Forest, west of Gazi. One more ISGEAG pilot is foreseen in the volcanic sediments near Naivasha town. The final project report of ISGEAG for VIA Water will be issued after all pilots have been executed and is to be expected in March 2019.

Colophon

Document title	.	2nd Technical Report, geophysics Kwale
Client	.	VIA Water
Status	.	Final Report
Datum	.	Mar 31, 2019
Project number	.	L16019 vw011 (VIA Water), 160705 (Acacia Water)
Author(s)		M. Groen*), H. Rolf**), and C. Rutto***)
With a contribution on sub-regional conceptual hydrogeology and geology by	.	Mike Lane ****)

*) Wiertsema & Partners, the Netherlands
**) SamSamWater Foundation, the Netherlands
***) KenGen Ltd, Kenya
****) Rural Focus Ltd, Kenya

Project management: Stefan Wildt

Table of contents

Abstract 4

Acknowledgement 5

1 Introduction 6

1.1 Contextual background of the ISGEAG project 6

1.2 Introduction to the second Kwale pilot 7

2 Kwale study area and fieldwork set-up 10

2.1 Geology 10

2.2 Fieldwork setup 13

3 Conventional methods (VES and HEP) 14

3.1 Measurements near the SWIM borehole (VES1 and VES2) 15

3.2 Near Borehole 5R (VES 3, 4 and 6) 17

3.3 Near Borehole 3 (VES5) 21

3.4 Conclusions related to the VES method 23

4 Application of Electrical Resistivity Tomography (ERT) 25

4.1 Fieldwork set-up 25

4.2 Results 29

5 Application of Time Domain Electro-Magnetic (TDEM) Sounding 35

5.1 Fieldwork set-up 35

5.2 Comparison of Zonge and WalkTEM 40

5.3 Results near Borehole 3 (BH3) 42

5.4 Results near Borehole 5 (BH5) 47

5.5 Results near the SWIM borehole 48

5.6 Additional WalkTem soundings outside the project area 51

5.7 Conclusions 55

6 Application of Audiomagneto-telluric (AMT) Soundings 56

6.1 Introduction of Audiomagnetotellurics (AMT) method 56

6.2 Field Set up 57

6.3 Calibration 58

6.4 Data Processing and Quality 58

6.5 Exploration depth. 58

6.6 Data Analysis 59

6.7 Results 59

6.1 Conclusions 61

7 Comparison of the resistivity methods 63

7.1 Comparison of methods and results 63

7.2 Synthesis related to conceptual hydrogeology 73

8 Conclusions and lessons learned 85

8.1 Conclusions 85
8.2 Lessons learned 89
References 90
Annex 1: Coordinates and raw field data of the TDEM Soundings 96
Annex 2: Coordinates and raw field data of the VES Soundings 97

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
m bgl	meters below ground level
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

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, KenGen Ltd., Acacia Water and SamSamWater Foundation, with relevant local stakeholders and students from Nairobi University (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. An important aspect of our approach is to start with a concept based on existing information. All the measurements and observations should be in agreement with this concept, if not the concept should be changed.

This report gives the outcomes of the second field campaign in typical coastal geological setting (coastal sedimentary rock and fresh-salt water intrusion issues) in Kwale County.

Thanks to the good reference data of Base Titanium Ltd it is shown that new geophysical methods such as TDEM, AMT and ERT are important improvements to explore the substrate at depths beyond 70 meters, which is more or less the depth of exploration of conventional methods as VES. Especially the TDEM WalkTEM of ABEM appears to be very useful for practice. The device is simple and convenient to use, and especially the built-in software enables to invert the soundings at the spot. In this way the measurement could be judged on quality and directly compared with the concept, while the measurement strategy can be directly adapted if necessary. The coastal area with a relatively low electrical resistivity at depth is particularly suitable for the application of TDEM.

Knowledge and skills are essential for all methods, both when used in the field and when interpreting a geo-hydrological concept. When using the conventional VES method, it has again been established that the current practice is challenging: the execution itself is often experienced but without consideration for the quality and significance for understanding the groundwater situation.

After geophysical pilots in Kajiado Town and Kwale, one more ISGEAG pilot is foreseen in the volcanic area of Naivasha.

Acknowledgement

The ISGEAG partners gratefully acknowledge the great support of Base Titanium Ltd and Mr. Mike Lane and Mr. Willy Sasaka (both Rural Focus Ltd). It was a privilege to work together. We gratefully thank Base Titanium for providing their impressive dataset and allowing us to beneficially use it for our research.

We specifically like to thank Mike Lane for continuously sharing his thoughts before, during and long after the Kwale field campaign and for his fruitfull discussions on the conceptual geology, laid down in his contribution to this report on the sub-regional hydrogeological context (chapter 7.2.2.).

We are grateful to ABEM/Guideline Geo AB Sweden for giving us the opportunity to work with the new and wonderful ABEM WalkTEM instrument and Mr. Sikander (Jos Hansen & Soehne Ltd) for his assistance and pro-active support. We are grateful to AGS (Aarhus GeoSoftware) for the free use of their powerful software (SPIA, Workbench). We thank Mr. Mwachala (Manken Geohydrotech Consultants Ltd) for allowing us to use his (Scintrex) SARIS instrument and we want to thank Earth Water Consultants Ltd for their participation in the fieldwork. Last but not least we are very grateful to VIA WATER a programme of Aqua for All, The Netherlands who made this all possible.

All ISGEAG reports will be made available on the SamSamWater website[1].

[1] SamSamWater: http://www.samsamwater.com/projectdata.php?projectid=86

1 Introduction

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, KenGen Ltd., Acacia Water and SamSamwater Foundation, relevant local stakeholders and students from Nairobi University (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 the second field campaign in typical coastal geological setting (sedimentary rock and fresh-salt water intrusion issues). After pilots in Kajiado Town and Kwale, one more ISGEAG pilot is foreseen in the volcanic area of Naivasha.

1.1 Contextual background of the ISGEAG project

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) and Audio Frequency Magneto Telluric soundings (AMT). Comparison and combination of 'new' and conventional methods, like VES soundings and HEP profiling, will help to better understanding of Kenyan groundwater systems. 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. An important aspect of our approach is to start with a concept based on existing information. All the measurements and observations should be in agreement with this concept, if not the concept should be changed.

Executing Kenyan partners are KenGen Ltd 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. For this Kwale pilot study, important local stakeholders were: Base Titanium Ltd, Rural Focus Ltd, the Kwale Gro gooD Project and the Kenyan Forest Service.

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 the instrumentation and 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. The Dutch associates bring their professional experience in the application and interpretation of geophysical methods into geohydrology.

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 500m 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 by combining TDEM and AMT.
VES	Vertical Electrical Sounding (VES) is a widely used, one-dimensional (1D) 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 dedicated 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 to an apparent resistivity time or 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. the SkyTEM system) are specific TDEM instruments.

1.2 Introduction to the second Kwale pilot

After execution of the first pilot in the Basement geology of Kajiado Town, this second geophysical field campaign was performed in the Gongoni Forest in Kwale County and the nearby coastal area near Gazi between 15th and 31st of March, 2018. A typical coastal geology with fresh-salt water intrusion issues and Pleistocene sediments on Jurassic transgression overlaying older formations of terrestrial sandstones (lower Jurassic period) deposited under arid circumstances. Besides continued co-operation with ISGEAG partners KenGen and Amref Health Africa, this geophysical field campaign took place in close collaboration with local partners Base Titanium Ltd, Rural Focus and the Gro for GooD project.

In contrary to the fieldwork in Kajiado, the project team could relate geophysical measurements to an extensive and reliable dataset of Base Titanium Ltd in relation to their boreholes and various groundwater monitoring wells. In this way, geophysical survey results could directly be compared with existing data and discussed with Mr. M. Lane (Rural Focus, Gro for gooD). Mr. Lane is a senior hydrogeologist, seconded to Base Titanium Ltd and has an extensive knowledge of the local and regional (hydro) geology.

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 of the Formation (including the pore water) at a specific depth and thickness, calculated from the apparent resistivity (by the so-called inversion).

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

Model
The, by 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 varies with the different methods. The more data points the less equivalence.

Equivalence 2
The hydrogeological interpretation of electrical resitivity is not unique: clay can have the same (low) resistivity as sand with brackish groundwater. Basement rock can have the same (high) resistivity as a superficial layer of very dry sand.

Residual
Residual (or fit or RMSE) is a figure (in %) that expresses how a calculated model differs from the measured field data: The percentual difference between the apperant resistivity as calculated by the model and the measured apperant resistivity.

Forward modelling
This is the process were a pre-assumed resistivity model, based on a geological concept is calculated into synthetic field data: "what field data is to be expected from a pre-assumed geology?"

Spread
When talking about 'spread' we talk about the distance between the transmitter ("current") electrode and the receiver ("potential") electrode. When the electrodes are moved along asurvey line a consistent distance ("the spread") must be maintained.

1.2.1 Process and partners

Besides Base Titanium Ltd, staff from Rural Focus and the Gro for GooD project and the ISGEAG project partners, students of both University of Nairobi (UoN) and the Kenya Water Institute (KEWI) were once again involved. University should play an important role is the dissemination of the new gained knowledge. Furthermore, the new WalkTEM of ABEM/Guideline Geo Sweden was used, while representatives of Kenyan Water Consultants Earth Water and Manken Consultants also joined the project campaign.

The input of Amref Health Africa (Kenya office) proved again its added value and was indispensable in terms of project management, logistics and local communication and liaison.

The new and wonderful ABEM WalkTEM could be hired from ABEM against a reduced price to promote its application and functioning in East Africa. ABEM likes to stay involved and kindly offered to assist in the organization of future geophysical learning events in the region. The local sales agent of ABEM equipment in Kenya, Mr. Sikander Mohammed of Jos Hansen & Soehne East Africa Ltd was present most of the fieldwork, and contributed in all fieldwork and post-discussions.

Gro for GooD[2] is a multiple-year project in the Kwale Region and is part of the UPGro (Unlocking the Potential of Groundwater for the poor) program that is managed by the University of Oxford (UO), University of Nairobi (UoN) and Rural Focus. The collaboration particularly with Gro for GooD related local partners, Rural Focus (RFL) and the Kenyan Forest Service (KFS) was valuable because of their knowledge of the area, geology details, relevant locations, transport and safety issues and the difficult negotiations within surrounding communities. This process of social grounding, however, was challenging and ultimately led to a full-stop of the geophysical field campaign in the second week. Nevertheless, this allowed the project team to practice more with application of the WalkTEM equipment in areas outside the study area; targeting areas were salinization problems were suspected.

Apart from the social issues, the process of daily operations and logistics went smoothly, thanks to the extensive preliminary preparation and planning and because of the frequent consultations with Mr. M. Lane before, during and after the mission and thanks to the professional role of Willy Sasaka of RFL. Two students of the Geological Department of the University of Nairobi (UoN) and one of the Kenyan Water Institute (KEWI) also participated in the geophysical field campaign in Kwale. The capacity and skills of these students were varying and, in some cases, still limited, especially linking their theoretical knowledge to practical application was an important issue.

Besides the students also two staff members of Earth Water Consultants participated. They participated well in the field, especially when new geophysical techniques were introduced and tested.

During two days, the fieldwork was joined by staff of Manken Geo Consultants. They were eager to get additional knowledge on the new technology and they kindly made their Scintrex SARIS instrument available for comparing various instruments in the execution of VES soundings.

At the end of the first week, a workshop was held with detailed explanation of the initial results and discussion about the link between the measurements and the local geological concept as well as an on-hands training on the application of uncertainty analysis in VES inversion. On the last day of the second week all results per method were extensively discussed in a wrap-up meeting.

1.2.2 Goal of Kwale field campaign

The overall ISGEAG goal is to determine to which extent, depth and resolution the different geophysical methods are able to establish and to validate the electrical resistivity of the substrate in relation to the known borehole lithology and to verify against the geological concept. It was expected beforehand that the TDEM method in particular should work much better in this area than in Kajiado because of the low resistances (conductors) in the subsurface, to be expected in the sedimentary coastal geology and salt water intrusion issues.
On the way to Kwale the team was able to conduct supplementary TDEM WalkTem soundings in Kajiado to compare WalkTem with Zonge and ERT under the basement geology. This proved to be very successful; the results were included in the Kajiado report.

[2] https://upgro.org/consortium/gro-for-good/

2 Kwale study area and fieldwork set-up

The study area is in the coastal plain of Kwale County, in the Gongoni Forest, south of Diani and north of Msambweni. Most of the investigations were done on the north side of the Forest, east of the Base Titanium mine, with an extension to the ocean at Gazi Bay. North and south of the actual project area are extensive sugarcane plantations of the Kwale International Sugar Company Ltd (KISCOL). See the project area in Figure 1 below.

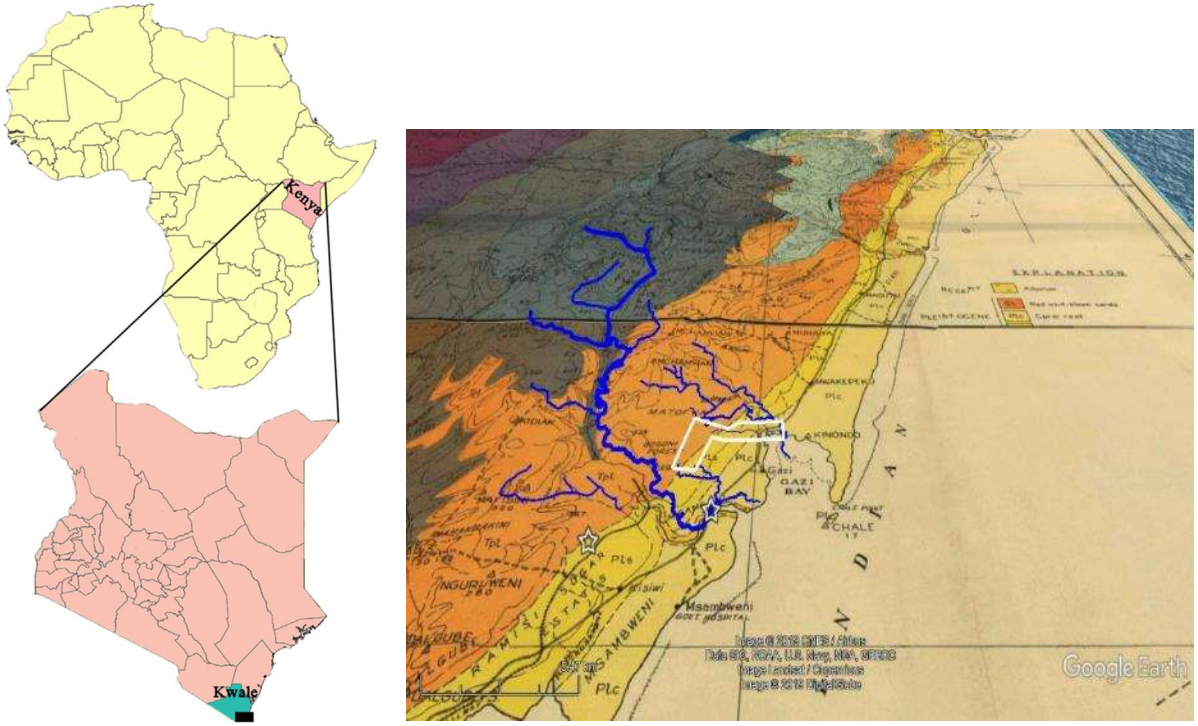


Figure 1. Regional location of the study area in Kwale County, southwest Kenya, on the Caswell 1953 geological map. The white outlined area is the study area in the Gongoni Forest with an extension to the coast near Gazi bay. Special soundings were done at two locations south of the study area, as given by the white stars on the map.

Gongoni Forest is an ecological protection zone, managed by the Kenyan Forestry Services (KFS). For their water supply, Base Titanium has a wellfield with a series of boreholes along a north – south oriented line through the center of the Forest. Some of these boreholes were used to verify the results of the geophysical methods.
A second target was the coastal area at Gazi Bay, where Base Titanium has a salt water intrusion monitoring (SWIM) borehole. At this location the geophysical methods were applied as well.
Extra soundings were done at two locations south of the study area, as given by the white stars on the map.

2.1 Geology

Beforehand, a hydrogeological concept was drafted by Mr. M. Lane (RFL). This concept is supported by a large number of production and exploration boreholes and the extensive Base monitoring network. The geology in Kwale is relatively well-researched in a number of (pre-2000) regional studies. The reader is also referred to a relevant recent article of Ferrer *et al.* (2019) that was published very recently. Full references can be found in the Reference list at the end of this report.

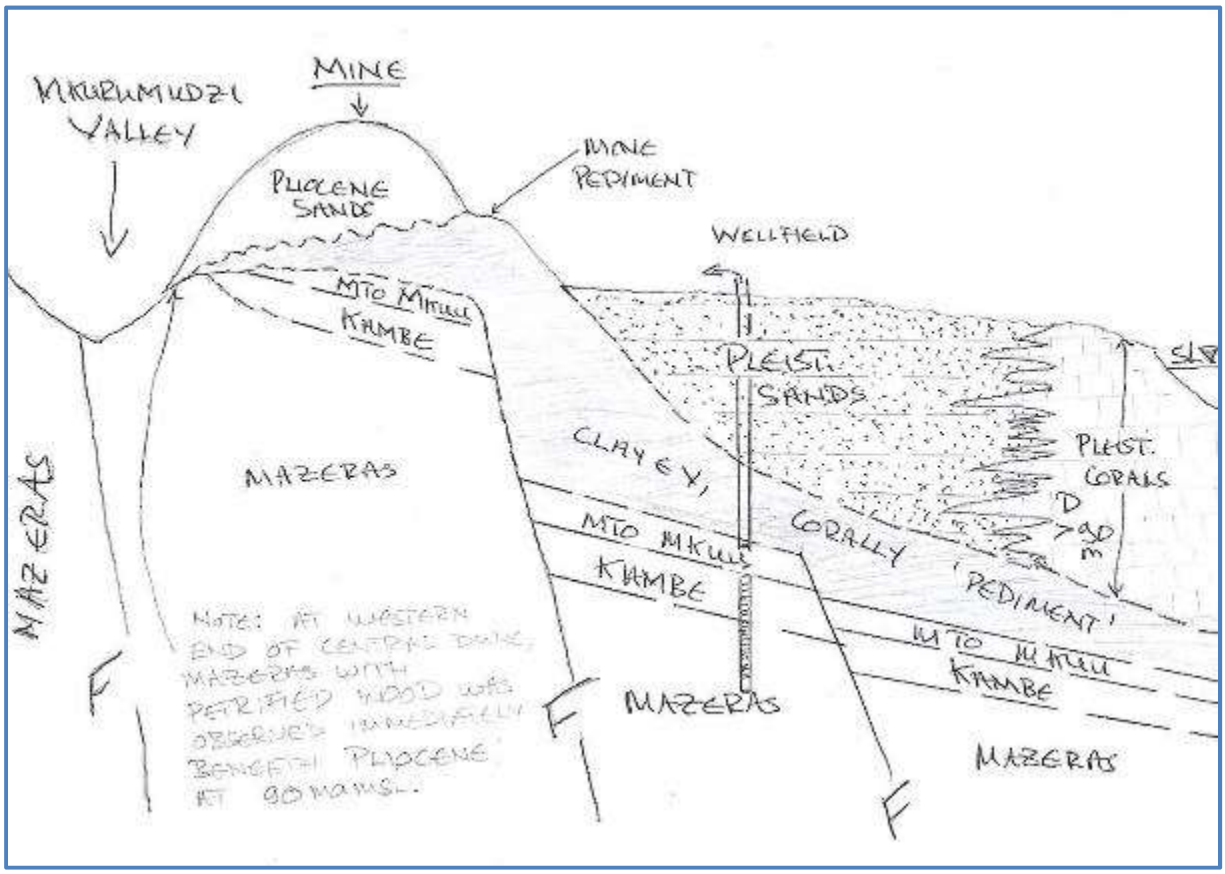


Figure 2. Hydrogeological conceptual model (figure credits: M. Lane, Rural Focus, February 2018)

The coastal geology of Kwale is a succession of:

- Coral reef limestone (Pleistocene coral reef)
- White and brown sands and occasional clays (Pleistocene lagoonal 'back reef' of the Kilindini Fmt)
- Red Pliocene sands (upper Pliocene Magarini Fmt)
- Clayey / shaley 'dirty' sandstones (upper Jurassic Mtomkuu Fmt)
- Grey limestones and shales (middle Jurassic Kambe Fmt)
- Grey, fine to medium grained quartz feldspathic sandstones (Jurassic upper Mazeras Fmt)
- The upper Mazeras sandstone formation rests upon older deep rocks of the Karoo/Duruma-series:
    - Lower Mazeras sandstone
    - Mariakani sandstone
    - Maji ya Chmuvi beds
    - Taru grits

The geological succession is also represented in Figure 3 on the next page and completed with resistivities found in literature. In Kwale County, groundwater is mainly abstracted from the shallow aquifer, formed by coral limestones and the Kilindini and Magarini sands. Major abstractions are from the Msambweni wellfield comprising the abstractions of Base and the wellfields of the KISCOL sugar estates, located north and south of the study area. A second major wellfield in Kwale is at Tiwi, 20km to the north supplying drinking water to Kwale and Mombasa Counties. These well fields are indicated in Figure 4 overleaf.

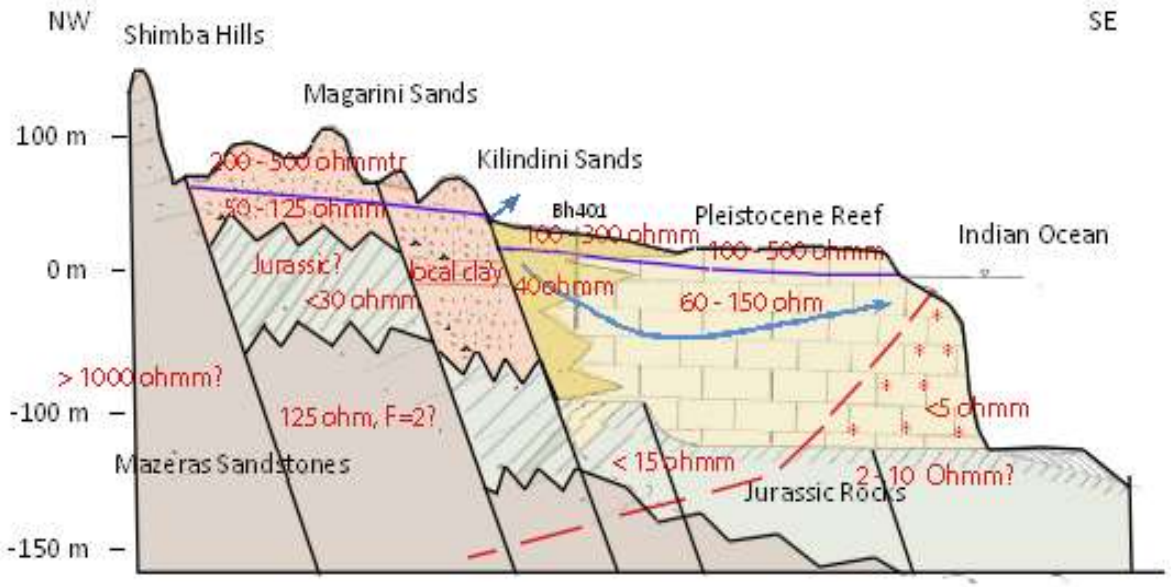


Figure 3. Cross-sectional representation of the Kwale conceptual geology, completed with electrical resistivity information from literature (e.g. Carruthers. 1985).

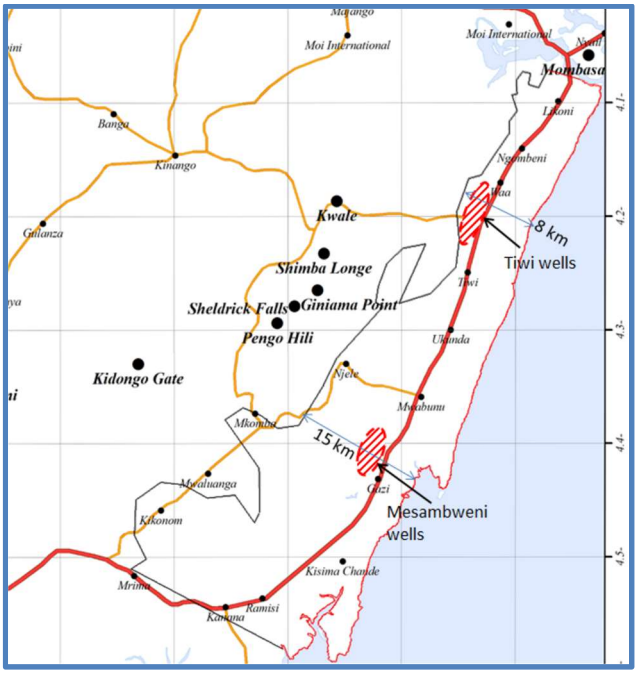


Figure 4. Major wellfields in Kwale County. The Msambweni wellfield is predominantly in use for industrial/commercial water for KISCOL and Base Titanium (source: Water Masterplan, Tahal Group, 2013). The Tiwi boreholes are supplying drinking water to Kwale and partly to the city of Mombasa to the north.

2.2 Fieldwork setup

The boreholes of Base Titanium abstract water from the Kilindini sands (shallow aquifer) and from the upper Mazeras sandstones (deep aquifer). The boreholes have a capacity of over 200 m³/hr.

Base Titanium is particularly interested in the depth of the Jurassic deposits beneath the Pleistocene sands/corals and the transition of these to the Mazeras sandstones, and how this extends to the east. With VES soundings this zone is indistinguishable. Without deep geophysics it can only be confirmed with expensive exploration drillings.

The measurements are predominantly executed near three reference points: borehole 3 (BH3), borehole 5 (BH5R) and the saltwater intrusion monitoring borehole (SWIM) near the coast. See also Figure 5 below. BH3, in the center of the forest, and BH5, at the northern edge of the forest, are two very well documented dual rotary drilled boreholes and were selected as major references for the ISGEAG geophysical research. A complication was the powerline running north-south along the wellfield, that may interfere with the electrical and electromagnetic soundings. The SWIM borehole was selected as a good reference to investigate geophysical methods on their capacity the measure saltwater intrusion.

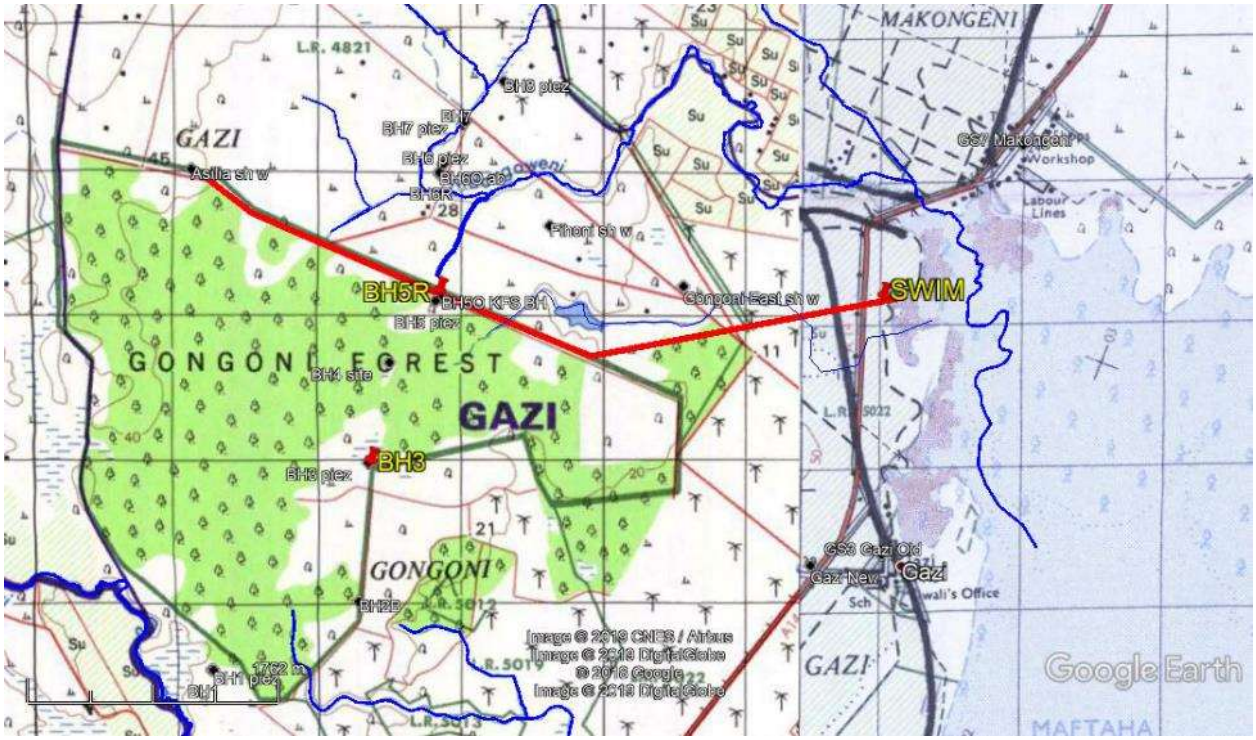


Figure 5. Locations of BH3, BH5 and SWIM on the 1991 Totography map. Red markers: the main ISGEAG fieldwork locations (BH3 BH5 and SWIM). The red line gives the intended full transect between BH5 and the SWIM monitoring well.

Apart from local soundings near the three reference locations it was intended to investigate a full geophysical transect extending from the SWIM borehole to BH5R (the red line in Figure 5). A major part of these measurements could not be completed due to unsolved challenges with the local community and landowners.
On the request of RFL, two special 'hit and run' TDEM-WalkTEM reconnaissance surveys were conducted near Vingujini and Milalani, two locations south of the study area surrounded by KISCOL plantations. Aim was to assess the extension of salt water intrusion.

3 Conventional methods (VES and HEP)

The application of conventional VES soundings was focused at three locations where the results can be referenced to reliable borehole information. See also Figure 6 below.

- VES1 and VES2 near the SWIM monitoring borehole
- VES3, VES4 and VES6 near Base Borehole 5R
- VES5 near Base Borehole 3

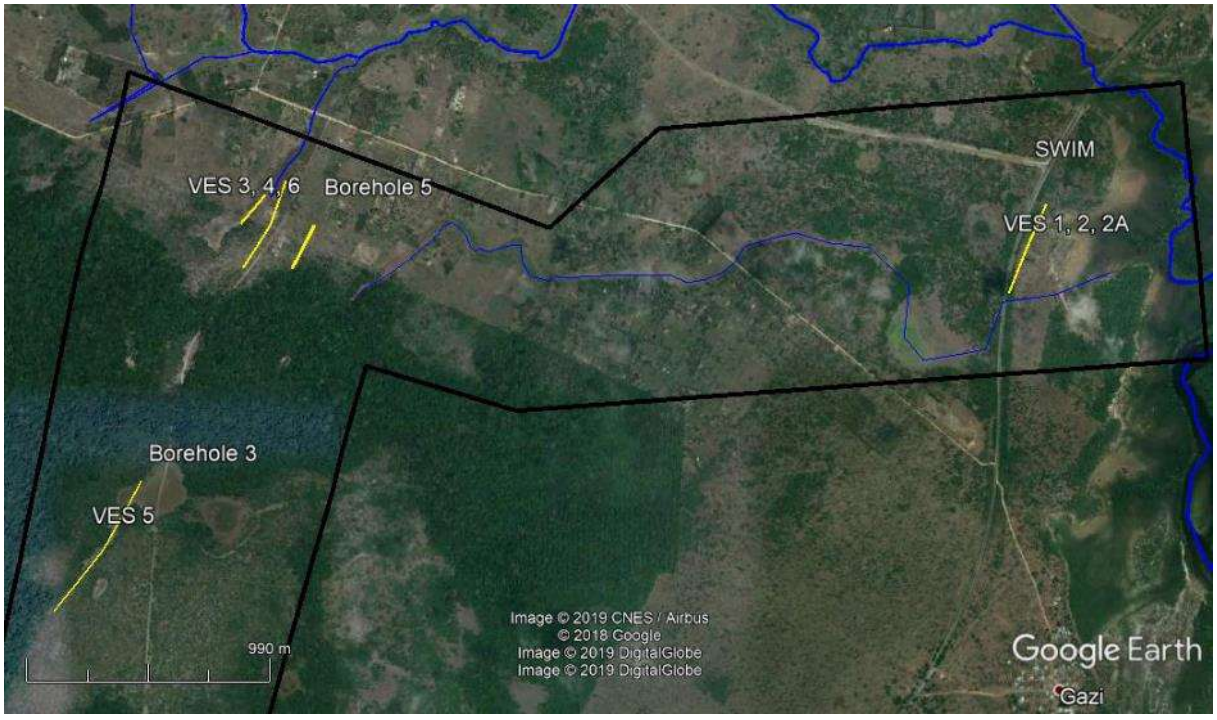


Figure 6. Google Earth image showing the locations near BH5 and BH3 in the Gongoni Forest and near the SWIM borehole.

Apart from the ISGEAG soundings, existing VES soundings were available from GSK (1991). Some raw, un-interpreted VES data from the Gro for GooD project were obtained, but these are outside the focus area and are not used in this study. All VES inversions were carried out using SchlumBG software[3].

The measured apparent resistivity field curve data were not 'shifted' (smoothed), which many Kenyan consultants routinely do. Possible interference effects from the nearby power lines at BH5R and BH3 were not investigated. The technical interpretation of each single ISGEAG VES sounding is discussed in more detail in a separate technical interpretation report (Rolf, 2019). This chapter only presents the final interpretation results.

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

3.1 Measurements near the SWIM borehole (VES1 and VES2)

Three soundings were made near the SWIM borehole, see Figure 7. VES2 was conducted closest to the SWIM borehole, using two different instruments (VES2 and 2A). VES1 was carried out 95m to the east, closer to the shoreline.



Figure 7 Google Earth image showing SWIM area VES locations and orientations

3.1.1 VES2 (2A) results

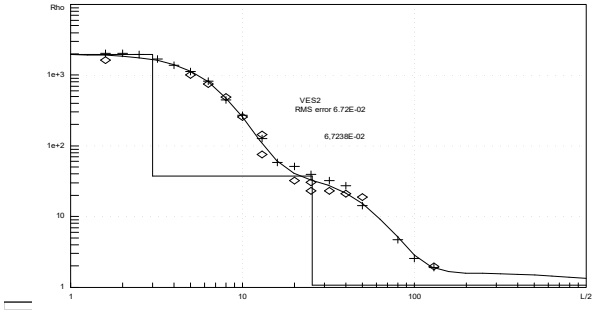
VES2 was carried out with the SAS1000 instrument and (provided by AMREF). VES2A was carried out with the 24V SARIS, kindly made available by MANKEN Consultants (compliments of Mr Mwachala), participating in the project. The SAS1000 data were less reliable for the longer electrode spreads; as a consequence, the data from both VES2 and VES 2A were combined in the inversion. The layer model for VES2 is shown below, Figure 8.

layer	*top (mbgl)*	*resistivity (Ωm)*	*stratigraphy*
1	0	1950 (*1850 – 2100*)	dry sandy topsoil
2	3 (*2.8– 3.2*)	37 (*34 - 45*)	Pleistocene coral limestones
			saturated, fresh
3	27 (*24- 29*)	<1.5	Pleistocene coral limestones
			saline

for details see technical interpretation report

Remarks:

Top of layer 2 compares well to measured groundwater level
AB/2 reach 130m Depth of Investigation 50 m
inversion of combined data of both the SARIS and SAS1000 Terrameters



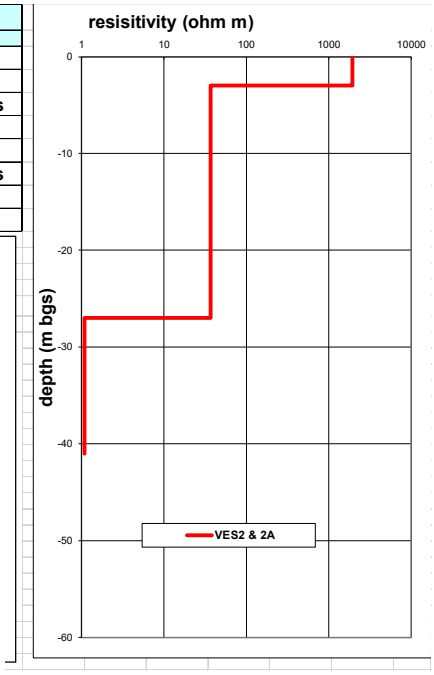


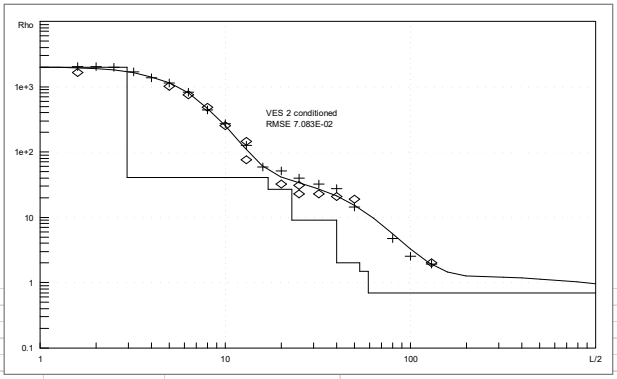
Figure 8. Interpreted layer model of VES2

The unconstrained model finds the interface between fresh and saline groundwater at 27 m (with 90% certainty in between 24 and 29 m).

There is reference information from the nearby SWIM borehole. The 90 m borehole was drilled entirely within the Pleistocene coral limestones. Base Titanium Ltd (Base) kindly provided reliable and detailed information on the electrical conductivity (EC) log, showing the EC of airlifted water from increasing depths during down-the-hole (DTH) hammer drilling. The data show the salinity gradient and indicates the positions of aquifers. Using this information, a 'conditional' inversion of the VES2 data was made by adding and fixing the layer depths according to the observed salinity gradient and optimizing the layer resistivities manually.

layer	top (mbgl)	resistivity (Ωm)	drilling EC(µS/cm)
1	0	1995	dry
2	3	40	shallow aquifer EC 900
3	17	27	EC 2650
4	24	9	EC 6010
5	40	2	middle aquifer EC 11.490
6,7	53	<1.5	deep aquifer
			EC gradually rising to 50.000

Remarks:
layer depths fixed acc. to fluid EC halocline SWIM during drilling
resistivities optimized
solution gives the same fit as the unconditioned VES inversion



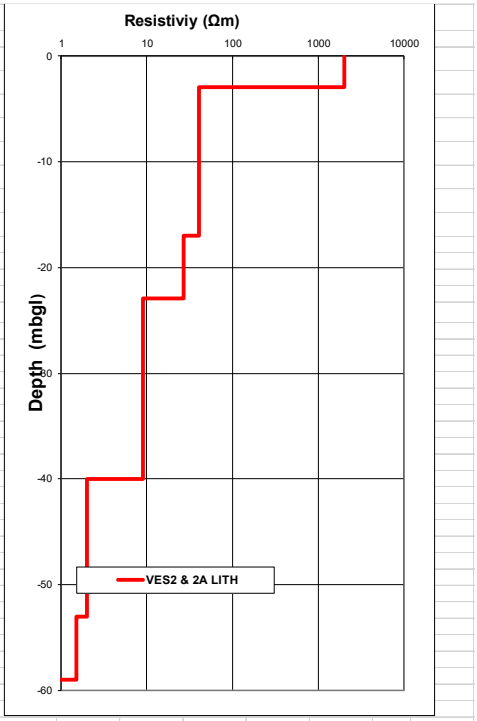


Figure 9. Drilling data-constrained layer model, VES2

Clearly this model is much closer to reality. The unconstrained VES model only comprises 3 layers, and shows a sharp fresh-saline interface. Taking into account the drilling EC data, a model with a gradual transition from fresh to brackish and saline water is obtained. The model has the same good fit, which illustrates an important limitation in the interpretation of electrical soundings: a given measured field curve can correspond to a variety of distributions of layer thicknesses and resistivities, which is known as equivalence. Unless additional geological or drilling data are available, the layer model would typically be restricted to 3–5 layers, the minimum number of layers that gives a good fit to the data.

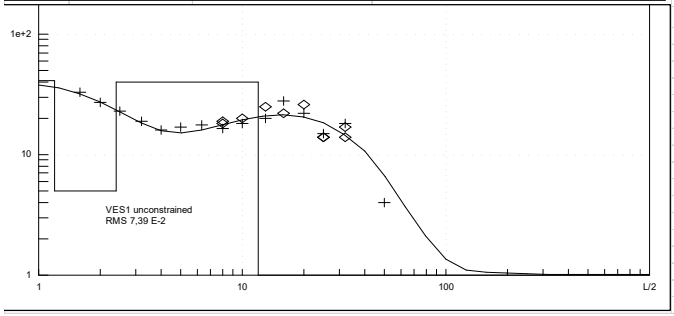
3.1.2 VES1 results

Sounding VES1 was conducted closer to the shoreline in the vicinity of a 5.8 m deep freshwater shallow well (EC measured as 500µS/cm).

In contrast to VES2, this sounding shows a shallow low resistivity clay layer, as can be seen from Figure 10 below. The fresh-saltwater interface is estimated to be less than 15m deep but deeper than 8m, as constrained by the nearby fresh water shallow well. The actual transition from fresh to saline groundwater is (as in VES2) undoubtedly less sharp than in this model. The groundwater level is not discriminated in the model. On the basis of the shallow well, it should be in the order of 4 m bgl, thus below the bottom of the shallow clay.

layer	top (mbgl)	resistivity (Ωm)	lithology
1	0	40 (35 - 45)	moistured top soil
2	1.2 (1 - 1.5)	5 (large)	clay
3	2.4 (large)	40 (large)	fresh water coral limestones
4	12 (8 - 15)	1 (large)	brackisch/saline

Remarks:
AB/2 reach 50 m only (difficult to get good readings from the SAS1000 terrameter at longer reach)
DOI ≈ 20 m
info from nearby fresh water shallow well: the interface depth was restricted to be deeper than 8m.



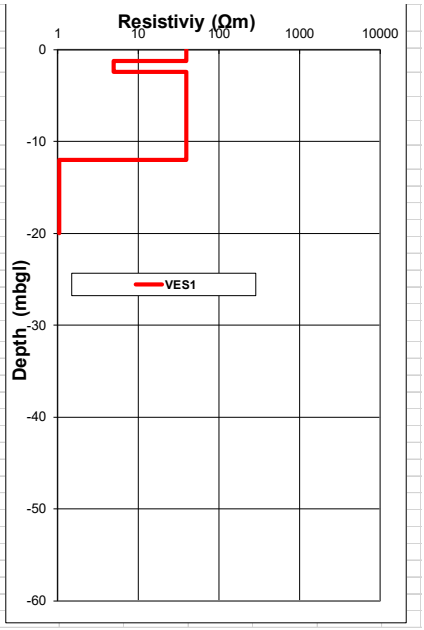


Figure 10. Layer model, VES1. The calculated resistivity values (top left table) are given with their uncertainty range. When the uncertainty is too large to quantified this is given as (large).

3.2 Near Borehole 5R (VES 3, 4 and 6)

Three VES soundings were carried out near Borehole 5R, see Figure 11 below. The length of the AB spreads with VES 3 and 6 were limited by forest growth to the south; they were also limited by the inability of the SAS1000 Terrameter to obtain good readings in this very dry, sandy area; dry sands are resistive and present current penetration problems.



Figure 11. Google Earth image showing BH5R area VES locations and orientations

VES4 was conducted as close as possible to the borehole, and relatively close to the N-S running powerline (which is an overhead line north of the Forest boundary and buried thereafter to the south). At the VES4 location five separate VES soundings were carried out with three different instruments. The soundings were made in both the Schlumberger and Wenner configurations. The use of different instruments gave us insight into differences in instrument performance, and also highlighted the issue of calibration of instruments.

3.2.1 VES3 results

VES3 was conducted 120 m west of Borehole 5R. The southern extension of the VES line was blocked by mature forest. The sounding was carried out using the Wenner array, in very dry sandy topsoil. Beyond 40m the SAS1000 encountered difficulties in obtaining viable readings (with high standard deviations observed).

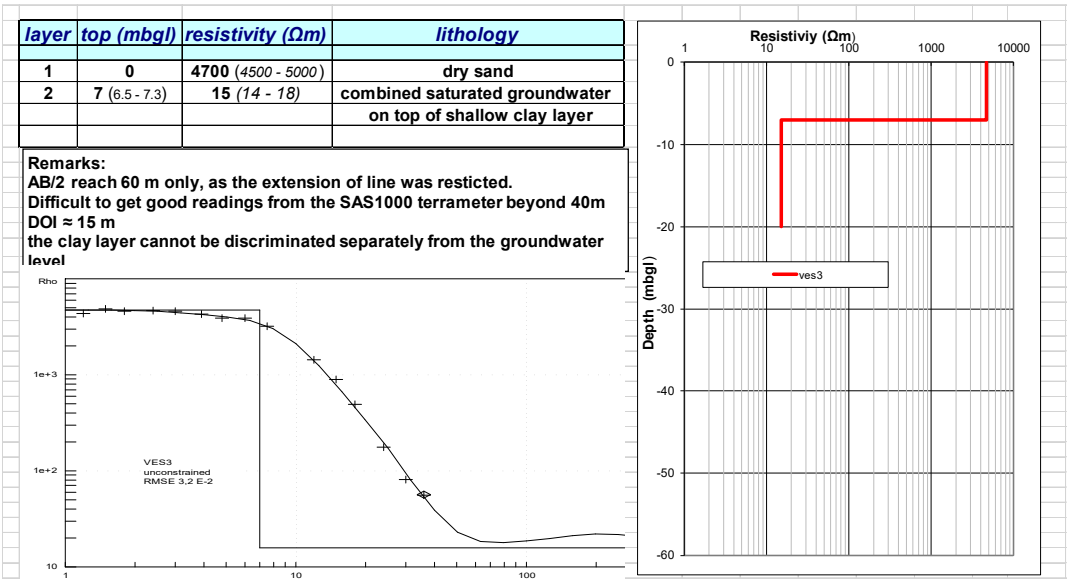


Figure 12 Layer model, VES3 (BH5)

Due to the short spread and the difficulty of obtaining good readings, VES3 only detects a low resistivity layer at 7 m bgl, below the high resistivity dry sands. The transition to low resistivity may represent the level of the saturated groundwater, which roughly agrees with the groundwater level estimated from Borehole 5. This shallow groundwater is probably perched on top of a clay layer. This clay layer is indicated by the VES data but the AB spread of the line was too short for the VES to discriminate the difference between the clay layer and the overlying saturated groundwater (see Technical Report, VES3).

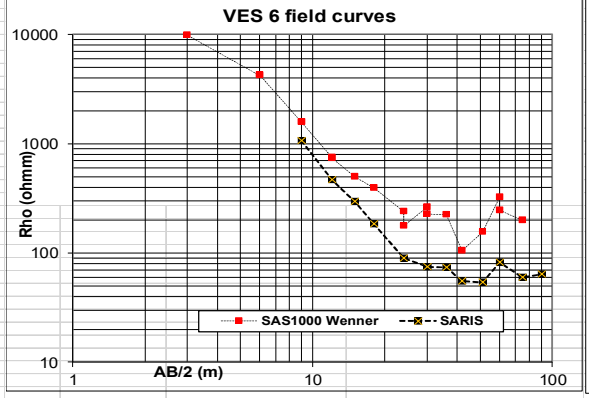
3.2.2 VES6 results

At location VES6 (140 m northeast of BH5), Wenner soundings were conducted with both the SARIS and the SAS1000 instruments. There was a significant offset between the two field curves, indicating a calibration problem with one (or both) of the instruments. This led to a significant difference in the results from the SARIS and the SAS1000, particularly for the last model layer.

The VES model indicated in Figure 13 shows no clay layers within the first 40m. The top of the 2nd layer at 3.5 mbgl probably represents the saturated shallow groundwater level in the sandy sub-surface, which broadly agrees with the measured water level in Borehole 5. The difference in results between the two instruments shows that calibration is a serious issue.

layer	top (mbgl)	resistivity (Ωm)	stratigraphy
SAS1000			
1	0	**11000** (8000 - 15000)	dry sand
2	**3.5** (3 - 4)	**190** (160 - 400)	saturated Kilindini sands?
3	**14** (5 -40)	**180** (160 - 210)	
SARIS			
1	0	**11000** (6000 - 19000)	dry sand
2	**3.3** (3 - 4)	**160** (40 - 600)	
3	**14** (7 -40)	**50** (40 - 60)	

Remarks:
Significant difference in field curves, leading to diference in resistivity of last layer.
AB/2 reach 75 m (SAS1000) 90m (SARIS)
DOI ≈ 40m



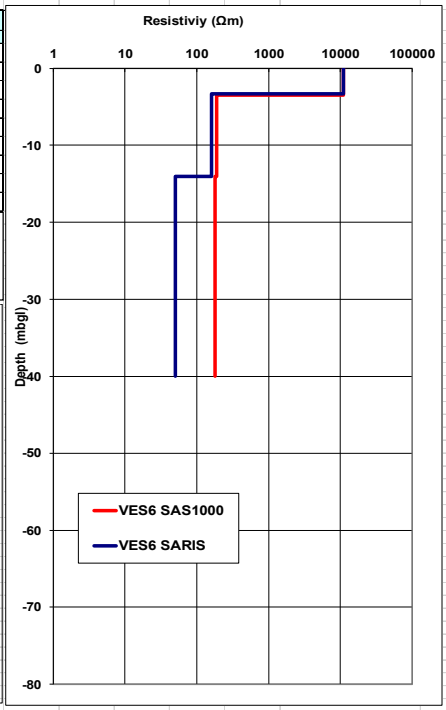


Figure 13. Layer model, VES6 (BH5)

3.2.3 VES4 results

At this location, the closest to Borehole 5, five different VES soundings were carried out using three different instruments: the ABEM SAS1000 (provided by AMREF), the 24V SARIS, kindly made available by MANKEN Consultants (compliments of Mr Mwachala), participating in the project, and the ABEM Terrameter LS that was made available by Jos Hansen Ltd (courtesy of Mr Sikander). Unfortunately, there was insufficient time to also test the SAS4000 machine that was provided by KenGen (used principally for carrying out ERT measurements).

The unconstrained results are given in Figure 14, and only shows the results of the SARIS instrument (Wenner and Schlumberger). The SAS1000 was clearly having difficulty generating sufficient current to obtain correct readings in this dry sandy area. The Terrameter LS gave incorrect data, probably 50% too low, due to a problem with the pre-set geometric factor in the instrument.

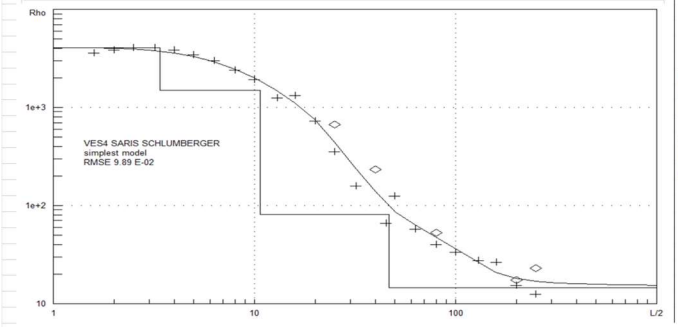
Reliable geology information was available from the nearby Borehole 5R (data courtesy of Base). VES4 data was re-interpreted conditionally on the borehole lithology. The procedure was the same as at the SWIM BH; the lithology can be classified as nine layers, and in the re-interpretation the layers were fixed in depth and the layer resistivities were optimized manually. The results of this exercise are shown below in Figure 15.

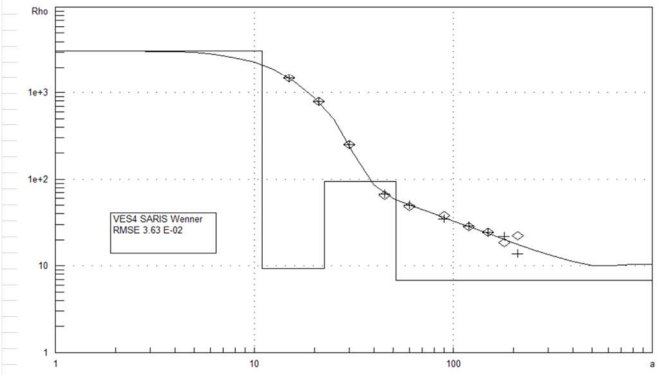
The constrained layer model (Figure 15) is a better representation of reality than the unconstrained model. More layers are distinguished and the resistivities are realistic for saturated sands, corals and clays. The interpretation also shows that the depth of investigation is limited: for the last two layers (8 and 9) different solutions can be found, giving the same (good) fit to the data. If the two layers 8 and 9 are combined as a single layer the resistivity is approximately 12 Ωm (the red line in Figure 14 on the next page).

The 'limestone' layer 8 could have a much lower resistivity (not shown in Figure 15); this could be 'real', since the thin Mtomkuu shale formation may occur immediately above the limestone. The VES data simply cannot distinguish between these two options.

layer	top (mbgl)	resistivity (Ωm)	stratigraphy
Wenner			
1	0	3130 (2500 - 3900)	Holocene & PLc Kilindini
2	11 (9 - 13)	9 (?)	PLC clay
3	22 (?)	95 (?)	Paleo channel?
4	41 (?)	7 (?)	Jurrassic Limestones
Schlumberger			
1	0	4080 (3500 - 4700)	Holocene & PLc Kilindini
2	3.4 (2 - 6)	1490 (690 - 3100)	dry Kilindini sands
3	10.6 (9 -12)	80 (58 - 116)	Paleo channel?
4	46 (37 - 60)	15 (12 - 18)	Jurrassic Limestones

Remarks:
Various model concepts, yes/no shallow clay layer
Last layer uncertain,
parameters highly correlated
different results with different instruments
AB/2 reach up to 250 m
DOI ≈ 60 m





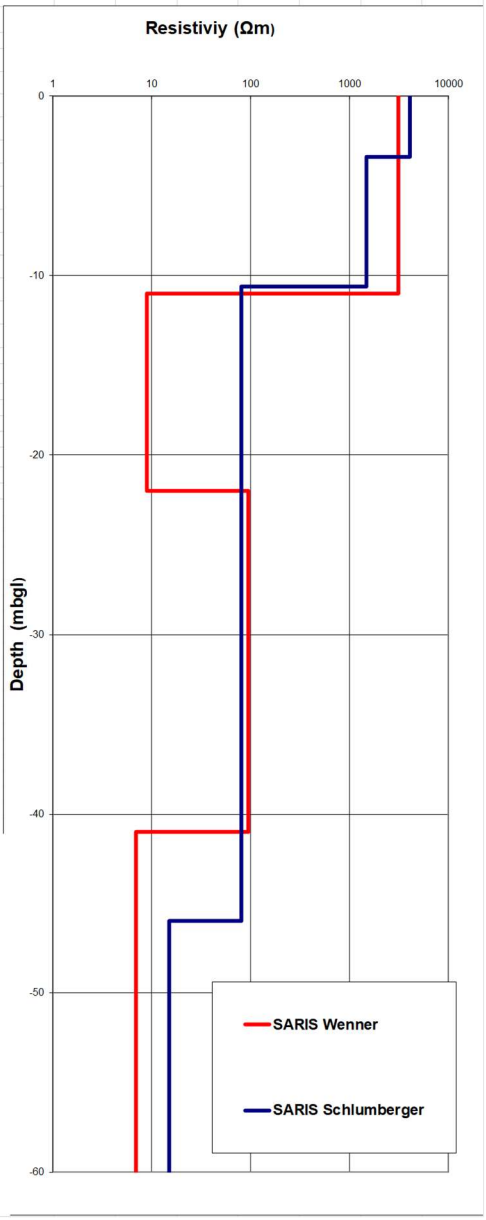
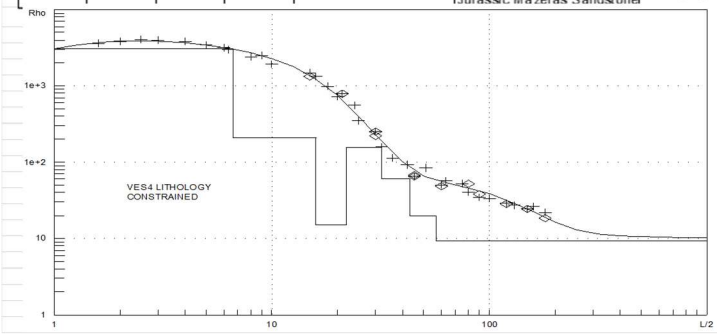


Figure 14. Unconstrained layer model, VES4 (BH5). Note: the results for the SAS1000 (too short a spread) and the Terrameter LS (unreliable data) are omitted.

Estimated resistivities (Ωm) VES4 with fixed layer depths according to BH5R lithology

Layer	From	To	D (m)	Description	Stratigraphy	Rho (Ωm)
1	0	0.04	0.04	false' (el. contacts)		220
2	0.04	0.6	0.56	dry sands	Holocene	8852
3	0.6	7	6	dry sands	Holocene & Plc Kilindini	3056
4	7	16	9	sands , saturated	Pleistocene Kilindini	210
5	16	22	6	clay	Formation	15
6	22	32	10	Corals, corally sands	Possibly palaeochannel deposits of early Cretaceous to early	156
7	32	43	11	saturated sands		60
8	43	57	14	Limestones	Jurassic Kambe Limestone	20 (12)
9	57			Sandstones	Jurassic Mazeras Sandstone	10 (12)



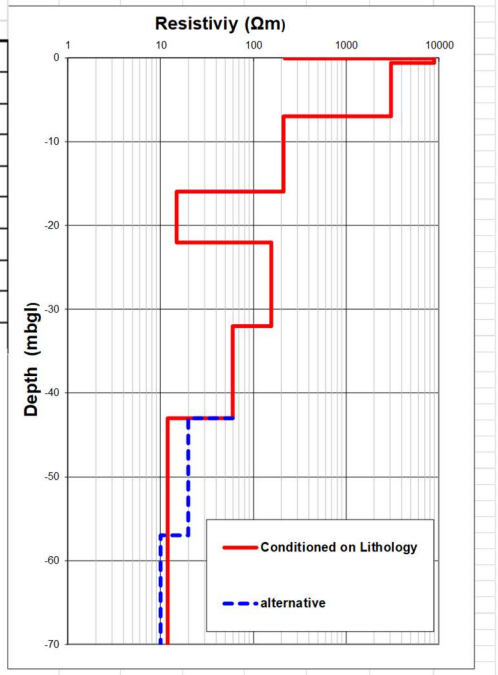


Figure 15. Constrained layer model, VES4 (BH5)

3.3 Near Borehole 3 (VES5)

VES5 was conducted near Base Borehole 3 (BH3), with a Wenner configuration using the ABEM LS Terrameter.



Figure 16. Google Earth image showing BH3 area VES location and orientation

3.3.1 VES 5 results

The unconstrained interpretation of the sounding gives a 4- or 5-layer model, including a thin 'false' top layer. Reliability analysis of the two models reveals that the 5-layer model cannot be accepted due to the uncertainty of the model parameters. This is illustrated in Figure 17, giving a number of equivalent model solutions, all having a 'good fit' to the data.

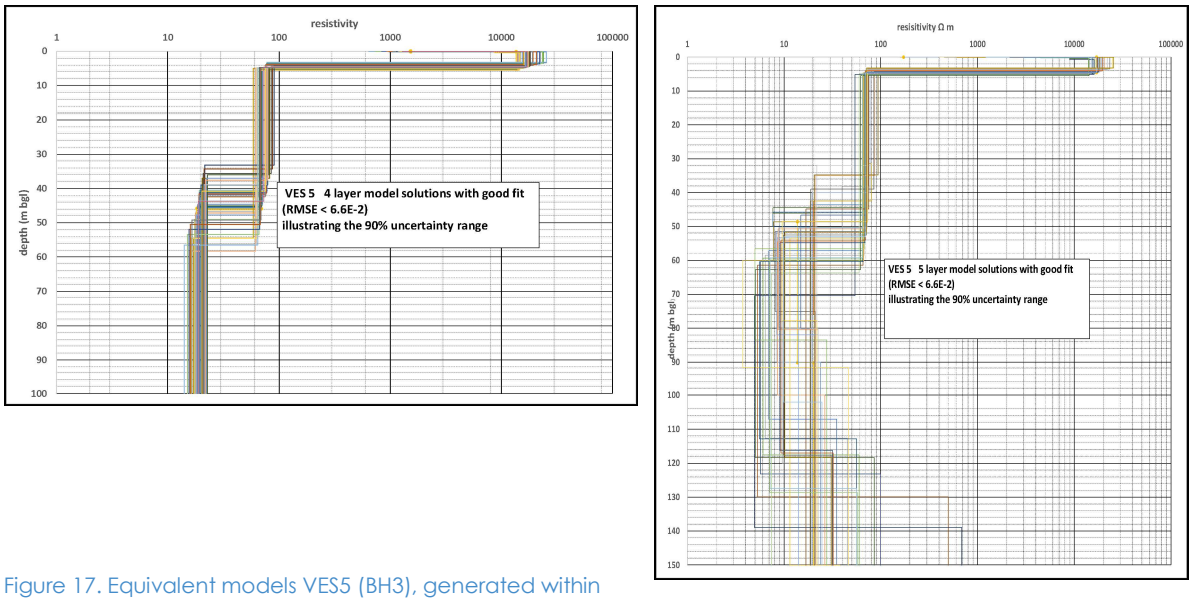


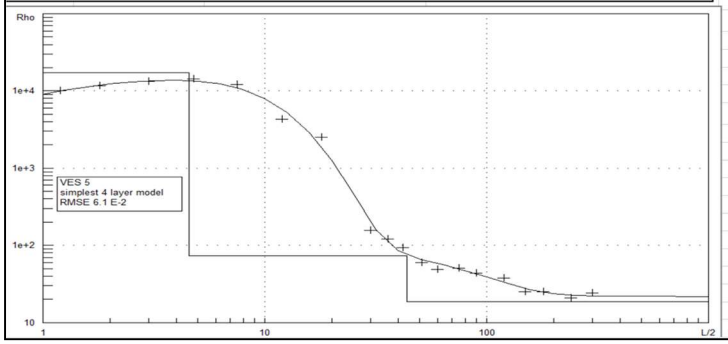
Figure 17. Equivalent models VES5 (BH3), generated within the uncertainty range. Left: 4-layer model and right: 5-layer model. For further information, see the Technical interpretation report [Rolf, 2109].

The analysis illustrates that beyond a certain depth (the 'depth of investigation' or DOI), the VES cannot reliably discriminate layers. One can add deeper layers in the inversion (like, in this case, the 5th, deep layer) but the uncertainty and correlation of the parameters values increases unacceptably. For further explanation, see the technical interpretation report.

In the case of VES5 the DOI is of the order of 80m; the 5-layer model is rejected because of the high uncertainty. The unconstrained 4-layer model is presented in Figure 17 (left). The VES can just discriminate the transition to lower resistivity material (the top of the Mtomkuu or Kambe Formations) at a depth of 35 – 55 m, with a best estimate of 43 m. The model does not clearly indicate the shallow clay layer, expected at around 20 m.

layer	top (mbgl)	resistivity (Ωm)	stratigraphy
ves4 Wenner			
1	0	1281 (L)	phony'
2	0.08	17127 (11833 - 24790)	dry sand
3	4.6 (3 - 6)	73 (57 - 95)	Jurassic Mto Mkuu
4	43 (35 - 55)	19 (16 - 23)	Kambe shales/limestones

Remarks:
Top of 3rd layer corresponds to estimated GW level
Unconditioned VES does not descert shallow (Kilindini) clays
AB/2 reach 300 m
DOI ≈ 80 m



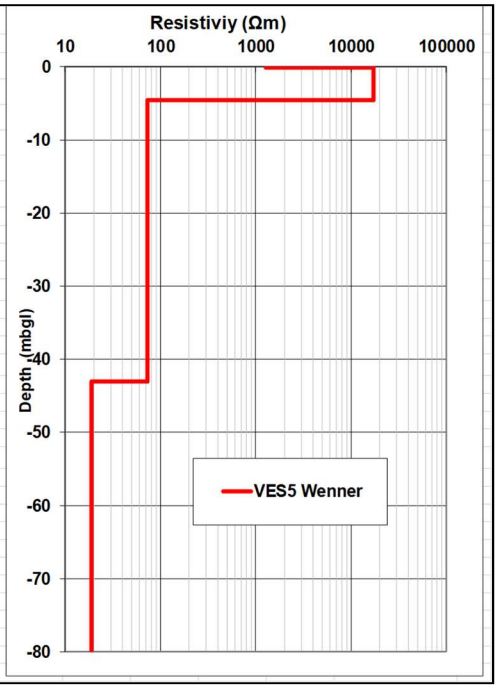
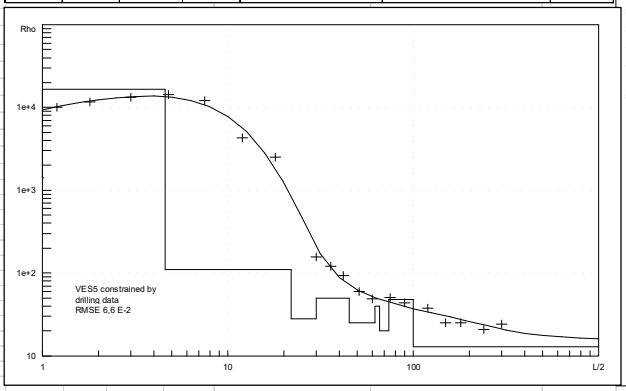


Figure 18. Unconstrained layer model, VES5. The unconstrained inversion has no clear indication for a shallow clay layer.

By referring to the Base Borehole 3 electric log and lithology, a constrained interpretation was made, classified with ten fixed-depth layers and optimizing individual layer resistivities manually. The mutual relationship between the layer resistivities are held proportional to the electric log data. The constrained layer model is shown in Figure 19 below.

Estimated resistivities (Ωm) VES5 with fixed layer depths according to BH3 drilling data

Layer	From	To	D (m)	Description	Stratigraphy	Rho (Ωm)
1	0	0.08	0.08	'false' layer		1420
2	0.08	4.6	4.52	dry unsaturated sands	recent/ Pleistocene	16760
3	4.6	22	17	sands saturated	Pleistocene Kilindini Fmt.	110
4	22	30	8	clays	Pleistocene Kilindini Fmt.	28
5	30	45	15	sandstones & corals	Jurassic Mto Mkuu Fmt	50
6	45	62	17	shales & limestones	Jurassic Kambe Fmt	25
7	62	66	4	sandstones (petr. wood)	Top of Mazeras Fmt	40
8	66	74	8	shales (&sandstones)	Up Tr. - Low Jur. Mazeras F	20
9	74	100 (end)		sandstones	Up Tr. - Low Jur. Mazeras F	48
10	>100			probably sandstones	Up Tr. - Low Jur. Mazeras F	13



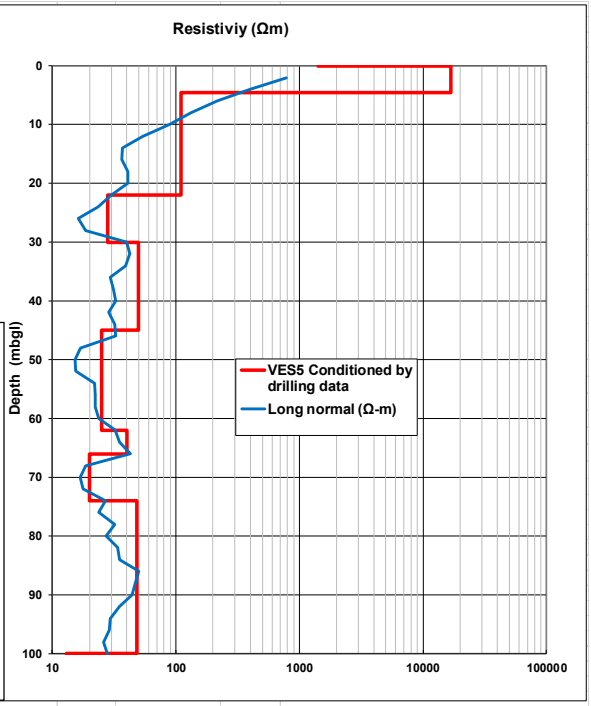


Figure 19. Constrained layer model, VES5 (BH3). In red: the constrained, 'many-layer' model. In blue: the electric log (LN).

This interpretation is closer to reality. However: the shallow Pleistocene clays that are present in Borehole 3 were not indicated in the unconstrained VES. This may be explained by the distance between the borehole and the measurement point (the VES5 location was 230 m southwest of the borehole); the clay layer may simply be absent to the southwest. Further considerations are in the technical report.

The resistivities of the deep Jurassic layers are all of the order of 10 – 60 Ωm, similar to the electric log results. Even the shaley zones (layer 6 and 8) do not show resistivities below 10 Ωm. The screened aquifer zones, shallow (Kilindindini sands, 25–40 m) and deep (Mazeras sandstone,84-99 m) are distinguished by 50 Ωm resistivity. The top of the Mazeras Formation (signified by petrified wood) is distinguished as a separate sublayer (layer 7).

3.4 Conclusions related to the VES method

VES interpretation

Referencing VES measurements to reliable borehole information clearly shows the limitation of electrical resistivity methods. The resolution of the VES method is restricted to models with four to five layers. Due to equivalence, VES soundings cannot accurately discriminate the many sub-layers without recourse to additional geological information, such as borehole lithological or electric log data.

The DOI in this dry sandy area is practically limited to approximately 60–70m. Beyond this depth the inversed layer parameters are uncertain; at greater depths, parameters are comparatively meaningless.

In models with more than three layers, the parameter values can be 100% correlated. This interpretation problem can only be tackled by restricting one of the parameters to a 'realistic' value from independent geological data.

Instruments

In the ISGEAG Kwale campaign three different instruments were used: an ABEM SAS1000 (AMREF), a Scintrex SARIS (Manken Consultants) and an ABEM Terrameter LS (Jos Hansen Ltd).

Of the three instruments, the 24V SARIS and LS are superior. They can generate sufficient current to obtain useful readings up to (at least) a 250m electrode spread. In this dry area the 12V SAS1000 was not able to generate useful measurements beyond an electrode spread (AB/2) of 80m.

The ABEM Terrameter LS (in our first experiences with the instrument, conducting VES soundings):

- Is found to be 'too user-friendly', making flexible operation for VES quite difficult without reading the manual carefully;
- We could however by-pass the fixed, pre-set menu of electrode distances as provided in the instrument; creating your own menu.
- The instrument gives measuring standard deviations for the potential and current electrodes separately, which we found helpful in tracing electrode problems;
- The LS machine can provide very high voltages (400V) to the current electrodes, which can be life-threatening under certain conditions if proper care is not taken. The danger is safe-guarded by a screen-warning that has to be acknowledged before pushing the 'measure' button. Other instruments with comparable voltages do not provide such extra safety rulings.
- The third ISGEAG campaign (Naivasha) revealed that the (preset) internal Geometric Factors of the LS instrument used, seems too low, giving 50% too low apparent resistivity readings when using the automatic protocol. A similar problem occurred with the same LS instrument that was used in Kwale.
- The LS Terrameter is a very powerful instrument, for example in conducting ERT: the multichannel option and very fast calculation of standard deviations make it a powerful and very fast instrument

Proper calibration (and correct operation) of resistivity equipment is an important issue that should be better addressed in Kenyan groundwater survey practices.

4 Application of Electrical Resistivity Tomography (ERT)

Three ERT profiles were conducted by KenGen using the ABEM LUND cable system and the ABEM SAS 4000 Terrameter. Beside the three ISGEAG ERT profiles there are results available from existing ERT profiles executed by Rural Focus in 2012 (courtesy of Base Ltd). The locations of all the ERT profiles are given in Figure 20 below, in red the Base ERTs, in yellow the ISGEAG ERTs. In this report only the data for Rural Focus LRBS1 are used for comparison to ISGEAG ERT1.

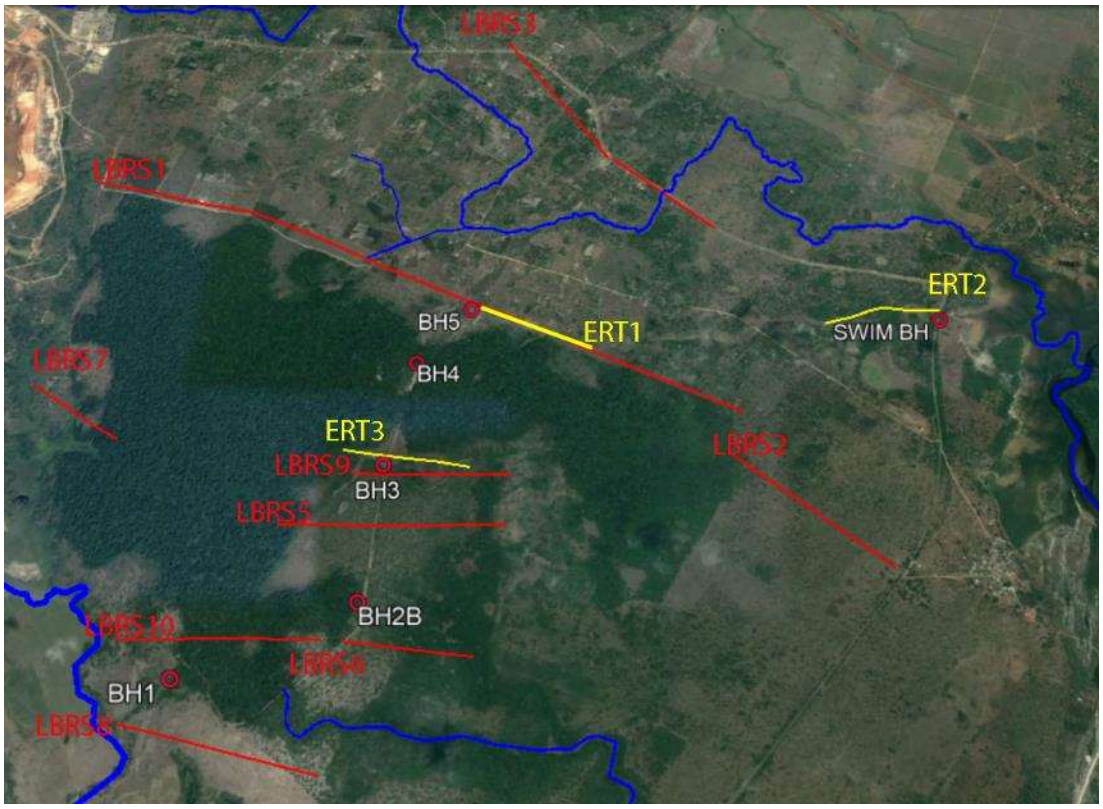


Figure 20. Location of the three ISGEAG ERT profiles (yellow), Base/RFL ERT profiles (red) and Base boreholes (red circles)

4.1 Fieldwork set-up

1) **Forward modelling.** A forward modelling is based on geological conceptual profiles derived from geological investigations and literature over many years (courtesy of Mike Lane, Rural Focus), see Figure 21. The forward model assumes a concept of formation resistivities and depths and calculates a synthetic model, being the model that should be expected as the outcome of the ERT if the assumed conceptual model was correct. Preliminary to the fieldwork, some forward modeling was done, Based on the existing conceptual views. The forward model is compared to the existing LRBS1 tomograph as conducted in 2012 over a roll along profile at the north side of the Gongoni forest, crossing the location of Borehole 5.

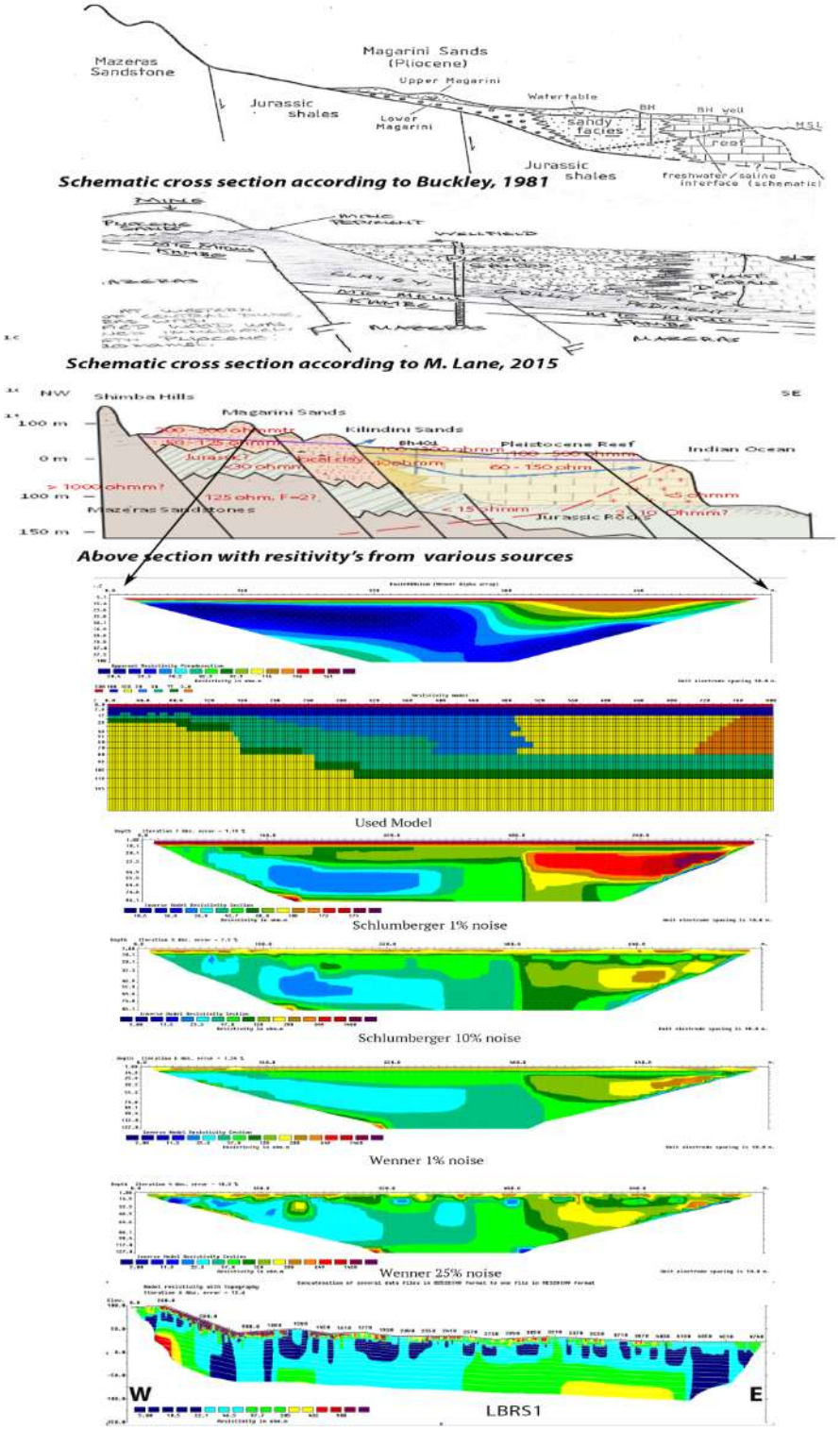


Figure 21. Results of forward models, based on existing concepts and compared to the existing, but re-interpreted LRBS1 tomograph below (courtesy of Base/Rural Focus).

Comparison of the forward models to the LRBS1 tomograph shows some similarity in both the location and the resistivity of anomalies.
Before using it for the comparison, the LRBS1 data had to be re-interpreted; a lot of data points had to be removed in order to achieve a reasonable inversion result with a reasonable fit.
Figure 22 illustrates the considerable data reduction that was required in the re-interpretation of the LRBS1 model.

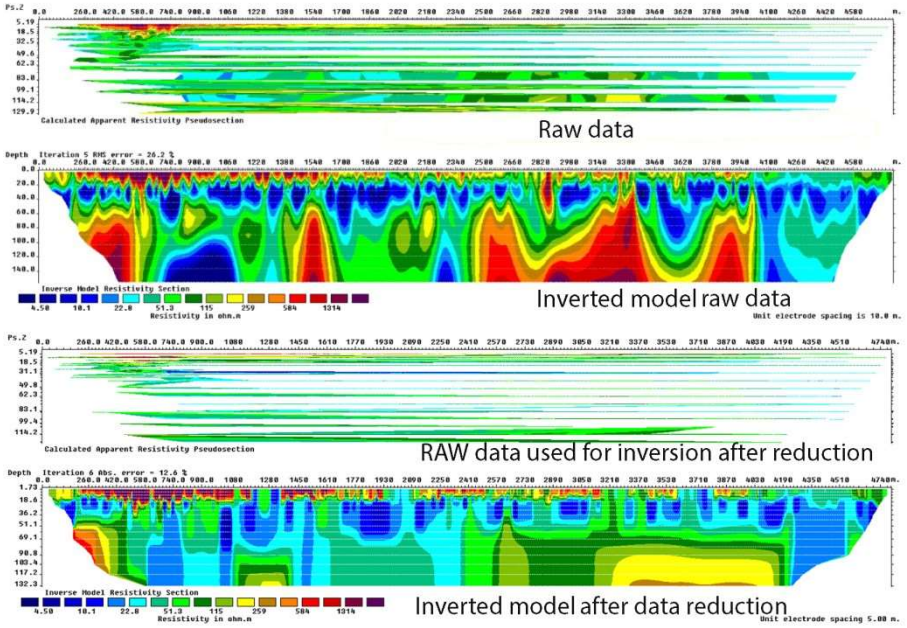


Figure 22. Example of data reduction effect on LRBS1 models; the white spaces between coloured lines in the data illustrate the eliminated data. Top two pictures: the original data set and tomograph. Lowest two pictures: data set after reduction and re-interpreted tomograph.

Erroneous data, probably due to bad electrode contacts in the high resistive topsoil, causes extreme resistivities of the deep layers and high Root Mean Square (RMS) errors. More than 50% of the data points had to be discarded or eliminated to get a reasonable inversion result with an acceptable RMS. The amount of eliminated data is visible in the data pictures in Figure 22 by the white zones in between the colored lines.

The re-interpreted result of LRBS1 indicates a zone of low resistivity from ca 20 – 60 m, differing in depth, but extending over the whole area, mainly concentrated in the shallow zone and extending over the whole area.

The deeper zone still shows some vertical anomalous structures that might correspond to the actual geology, indicating major fault zones. The blocky aspect is due to the robust inversion. If the data quality is poor the visual presentation of the tomograph can be altered by using a simplified color scheme, hiding the many unlikely details and just retaining the dominant, main structure (see Figure 23 below).

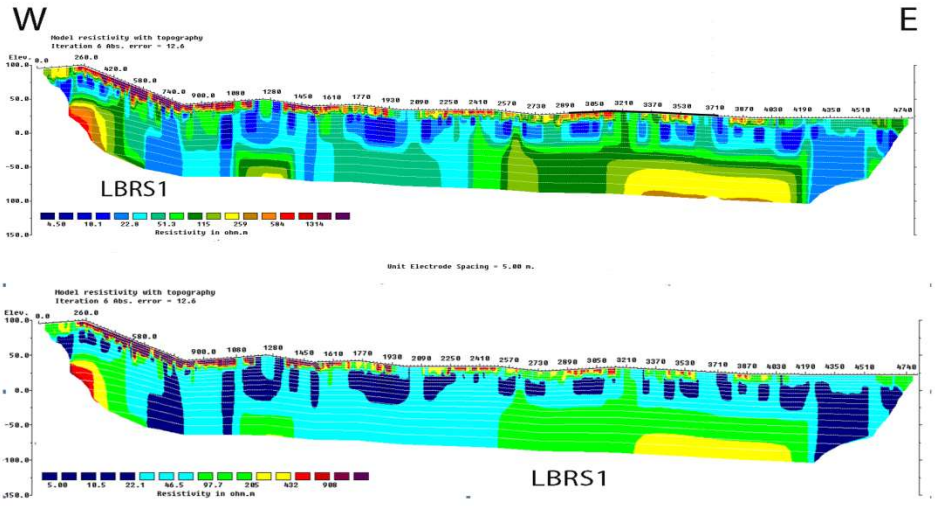


Figure 23. Re-interpreted LRBS1 tomograph with detailed and simplified color schemes.

2) **Exploration depth**. The exploration depth of ERT profiles is basically the same as in the VES and HEP methods. As a rule of thumb, it is roughly 1/6 of the maximum AB (maximum distance between the current electrodes or the dipole-dipole pairs). It depends also on the electrode configuration used and the actual resistivity of the geological formations. The target of this research is to investigate the geology as deep as possible, at least up to the depth of the Mazeras aquifer in which the deeper screens of the Base boreholes are positioned (at a maximum of 110 m). This is why it was decided to use the maximum stretch of the cables of 800 meter, with an expected ERT exploration depth of 800/6 = 133 m).

3) **Direction of the profiles:** The intended transect was a roll-along ERT from the SWIM monitoring borehole, perpendicular to the coast towards the wellfield, crossing near BH5. This would be more or less the transect of LRBS1 with an extension to the coast. This full profile could not be completed due to communication problems with the local landowners and community. After long discussions the fieldwork had to be stopped and only two parts of the transect were done: ERT2 near the SWIM BH and ERT1 east of BH5. A third ERT3 was conducted near BH3 in east-west direction. Unfortunately, this transect had to cross the powerline due to restrictions on entering into the Gongoni Forest Reserve. The powerline may have induced severe coupling effects to the ERT data.

4) **Electrode configuration:** The best possible electrode configuration depends on many things. In this area with a highly resistivity top soil (dry sand), extra electrodes, and adding salt water and bentonite around the electrodes were definitely required. The Wenner configuration was selected as the preferred set-up, being expected to have the least significant electrode current problems. The Schlumberger configuration or gradient was carried out as an alternative because of the higher resolution. Due to communication problems with landowners, there was no time to try other configurations, like the dipole-dipole. The cable length was 800 meters, divided over 4 cable reels. Each reel is 200 meters; 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. In total 64 electrodes were in use. The maximum possible distance (with these cables) between the electrodes was 10 meters. The expected exploration depth with the cables fully stretched is in the order of 130 – 150 meters. The same cable can be used with smaller electrode distances. In that case the cable is not fully stretched and a measuring tape must be used for the correct electrode distances. ABEM SAS 4000 is capable of measuring 4 channels at the same time (4 potential electrode positions). The newer ABEM LS instrument is capable of 8 or 12 channels at the same time.

5) **Electrode test**. Despite the adding of salt water and bentonite around the electrodes, almost all the electrode contact resistances were far above 1 kΩ, due to the extremely high resistivity top soil. GPS points for each electrode position were collected, meanwhile assessing additional field information on geology, hydrography, topography, vegetation, roads, houses and power lines. WGS84 was prescribed as the standard GPS coordinate system, especially for its direct application into Google Earth.

6) **Standard deviation**. For the calculation of standard deviations, two full measurement cycles are required with the SAS 4000 in use. The new ABEM LS instrument of is able to calculate the standard deviation within one measuring cycle, which reduces the total data acquisition time by at least 50%. Due to the unfavorable conditions of the top soil, standard deviations were high, even above 10%. Additional data-stacking and/or averaging was required. In the data set, there were a lot of data points with negative signs. A negative sign indicates that the self-potential of the earth is too large to be ruled out by the induced current of the ERT Instrument. In most cases, this is caused by bad electrode contacts.

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.** The ERT fieldwork gave many challenges for the (KenGen) team: the access restrictions of the Gongoni Forest Reserve, the powerlines and – most of all – the

landowner issues. While setting up the electrodes on the ERT1 transect the team had to stop and could not continue adding saltwater to the electrodes. This resulted in the loss of at least of 1/3 of the data points. This may be the reason that the high resistivity top layer is missing in large parts of the ERT1 tomograph.

Inversions were executed with RES2DINV software. After removing data outliers, a first 'standard/robust' inversion (see the manual for RES2DINV, [Geotomo, 2010]) was calculated, subsequently followed by several other inversion options. The smooth inversion assumes smooth resistivity changes, while the robust inversion assumes sharp boundaries. Based on the RMS of individual points in the inverted model, a second data reduction was done. After this, a better fit was also achieved by the option of doubling the amount/number of electrodes in the inversion (model refinement). Using the Base borehole information, inversions with one or more constrained boundaries were also tested. The depth of these pre-set boundaries is indicated as black lines in the tomograph.

4.2 Results

This paragraph gives the results of the three ERT soundings near the Base boreholes (ERT1 and ERT3) and near the SWIM monitoring borehole at the coast (ERT2).

4.2.1 General observations related to ERT1 and ERT3

ERT1 and ERT3 were conducted at the northern edge of the Gongoni Forest (ERT 1) and inside the forest at some open space near borehole 3. Several inversion steps with different parameters and boundary constraints are presented in Figure 24 on the next page, both for ERT1 and ERT3. Going down in the figure, progressive correction (data reduction) was applied in several stages. The inversions with the lowest RMS percentage are at the bottom, given in a simplified colour scheme.

The data quality is low and the results are disappointing. The difficult field circumstances gave great problems with electrode contacts, causing many bad data points. During the process of many trial inversions, substantial data reduction had to be applied, removing data points. Over 30% of the data had to be deleted. Constraining the inversion on borehole information, though statistically improving the fit, did not increase the likeliness of the inversion very much.

General observations that were being made in relation to ERT1 and ERT3:

- Both ERTs indicate the existence of a non-uniform shallow low resistivity layer (the blue zones) around 15 - 60 m of varying thicknesses, depending on the inversion used and the amount of data reduction. The shallow low resistivity zone in the tomograph may be a good indication of the presence or absence of the Pleistocene (Kilindini) clay layer. At a few locations the blue zone shows two separated layers, at others only one or none;
- The tomographs do not give consistent information that fits in the context of the deeper conceptual geology. Obviously, the contrasts of the layers both in thickness and resistivity is not large enough and the quality of the data is too poor to reveal the differences between the Pleistocene sands, corals, the underlying Jurassic limestones and shales and upper Mazeras sandstone Formation;
- The deeper parts of the tomographs just show an irregular scattered pattern of medium resistivity zones, generally in the order of 15 to 60 ohmm, thus not indicating very high resistivities nor very low resistivities (saline pore water) for the Mazeras sandstone.

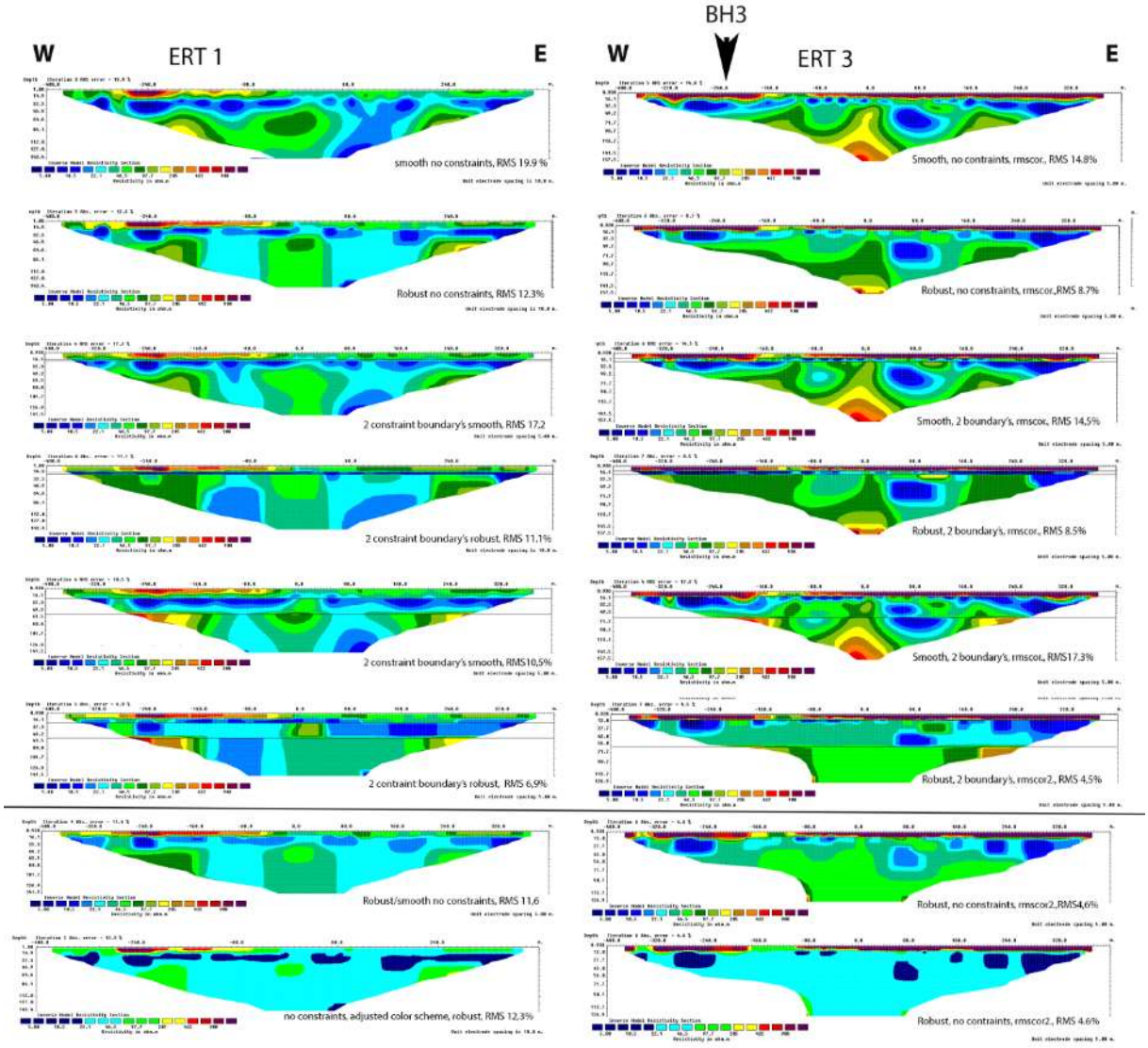


Figure 24. Tomographs of inversion trials, trying smooth and robust solutions, increased data reduction and boundary constraining on the ERT data. Left: ERT1 east of Borehole 5 (the location of BH5 is at the west-end of ERT1). At the right: ERT3 crossing the wellfield near borehole3. The location of BH3 is also the crossing point of the powerline.

4.2.2 Specific considerations in relation to ERT1

The quality of data is particularly poor in ERT1 (BH5). During the set-up of the line, serious problems arose with landowners and no measures could be taken to reduce the electrode resistance. The ERT protocol was started with the Schlumberger configuration, which is unfavourable under these circumstances. It was not possible to continue with other protocols (Wenner or Dipole) or to execute the intended full transect towards the SWIM borehole.

The Schlumberger configuration would normally give 680 data points, but only 400 points could be measured. After data correction only 320 points remained.

The many inversion trials on ERT1 were presented in Figure 24. After considerable data elimination, the robust unconstrained inversion with a 12.3% RMS in a simplified colour scheme was selected as the most trusted for further use, as presented in Figure 25 on the next page.

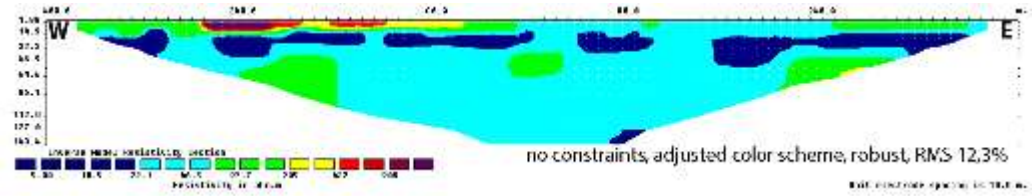


Figure 25. ERT1, the most-trusted inversion. Borehole 5 is a short distance from the western end of the profile.

In Figure 26 below, ERT1 is compared to the (re-interpreted) tomograph of Base/RFL LRBS1:

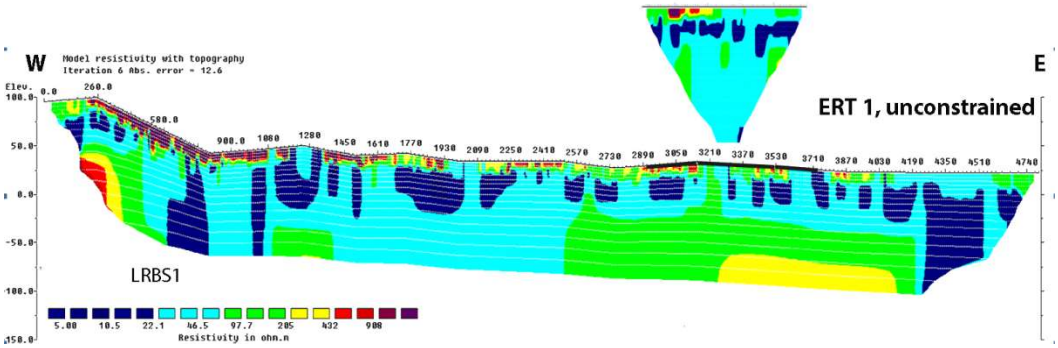


Figure 26. ERT1 compared on top of the Base/RFL LRBS1 tomograph. Borehole 5 is at the 2870 m position in LRBS1.

The resemblance between the two independent tomographs is limited. While LRBS1 may indicate an actual geological structure (fault) at the ERT1 location, this is not clearly supported (nor denied) by ERT1: apart from the low data quality and the used Schlumberger configuration, the ERT1 line is also too short to attach geological value to the vertical structures observed in the tomograph.

Nevertheless, when comparing LRBS1 near borehole 5 to the geological map and lineaments Based on satellite images and the pattern of rivers, consistency is observed that gives support for the presence of a major fault zone around 250 m east of BH5, and if so, there may also be additional fault zones along the LBRS1 profile, as tentatively indicated on the map in Figure 27.

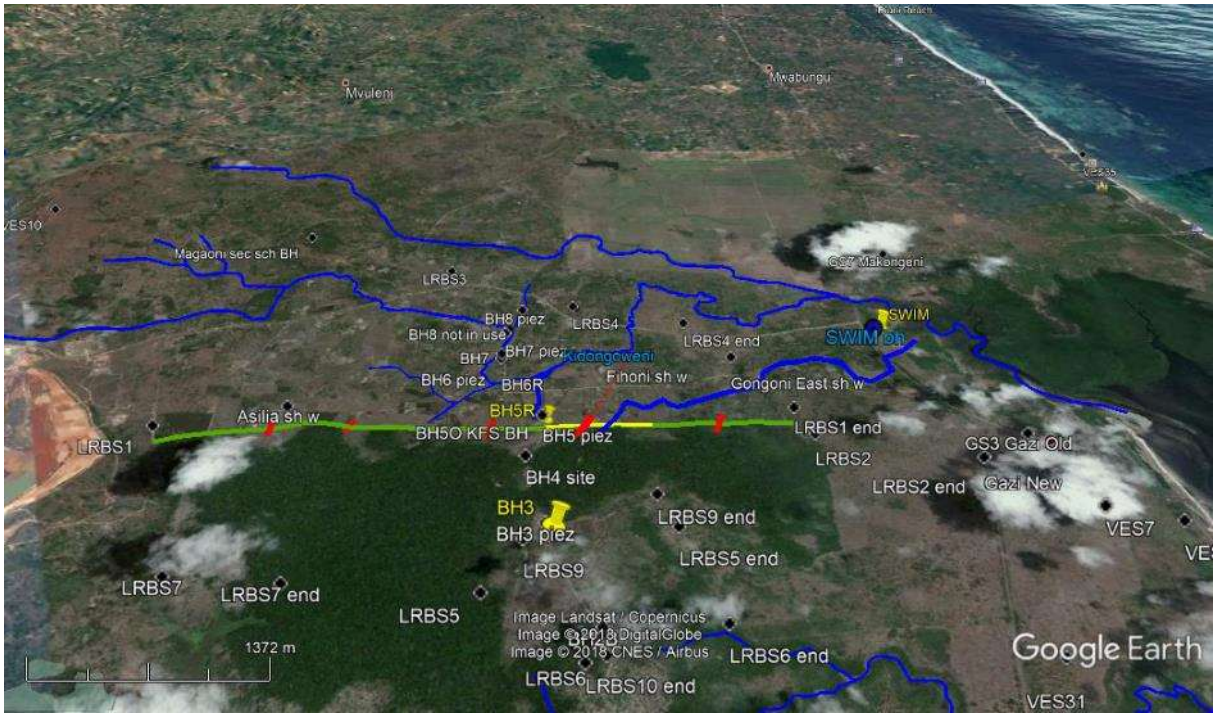


Figure 27. Tentative fault lines as inferred by vertical structures in Base/RFL ERT LRBS1 (green line). The short reds on the ERT line are the fault crossing positions (at 840, 1450, 2400, 3110 and 4200 m along the LRBS1 line; borehole 5 is at 2860 m). The ISGEAG ERT1 is given as yellow line.

4.2.3 Specific considerations in relation to ERT3

The data quality of ERT3 near Base Borehole 3 is slightly better than ERT1 because more points could be measured and used in the inversion, but still far from good. The data reduction is illustrated in Figure 28. The top three pictures give the uncorrected data and results (from top down: the measured apparent resistivity, the calculated apparent resistivity and the resulting tomograph (RMS 76,7%). The next three pictures give the same results for the final, corrected data set.

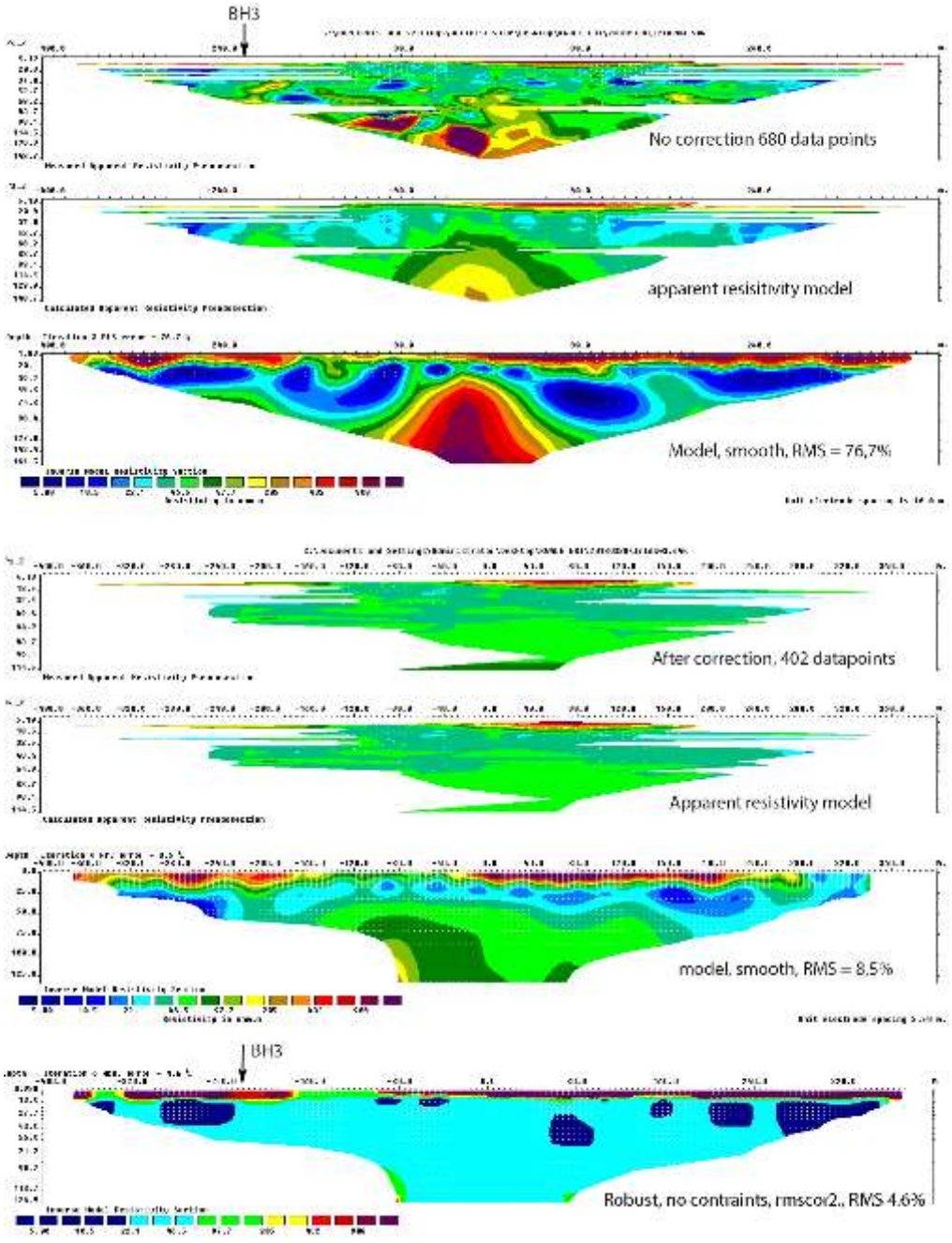


Figure 28. Inversions of ERT3, effect of data correction. The top three pictures give the uncorrected data and results, from top down: the measured apparent resistivity, the calculated apparent resistivity and the resulting tomograph (RMS 76,7%). The next three pictures give the same results for the final, corrected data set (RMS 8,5%). The picture at the bottom gives the tomograph in the simplified colour scheme.

The shallow, non-uniform clays are well-distinguished as well as a high resistivity superficial layer over parts of the area. As in ERT1, the lower resistivity Jurassic zone, expected at depth of around 50-75 m, is not clearly detected and there are no indications for very high or very low resistivities in the deepest zone of the tomograph.

The powerline adjecant to BH3 is crossing at position -230m in the tomograph, which is on flank of the tomograph, where much of the data has been eliminated. It is therefore not clear to what extend the results are interfered by the powerline. In 2012, the LRBS9 ERT line was conducted by RFL, almost at the same location and the same direction (see location map Figure 20). In that year, the powerline didn't exist and so the LRBS9 ERT was not interfered with powerlines. Comparing both ERTs could give information on the effect of underground high voltage powerlines on DC electric soundings. This was considered but, unfortunately, re-interpretation of LRBS9 turned out to be not possible due to its poor data quality.

4.2.4 Specific considerations in relation to ERT2 near the Coast

ERT2 was executed perpendicular to the coast starting on the west side of the main road, opposite the SWIM piezometer borehole. See Figure 29 below.



Figure 29. Location of the ERT2 line (in yellow). In red: the 10 masl elevation contour. In blue: ephemeral stream.

Due to good resistivity contrasts and relatively clayey topsoil, the data quality is much better than ERTs 1 and 3. More than 400 data points could be used for the inversion. The inversion result is shown in Figure 30.

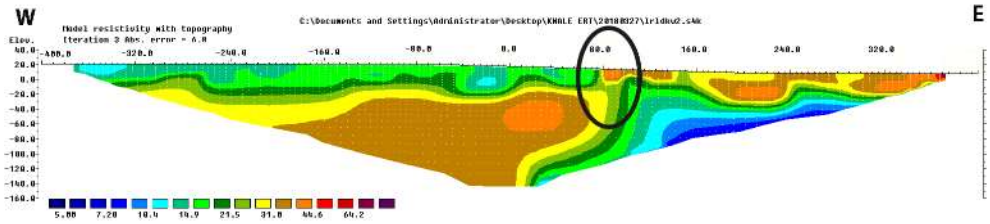


Figure 30. Inversion result for ERT2, topography corrected, showing the saline water interface.

On the ocean side (right), the tomograph shows the clear intrusion wedge of saline water, gradually changing to brackish and fresh water towards the landside. On the landside the result indicates a low resistivity layer (clayey sand) at surface. As a remarkable observation, the low resistive top layer ends abruptly where the interface starts. At the same position the intrusion shows a local up-coning of brackish water (the circle mark in Figure 30). This may be related to an interesting phenomenon of upward seepage of fresh water, flowing out to the corally topsoil. A remaining research question would be: where does this seepage water flows to? There are no significant shallow aquifer abstractions nor surface water in this area.

The change to the deeper underlying aquifer (Jurassic shales, sandstones) is not discerned in the ERT. The reliability of the inversion decreases with depth (as in VES and TDEM). Unless there is a large contrast in (vertical or lateral) resistivity, deeper layers cannot be discriminated.

In Figure 31, a perspective view is constructed of ERT2 on the satellite data and the geological map. The red line indicates the change in topography (10 MASL contour) which coincides with a change in geology (from coral reef to the backreef sands) and the edge of the saline interface at ERT2.

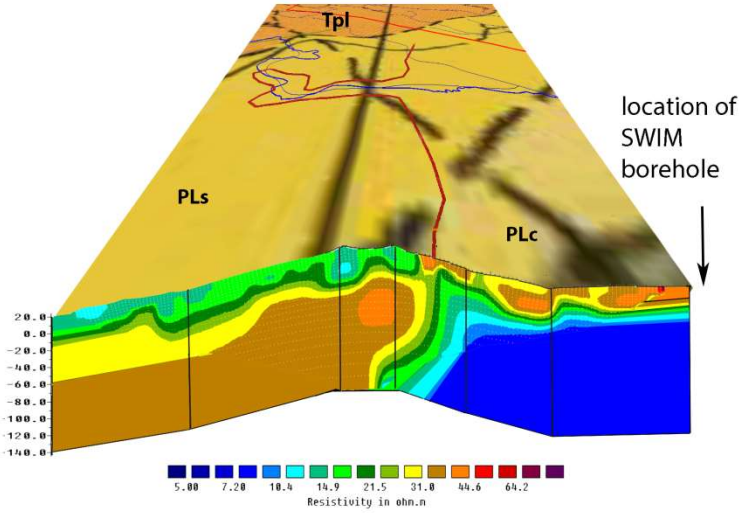


Figure 31. Perspective view of ERT2, compared to geology map and land elevation; the red line is the 10 MASL elevation contour line.

The change in topography at 10 MASL can be used to give a first approximate mapping of saline intrusion along the Coast and salinization risks. This is elaborated in synthesis chapter 7.2.

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

During this second field work period two instruments, a Zonge GDP32-II receiver and ZT30 transmitter (KenGen) and a WalkTEM from ABEM were applied. For the description of the Zonge instrumentation the reader is referred to paragraph 5.2 on TDEM in the ISGEAG Kajiado report (Groen e.a. 2018, Acacia Water), or the description later on in this chapter.

The WalkTEM instrument is made by Guideline Geo (ABEM) in Sweden. It is a recent development in TDEM instrumentation derived from the airborne SKYTEM system. The system has many new features which makes it easy to use and is compact and easy for transportation. The combination with an improved vertical resolution (more time windows) as well as a potentially high lateral resolution makes the instrument unique. The use of high current in combination with the relatively small transmitter loop and modern electronics makes this high resolution possible. High resolution both shallow and deep is achieved by applying the so-called dual moment, which means that in one measurement sequence two different transmitter currents are used with different frequencies. Another important feature is the possibility to combine all the measurements at one sounding location and invert them at location, visualized on the display. The data points used in the inversion are selected automatically based on intelligent algorithms. These are major advantages compared to other instruments.

The setup of the instrumentation is convenient and flexible (Figure 32 on the next page), with a transmitter loop of 40 X 40 an exploration depth can be reach up to 150 meter or more. The transmitter loop can be increased up to 100 X 100 which increases the exploration depth. The 2 receiver loops consist of a double wire 10 x 10 m and a smaller multi coil receiver. They can be used in combination. Bigger loop sizes of even more than 100 m can also be applied for deeper soundings as well as an extra high-power transmitter for very deep soundings (> 800 m).

Besides the measurements in the ISGEAG project area near the Base wellfield, the WalkTEM was also used at two locations 5 km south of the actual Kwale project area. The latter was to investigate evidence for seawater intrusion (see paragraph 5.5).

5.1 Fieldwork set-up

In Kwale, multiple soundings (both Zonge and WalkTEM) were carried out on 3 transects (see Figure 33). Two transects were selected at the well field near borehole BH3 and borehole BH5, perpendicular to the line of wells. A third transect extended from the SWIM piezometer borehole to the west, perpendicular to the coast. The plan was to make a full transect from the SWIM borehole to borehole 5, but very unfortunately that couldn't be finished due to social issues.



Figure 32. ABEM WalkTEM instrumentation; the equipment fits all in two standard suitcases (without the 2 Heavy Duty car batteries).

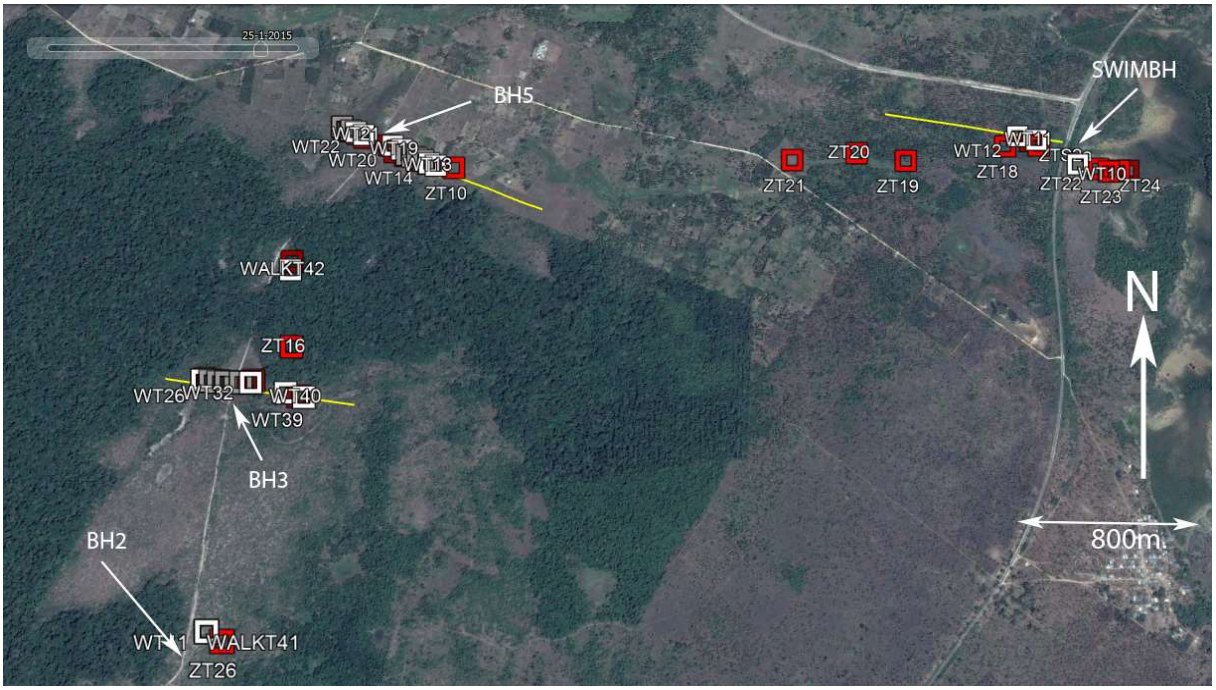


Figure 33. Overview of the TDEM sounding locations both Zonge (red) and WalkTEM (white). The yellow lines are the ISGEAG ERT profiles.

1) **Initial Forward modeling**. Using existing information from boreholes and VES soundings, forward modelling was applied to test the TDEM sensitivity for changes in the geology (e.g. the presence of the Jurassic shales) and the presence of saline groundwater at great depth. This forward modelling showed that the presence of thin shale layers can be distinguished as well as the difference between low and high resistivity at great depth. See Figure 34, in which two models with and without a shale layer are compared with low and high resistivity at great depth;

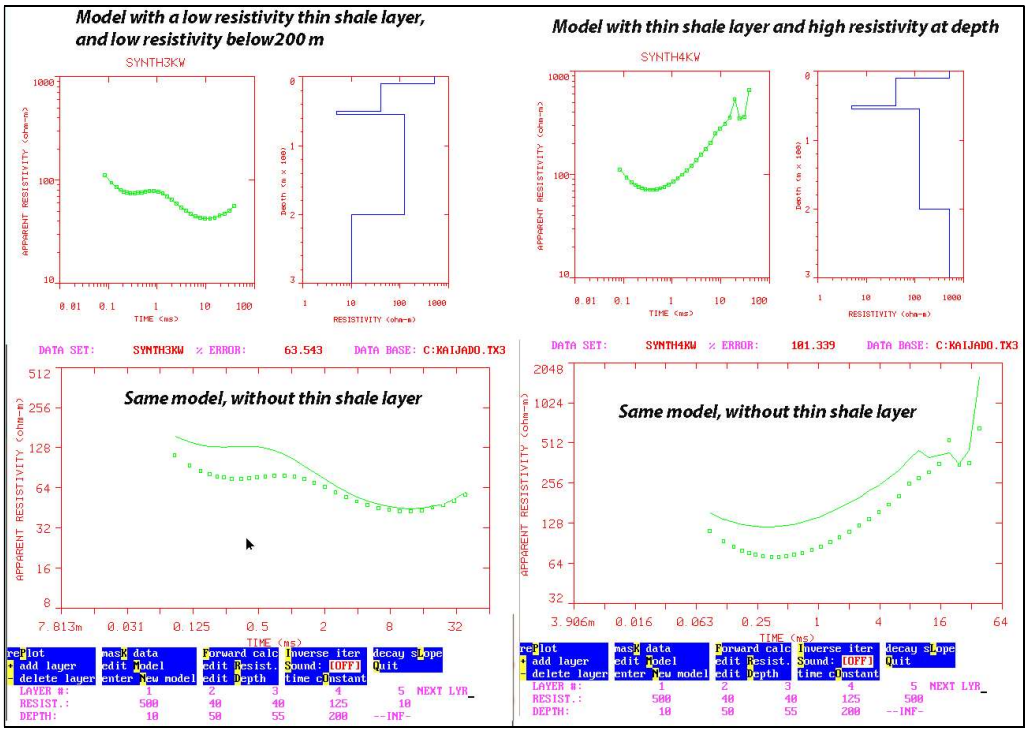


Figure 34. Forward models with loop size of 100X100, Tx current 10 amp, Zonge instrumentation. Left figure is low resistivity at depth and the effect of a thin shale layer on the sounding graph, right is the same with high resistivity at depth.

2) **Optimum loop size.** In Kwale the main purpose was to mutually compare TDEM with AMT, ERT and VES and particularly also with the Base Ltd borehole information. TDEM soundings were executed close to the boreholes and along the 3 ERT transects. Because we used both WalkTEM and Zonge, loop sizes of 40 X 40 m (WalkTEM) and 100x100 m (Zonge) were applied with various transmitter currents and frequencies. The transmitter loops were single turn (small Tx delay time) and the receiver loops were multi turn (Zonge/WalkTEM), and both single and multi-turn for WalkTEM. A single turn loop has only one wire in a loop, multi turn has more than one loop;

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. (both Zonge and WalkTEM);

4) **Testing**. With the Zonge system, loop sizes of 100 x100 were executed with different currents (3-10-20 amp). Transmitter loops (with only one turn) and frequencies of 4, 8, 16 and 32 Hz were tried. As standard 4, 16 and 32 Hz were selected to be used at each station with different currents. With WalkTEM a loop size of 40 X40 m was applied, low, medium moment (at the same time) and high moment. Frequencies were 12 – 200Hz Hz, and currents 1-7-15 Amp;

5) **Filter.** Standard filtering was applied: anti Alias filter and a Power line notch filter. In the Zonge instrument gains were set in the fully automatic mode of the Zonge instrumentation, which gave the best results. WalkTEM has automatic built-in filters and gain settings as well as manual options. Automatic gain was also used with WalkTEM;

6) **Standard deviation:** Zonge: During acquisition standard deviations of both decay and resistivity of a single (mid) time window were monitored. Frequencies of 32 Hz (8192 measurements or cycles), 16 Hz, (4096 measurements) and 4Hz (2048) were sampled and averaged. During measurement the standard deviation was observed of the averaging process of a single time window. This is an indication of the quality and repeatability of the data. See the ISGEAG Kajiado report TDEM chapter for an example of a raw data file. WalkTEM: during acquisition all the data points are visible as a graph on the display. Visual inspection of the

smoothness of the complete decay curve works better than monitoring the standard deviation of a single time window;

7) **Data check.** After removing outliers, first smooth inversions were reasonable and made sense indicating increasing resistivity with depth. With Zonge equipment the data needs to be downloaded, converted and uploaded in an inversion program. WalkTEM calculates a first, preliminary smooth model direct after acquisition in the field and shows the results on the display. Several data curves can be combined and deletion of 'too early' and 'too late' arrivals (background noise) is done automatically with WalkTEM;

8) **Soundings.** After these tests, Zonge 100 X 100 and WalkTEM 40 X 40 transmitter loops were executed along the selected transects. With Zonge, measurements were made with currents between 10 and 20 amps and with frequencies 4 Hz, 32Hz and 16 Hz. The WalkTEM soundings were measured in dual moment, high moment with single turn and multi turn receivers;

9) **Interpretation and profiling.** The first step in data interpretation is to judge each set of soundings (high and low moment for WalkTEM and different frequencies for Zonge). The next step is to select the data points for inversion for a first 1D smooth inversion. This is done with the SPIA software for both WalkTEM and Zonge and the WalkTEM smooth models are compared by the preliminary inversions as calculated in the field by special designed software on the instrument itself. Close to the Base boreholes the results of the smooth inversion are compared to the borehole data and the information is used for constraining the layered model inversion by fixing depths and/or resistivities of certain layers to see if this leads to a better fit. The knowledge from these constrained layer models is used in the inversion of the other soundings at the same profile or even other transects. This eventually results in a 2D resistivity profile of the layer models. This profiling has been done both by a 1D extrapolation by hand as well as with semi 2D 'automatically' inversion software: WORKBENCH software (Aarhus University, Denmark), WINGLINK (KENGEN) and with the web-Based freeware GEOMODEL software[4]. Results of the WINGLINK software has not yet been received from KENGEN. More practical issues of the interpretations and profiling are discussed in the applications given in the next chapters.

   It is important to note that in the inversion process deleted raw data points at late time windows will influence the Depth of Investigation (DOI). The choice to delete data points depends on several issues. The first selection is based on the standard deviation between the repeat of a series of soundings on the same spot (repetitions). The standard deviation is presented as error bars in the raw data. Deleting or keeping these points will affect the results of all the inversions both 1D and automatic semi 2D interpolation of soundings. In the automatic semi 2D interpolation programs, lateral influence ('contour preference') of a single sounding can be adjusted, by changing the contour preference parameter; horizontal layering can be over-exaggerated or underestimated. This is illustrated in Figure 35 and Figure 36 on the next page where the effect of selecting data points for inversion both in 1D and 2D is shown.

[4] https://geomodel.info/tdem/index.php

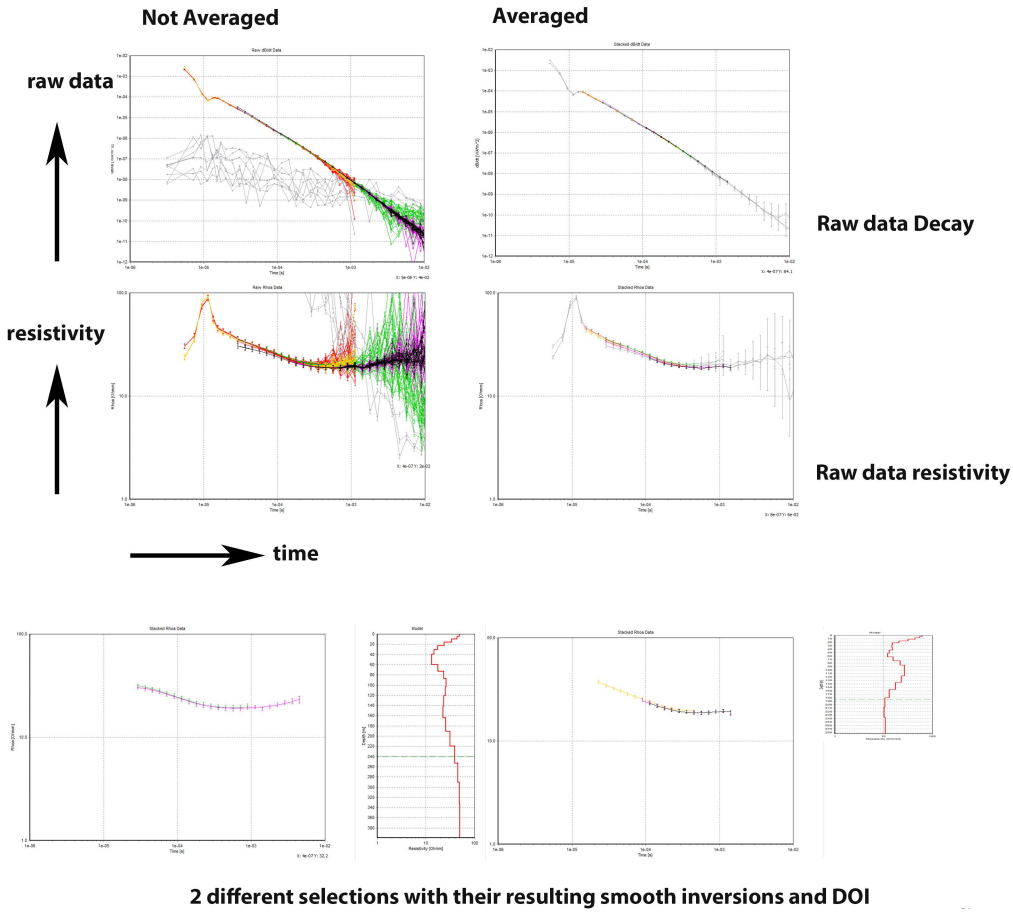


Figure 35. Effect of data selection on DOI: examples of one sounding. Above left side are all repetitions of the transients, left averaged with error bars. Below the effect of data selection (Based on the error bars) on the DOI

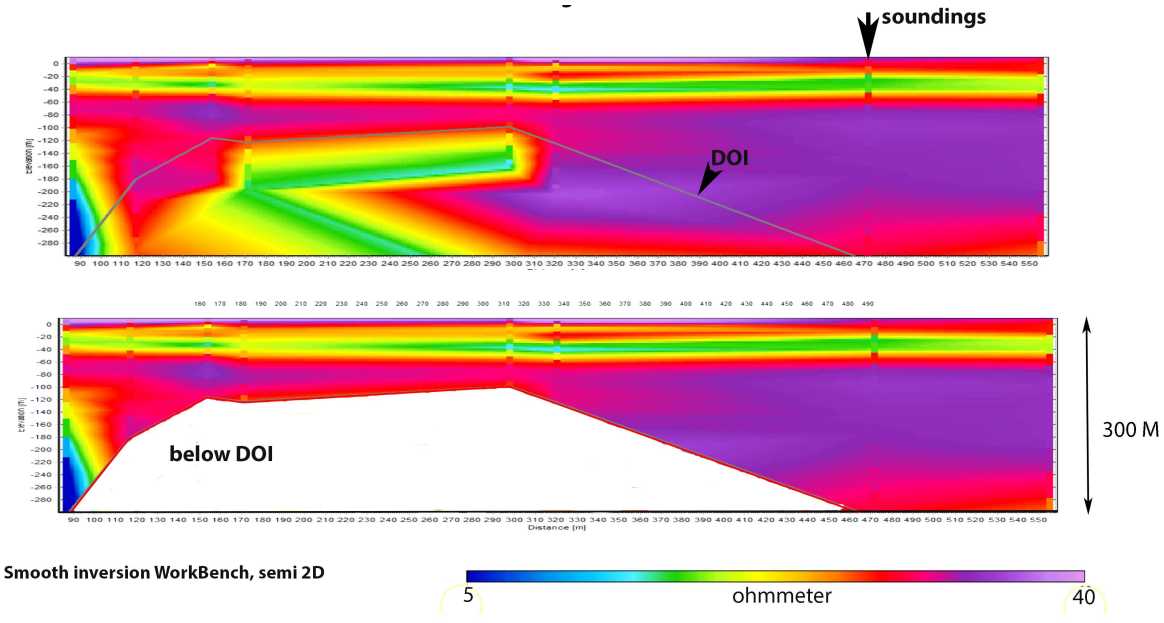


Figure 36. Semi-2D tomographs, Based on 1D smooth inversions.

5.2 Comparison of Zonge and WalkTEM

The instrument settings and antenna loop size for the Zonge soundings were focused on deeper layers, in combination with AMT. The WalkTEM settings and antenna loop size were selected to give the best resolution results on the first 150 meters. Note that, with the WalkTEM it is also possible to conduct deeper soundings with other settings, bigger loops or even stronger transmitters. In Kwale we did not use these options.

An attempt was made to combine WalkTEM and Zonge data in one joined inversion but due to differences in instrumentation and calibration, this was not successful. This is explained in Figure 37 below where the Zonge and WalkTEM are compared.

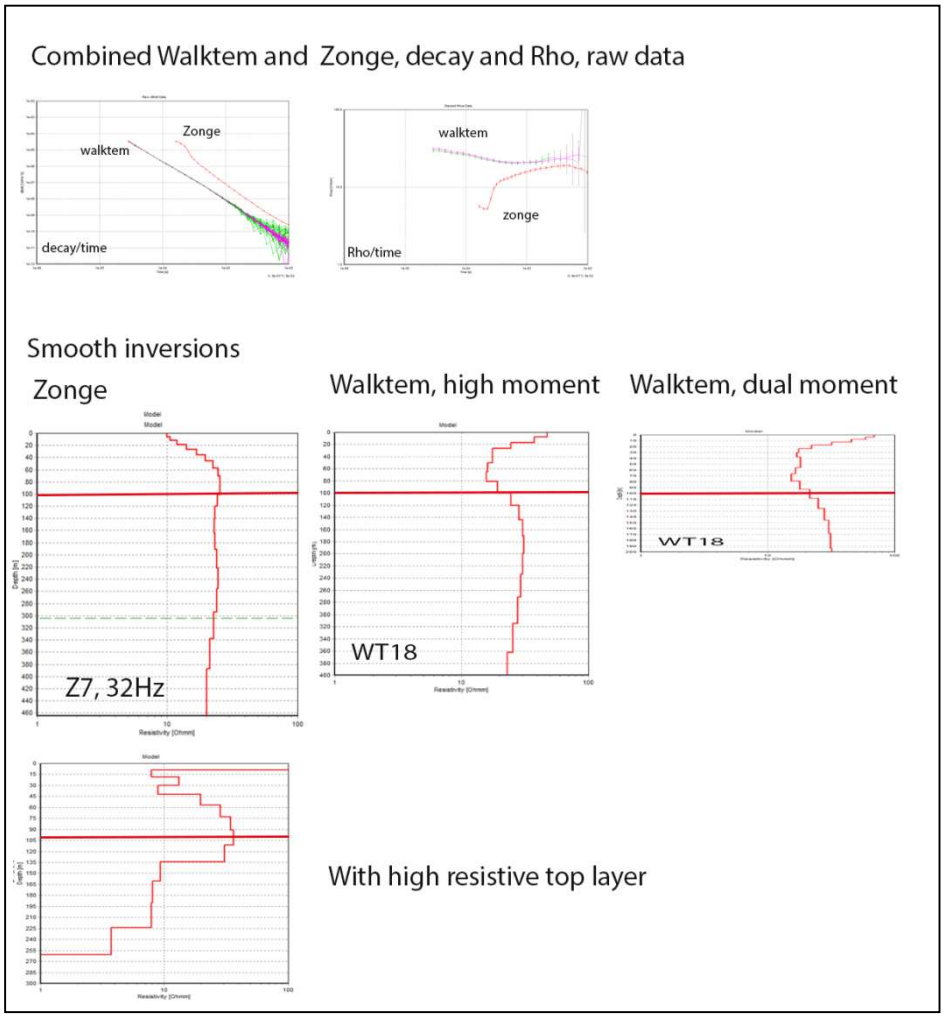


Figure 37. Differences between Zonge and WalkTEM soundings for the same location. On top: raw data sets; in the middle 32Hz Zonge smooth model and WalkTEM models; below: the unconstrained 4Hz Zonge smooth model and the same model constrained to have a high resistivity top layer.

At the top, in this picture the raw data is visible for both systems, both the decay and resistivity-time graphs. The graphs in the middle give the unconstrained smooth inversions of the 32Hz Zonge and WalkTEM, and the graphs at the bottom compare the unconstrained 4Hz Zonge inversion with a solution that is constrained by adding a thin high resistivity top layer.

The figure demonstrates that the Zonge soundings are lacking the required early time data points to discriminate the thin (but important) high resistivity top layer, which is completely absent and due to that, the low resistivity layer is shifted upwards in depth: at surface instead of at 20 – 60 m as in the WalkTEM (see graphs in the middle). In the WalkTEM the maximum resolution for the shallow underground comes from the dual moment data (right graph, middle row). In the 4Hz Zonge inversion, beyond 100 m the soundings are giving a clear transition to low resistivity at depth (last row, left).

Combining 4Hz and 32Hz Zonge and constraining the inversion by a thin high resistivity top layer, the shallow low resistivity layer is still at a wrong position (last row, right).

Be aware that the resistivity values in the smooth model do not represent the true formation resistivity. TDEM is not very sensitive in the high resistivity range and the equivalence can be high.

With the SPIA software it is possible to combine data from different soundings, frequencies and currents and select the best points from each (shallow, intermediate and deep) and run a combined, integrated inversion. With the Zonge inversion software this seems possible as well, but such integrated inversions are not applied by KenGen. As an example, given below (Figure 38), different frequency data from a Zonge sounding are combined and integrated in a SPIA inversion. In Figure 39 a constraint smooth inversion with a high resistive top layer is compared with an unconstraint smooth model. This proves that this model also fits but due to the set up and resolution of the instrument not visible in the raw data. We have chosen not to constrain the smooth model inversions.

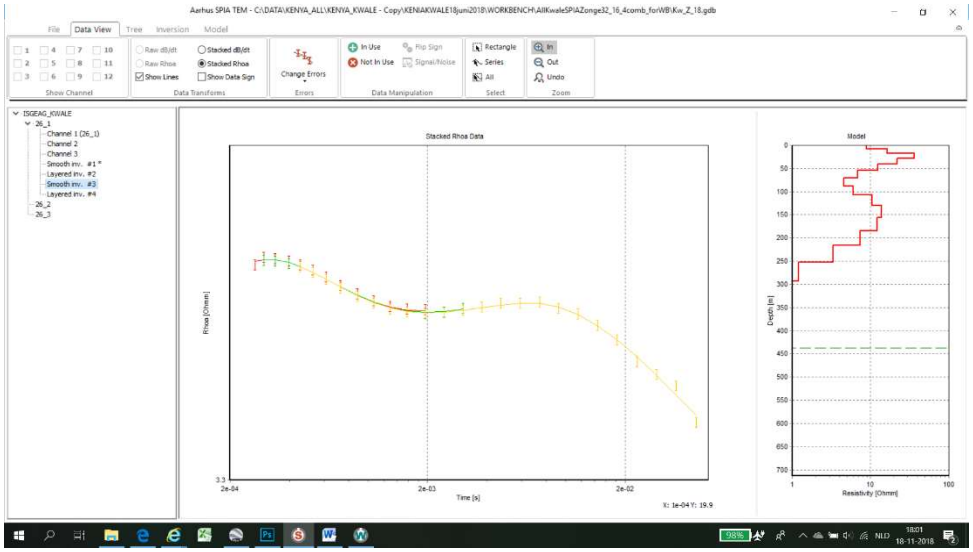


Figure 38. Integrated SPIA inversion of 4Hz, 16Hz and 32Hz Zonge sounding data. The inversion gives a better solution, but still the high resistivity top layer is missing and the depth of the first low resistivity layer is not accurate.

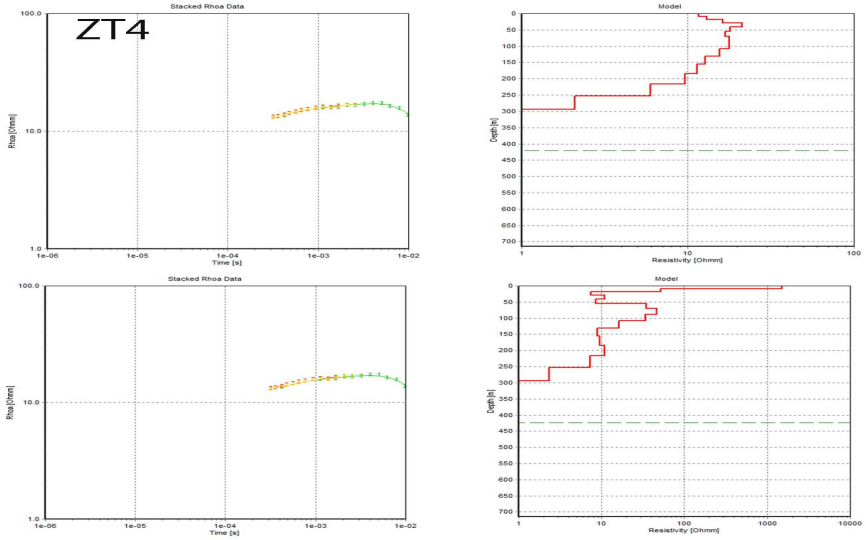


Figure 39. Example of a difference between constrained and unconstrained smooth model (Zonge)

KenGen was asked to carry out the integrated inversions for all the Zonge soundings with their own software WINGLINK, but the results have not yet been received by the other partners.

5.3 Results near Borehole 3 (BH3)

Borehole 3 is a good reference and starting point for the interpretations of the soundings because, (with compliments of Base Ltd), reliable geological and resistivity (downhole electrical) log were made available for this borehole (BH3). In this paragraph also other issues of the inversion process will be discussed.

As a start to the interpretation process, a WalkTEM measurement close to BH3 was verified against these existing logs. Please keep in mind that the resolution of the TDEM sounding and the resistivity log are completely different. The vertical resolution of the resistivity log is much higher than the TDEM sounding and laterally, the log gives very local resistivity information of the first meters around the borehole surface. TDEM on the other hand integrates much more sub surface area, increasing with the depth and the loop size.

The results are illustrated in Figure 40. Kindly note that the borehole geo-log is not done at exactly the same location as the resistivity log: the resistivity log is taken in the BH3 piezometer at 50 m north of the production borehole BH3. There is a clear depth-shift between the production borehole lithology log and the resistivity log of the piezometer, in particular of the shallow clay layer.

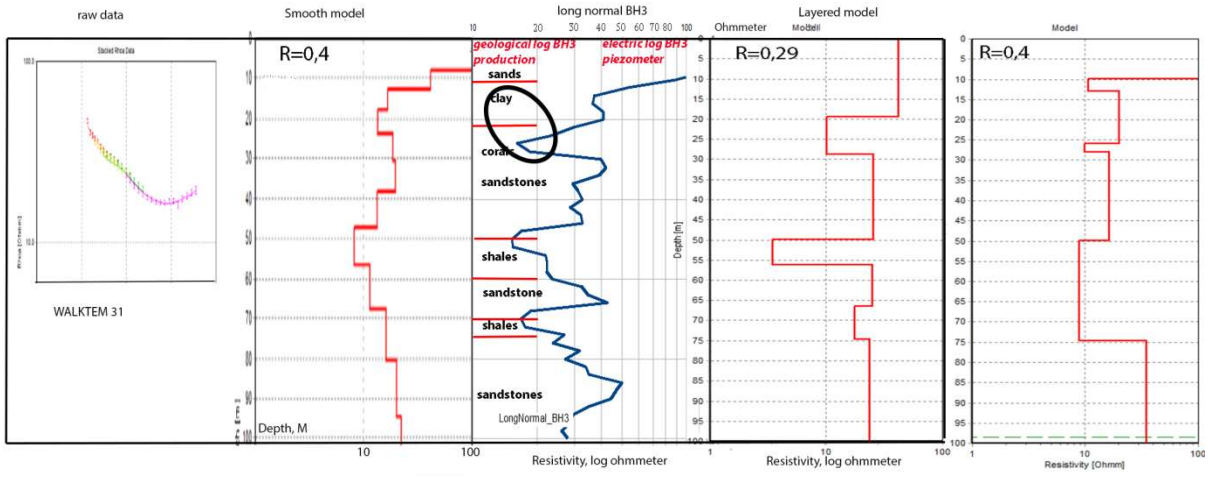


Figure 40. WalkTEM sounding number WALKT31, close to BH3 inverted with a model Based on the borehole log. From left to right: TDEM measured data, smooth model, lithology and LN resistivity log info BH3 and two versions of interpreted layer models.

The layered inversion was carried out by fixing the depths according to the low resistivity clay and shale zones in the drilling data and optimizing the resistivity. The residual (or fit) of the two model alternatives was 0,29% and 0,4%, which are both good.

These two models illustrate the problem of equivalence: in the first alternative the shallow clay is concentrated in one layer and the deeper shale layers are split into two layers, giving a slightly better fit. Note that in the geo log of BH3, the sandstone layer in between the two shale layers is marked as the top of the Mazeras Formation, marked by the finding of petrified wood in the drilling cuttings.

In the later time windows (the deeper zone - say below 90 m) the smooth model does not show much variance in resistivity, meaning that the resistivity contrasts are too low to discriminate thin layers. The smooth model itself suggests a 5-layer model concept. Verification with the drilling data indicates that the model could be extended to 7 layers. The result shows a dominant low resistivity layer of the (Jurassic) shale zone at 50 – 60 m overlying the top of the fractured (Mazeras) sandstone aquifer and the low resistive (Pleistocene) shallow clays at 20 m. Also note that the sounding cannot 'see' the very high resistivity (> 1.000 Ωm) dry sand topsoil as TDEM is based on induction: the method particularly finds low resistivity zones ('conductors') below high resistivity layers.
The Base BH3 is a unique case, where excellent borehole information and even a reliable resistivity log were available. The borehole resistivity log and excellent lithology data give essential and detailed information that is extremely useful for the verification and the interpretation of TDEM sounding. As an important observation (confirmed by the resistivity log), the resistivity of the Mazeras sandstone

formations is much lower (typically around 30 Ωm) than often assumed in the literature. The reason for this is not yet clear, it may be due to clays, silt or conducting minerals in the sandstone matrix, which would reduce the matrix resistivity.

An important observation is that with a decreasing distance of the soundings towards the powerline that runs along the boreholes, the standard deviation of the time windows increases, thus implicating a decreasing of the DOI. On the other hand, WALKTEM 31, located close to Borehole 3 and the powerline (<<100m) still fits very well to the borehole logs. It is therefore concluded that, although there will be an effect of powerlines on TDEM data, the severity and lateral extend of this could not be established. There was not enough time in ISGEAG field to explicitly investigate and quantify the effect of powerlines. In Figure 41 below, borehole lithology information from three Base boreholes (BH2, BH3 and BH5) are compared to the smooth inversions of nearby WalkTEM soundings.

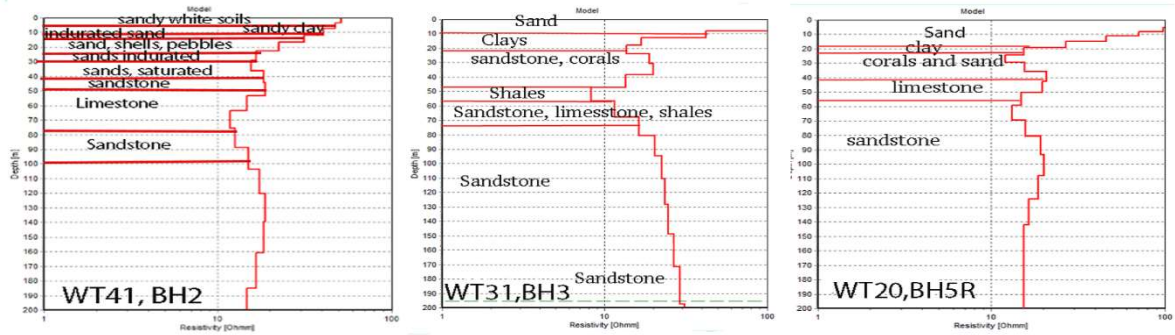


Figure 41. Lithology of Base boreholes BH2, BH3 and BH5R compared to smooth WalkTEM models of nearby soundings

In general, the pattern of the WalkTEM soundings is consistent, showing two zones with a relative low resistivity. The first zone represents the shallow Pleistocene clays at variable depths of 10 – 35m. The second zone is present in all the soundings at depths of 50 – 70 meter, correlating with the shales/limestones of the Jurassic Mtomkuu and Kambe Formations. The next step in the interpretation process is to compare the inversions of the other soundings along the transect close to the borehole (BH3) to evaluate the lateral change, see Figure 43 on the next page.

The smooth inversion shows distinct changes in resistivity along the profile at comparable depths. This correlates with the lateral extension of the low resistivity (Jurassic shales) zone. The smooth models also indicate a separate shallow clay layer at 15-25 m showing up in WalkTEM 30, 31 and 32. Relatively high resistivities are found at depths starting at 80m, in accordance with the depth of the Mazeras sandstone aquifer and the screened sections (84 – 99m) of production BH3. At the second row of pictures in Figure 43 the smooth models are presented in layers, using a visualization method as illustrated in Figure 42 on the next page.

After the evaluation of the smooth inversions, a layered interpretation was carried out, using a layer concept that is consistent with BH3. This can be done either by fixing the resistivities or by fixing the depth (or both) depending on the borehole information. As in VES sounding interpretation, using additional layers will lead to a better fit (eventually leading to the smooth model) but will not necessarily represent the reality better. The additional shallow clay layer (Pleistocene Kilindini Formation) that was indicated in WalkTEM 30 – 32 indeed improved the fit of the layered models. Other soundings did not show improvement on this layer.
The differences between the layered inversions clearly show the issue of equivalence and the importance of relating the interpretation to drilling data. Equivalence can be tested by comparing various concepts for the layer model. Figure 44 gives an example of such comparison on WALKT21 (BH5 transect). The smooth inversion indicates an effect of the shallow clay layer. Two different layered inversions were carried out, with and without the shallow clay layer. The fit of the two alternatives is the same and it becomes clear that the shallow clay layer is much less evident than the second (shale/limestone) layer. In the layered inversions, when a second clay layer can be modelled with the same fit compared to the 'no shallow' layer option, and there is no clear indication in the smooth inversion, the option without the shallow clay layer has been adopted.

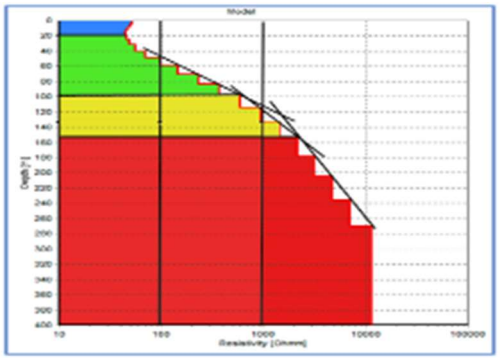


Figure 42. Example (ISGEAG, Kajiado) of a simple visualization method, that was applied on the smooth model data (2nd row in Figure 8). The color scheme is based on changes in the gradient (resistivity versus fixed depth).

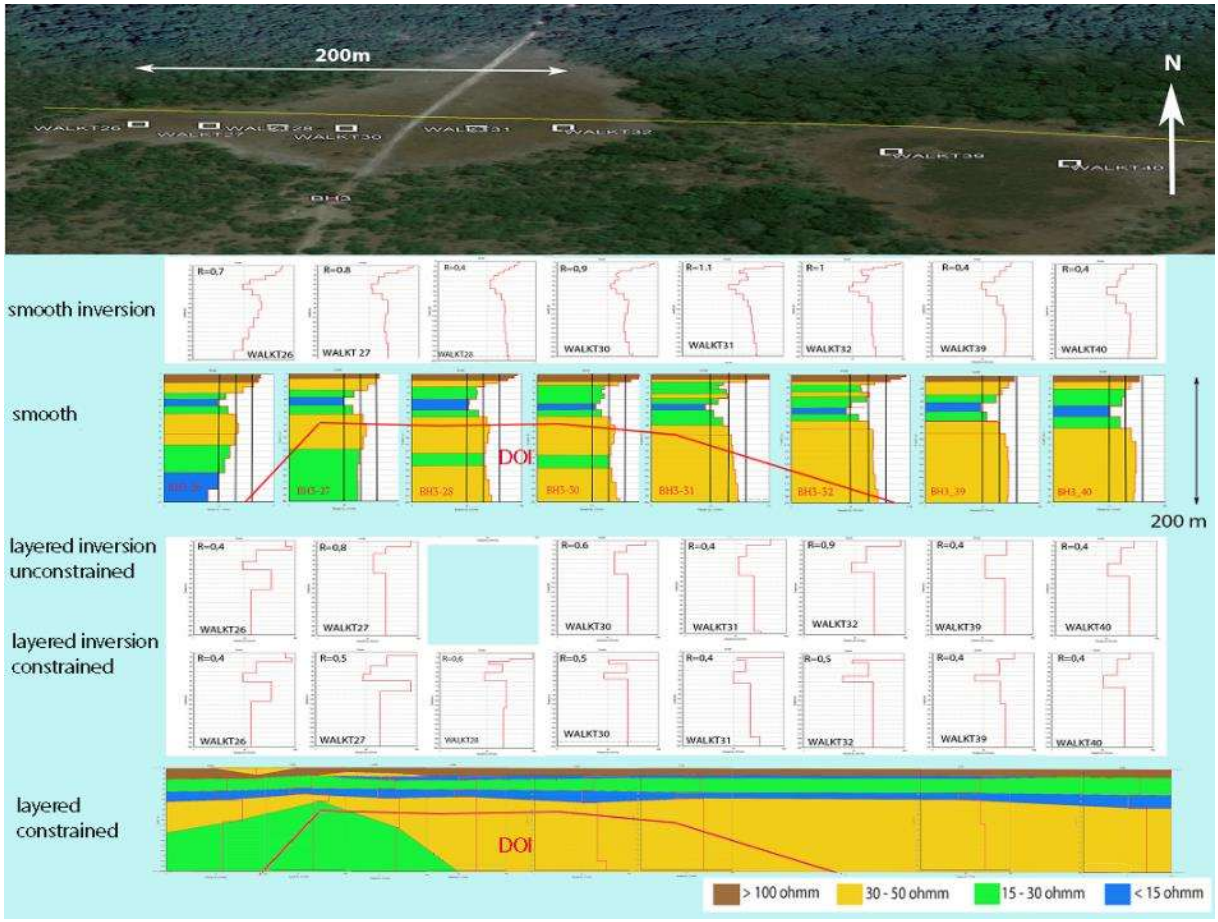


Figure 43. Several stages of interpretation of WalkTEM soundings at transect borehole BH3. The layered inversion with constraints related to the geological log of BH3. The fit is indicated as R (%). As a red line the DOI calculated with the automatic 2D workbench software also indicated

In Figure 45 on the next page, the final profile is presented for the BH3 section. The profiling is done by interpolation of the layer models and (lower picture) by integrated data inversion using the Aarhus University Workbench. The pictures also give the DOI according to the selected points Based on the standard deviations, illustrating possible interference caused by the underground power line were the DOI decreases. It is obvious that automatic contouring influences the picture and at that information is being last by applying layered models.

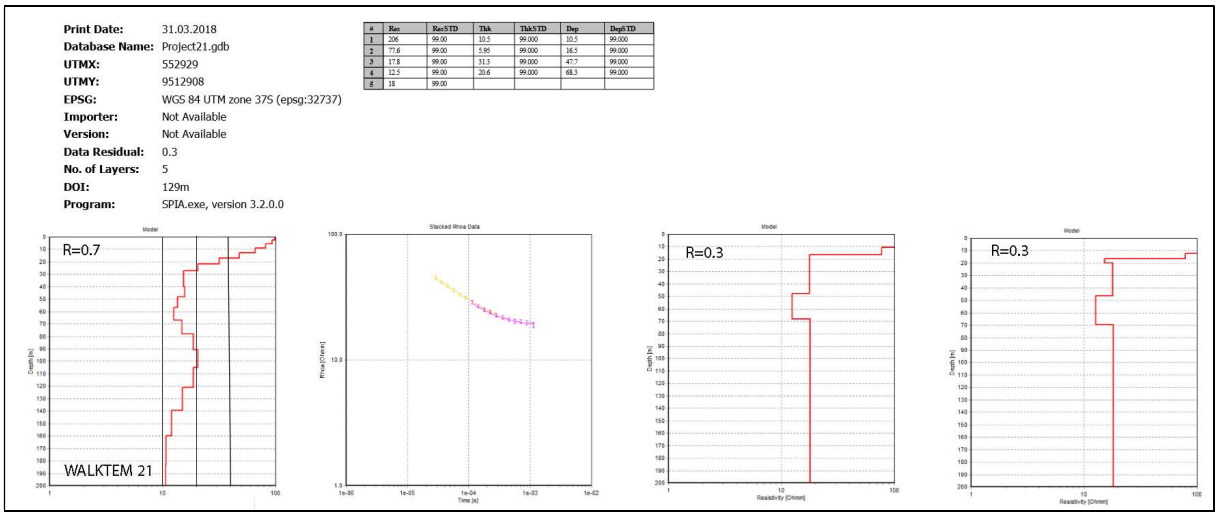


Figure 44. WALKT21 (BH5 transect), comparison of smooth and layered inversions with and without the shallow clay layer. The shallow clay may exist, but is much less significant than the second low resistivity layer at 60m.

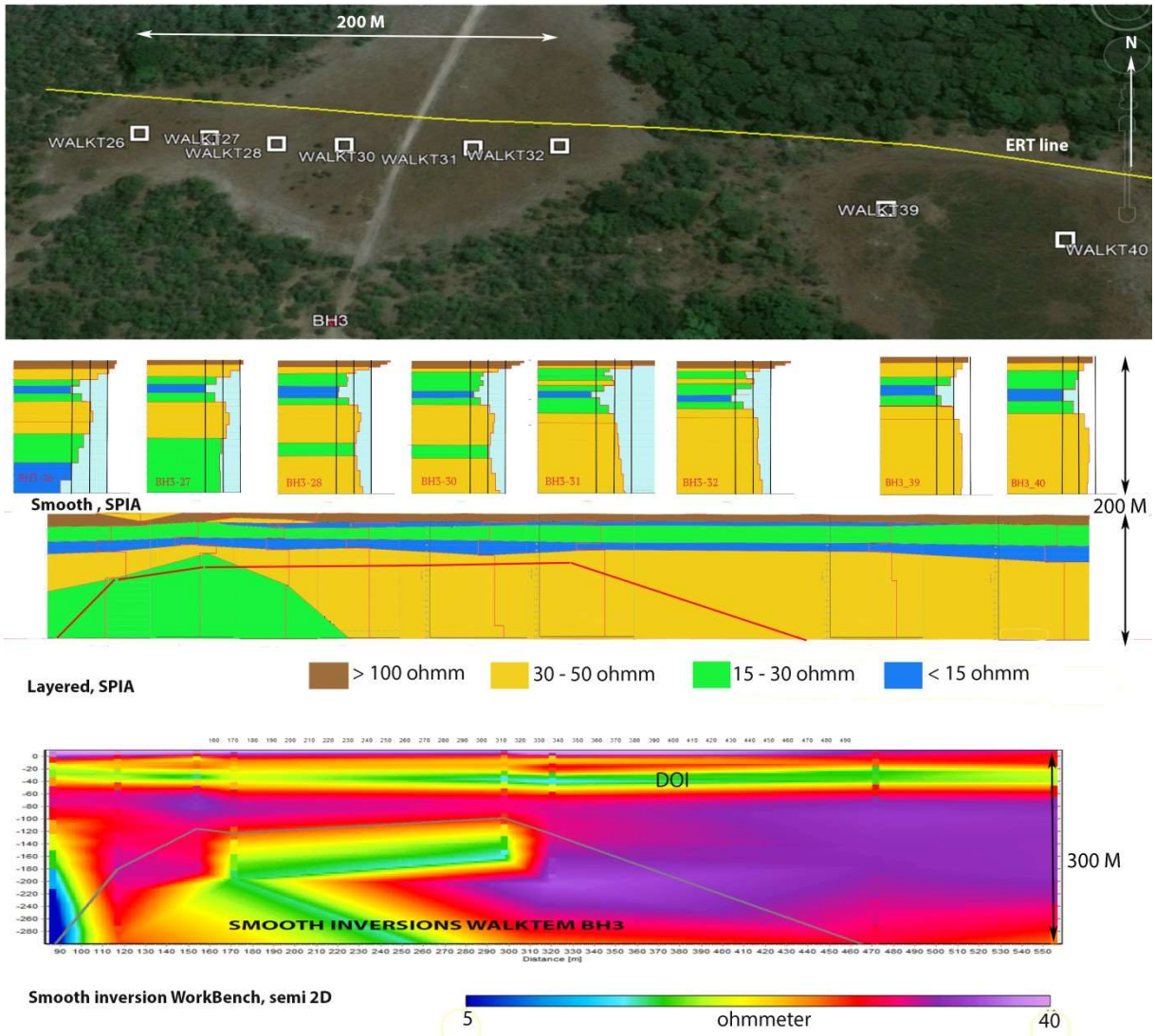


Figure 45. WalkTEM BH3 profile: smooth inversions, Layered inversions (SPIA) and Smooth semi 2D profile (WorkBench).

The same procedure has been applied for the Zonge TDEM soundings (see Figure 46 below). With the ZONGE soundings, the layered modeling and interpolation (bottom picture Figure 46) was done - as an

example – by the online, very basic freeware program GEOMODEL (www.geomodel.info). Geomodel was used with ZONGE TDEM, as an alternative because the semi 2D inversion with WinGLINK, (used by KENGEN) was not (yet) available.

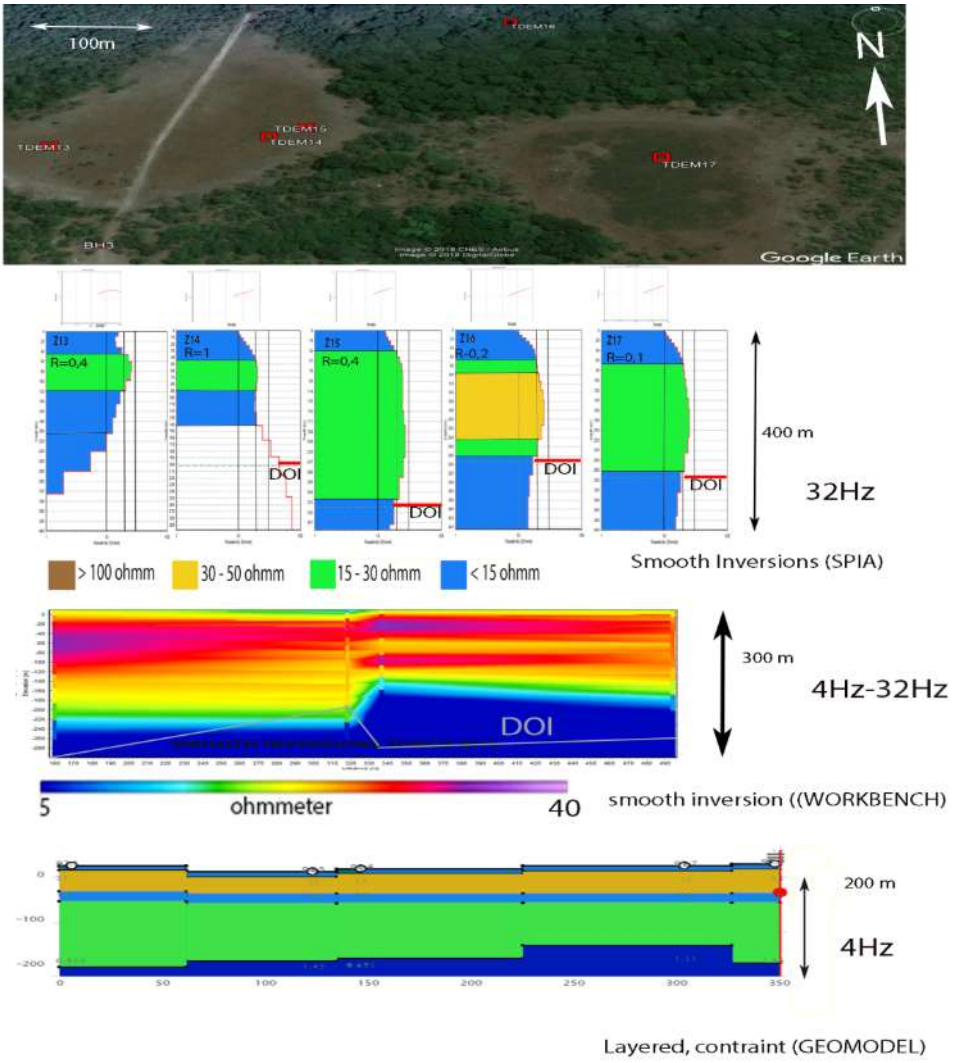


Figure 46. Smooth and layered inversions Based on Zonge soundings. Note that the top graph is from the 32Hz and the middle and lowest are from the 4Hz data

In this image the Zonge smooth inversions are unconstrained. All inversions show incorrect solutions when compared with the borehole information and the WalkTEM results, due to the low resolution (amount and distance of the time windows), the large transmitter loops and the lack of resistivity contrast. The results for the 4Hz Zonge data are reliable for the deeper zone, showing a transition to very low resistivity at around 200 - 250 m. Most of the WalkTEM soundings did not reach this exploration depth because of the smaller (chosen) loop-size. The WalkTEM soundings that did reach such depths also indicated a decrease in resistivity, consistent with the Zonge 4 Hz results.

From these results it becomes clear that besides the choice of instrumentation, the setup of the instrumentation, the selection process of the raw data for inversion and the software in use, considerably influences the final "picture" of geological and hydrogeological situation of the area.

5.4 Results near Borehole 5 (BH5)

The WalkTEM results for the BH5 transect are shown in Figure 47. As in the BH3 profile, there may also be influence of the power line: the green colored zone of relative low resistivity in the middle of this figure may be due to the disturbance effects caused by a North-South oriented, high voltage power cable. The cable at this location is above the surface north of the crossing point and underground south of the crossing. Unfortunately, time did not allow us to further investigate the effects in detail, e.g. by shutting off and on the power. As explained above. The DOI is depending on the selection late raw data points in use for inversion; this selection is based on the standard deviation between the repeated series of soundings on the same spot (repetitions), as presented by error bars in the raw data.

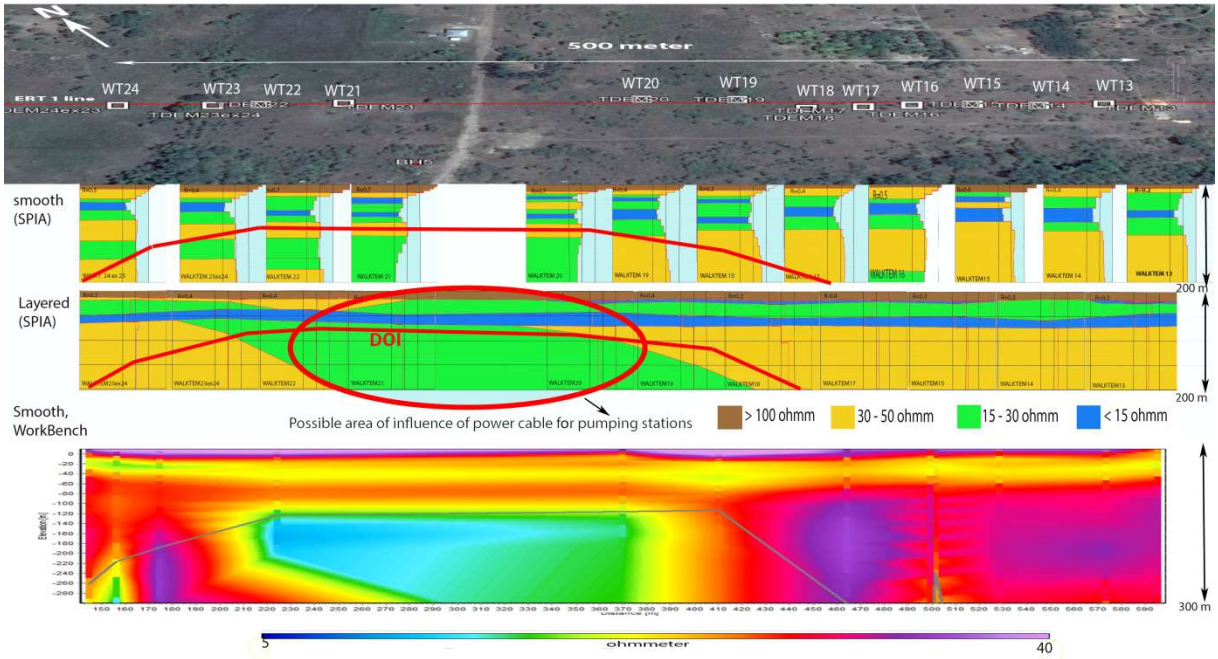


Figure 47. Inversion results of BH5 WalkTEM transect, both smooth (above) and a 2D profile Based on layered inversions with SPIA 1D, and semi 2D WORKBENCH

The BH5 section basically shows the same model concepts: non-continuous presence of the shallow Pleistocene clay layer and a continuous low resistivity zone of the Jurassic shales/limestones zone, overlying the Mazeras sandstone aquifer, having resistivities in the order of 30 – 40 Ωm.

The Zonge soundings results show the differences between the inversions on 32 Hz and 4Hz data. As in the BH3 profile, the inversion results for the 32 Hz data give incorrect models for the low resistivity layers in the first 100m and are not reliable for the deeper zone and. The Zonge (4Hz) data show an overall transition to low resistivities at greater depths. See also Figure 48 on the next page.

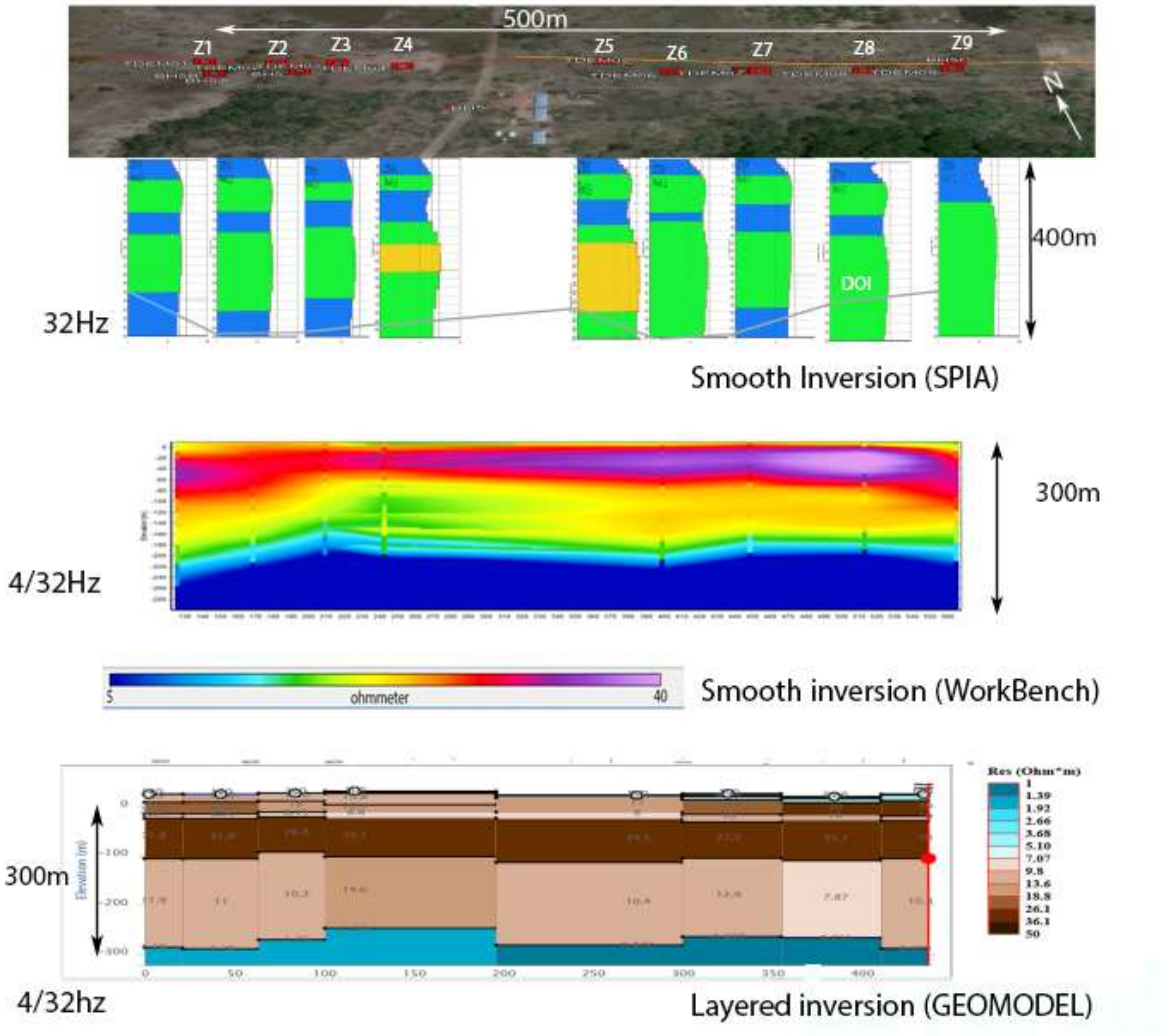


Figure 48. 32 Hz and 4Hz Inversion results on the Zonge BH5 transect. Both smooth and layered inversion results

5.5 Results near the SWIM borehole

WalkTEM and Zonge soundings were carried out along a transect perpendicular to the coast, that extended from the SWIM borehole in the east to a point 600 meters west of BH5. Locations and results are presented in Figure 49 (WalkTEM) and Figure 50 (Zonge).

The results give clear indications for the presence of saline groundwater water at the coast. The aquifer system up to 90m consists of (multiple) shallow aquifers, related to recent and older Pleistocene coral reef sediments up to at least 90 m. According to the SWIM borehole EC drilling data (Figure 51), the aquifer system can be subdivided into 4 (coral) sub-aquifers.

The shallow aquifer zone must be underlain by a confining layer at depth of 60 – 110/120 m, consisting either of low permeable coral limestone and (may be) Jurassic shales/limestones. Up to 90 m depth however, no shales or (Kambe) limestones were indicated in the SWIM borehole. So, most likely the confining layer just consists of low permeable Pleistocene coral in the deepest zone of the SWIM borehole. The top of the deep aquifer is well marked by the TDEM soundings at 110/120 m depths, as a transition from very low to higher (order 40 Ωm) resistivities. This could well be the coastal extension of the deep Mazeras sandstone aquifer.

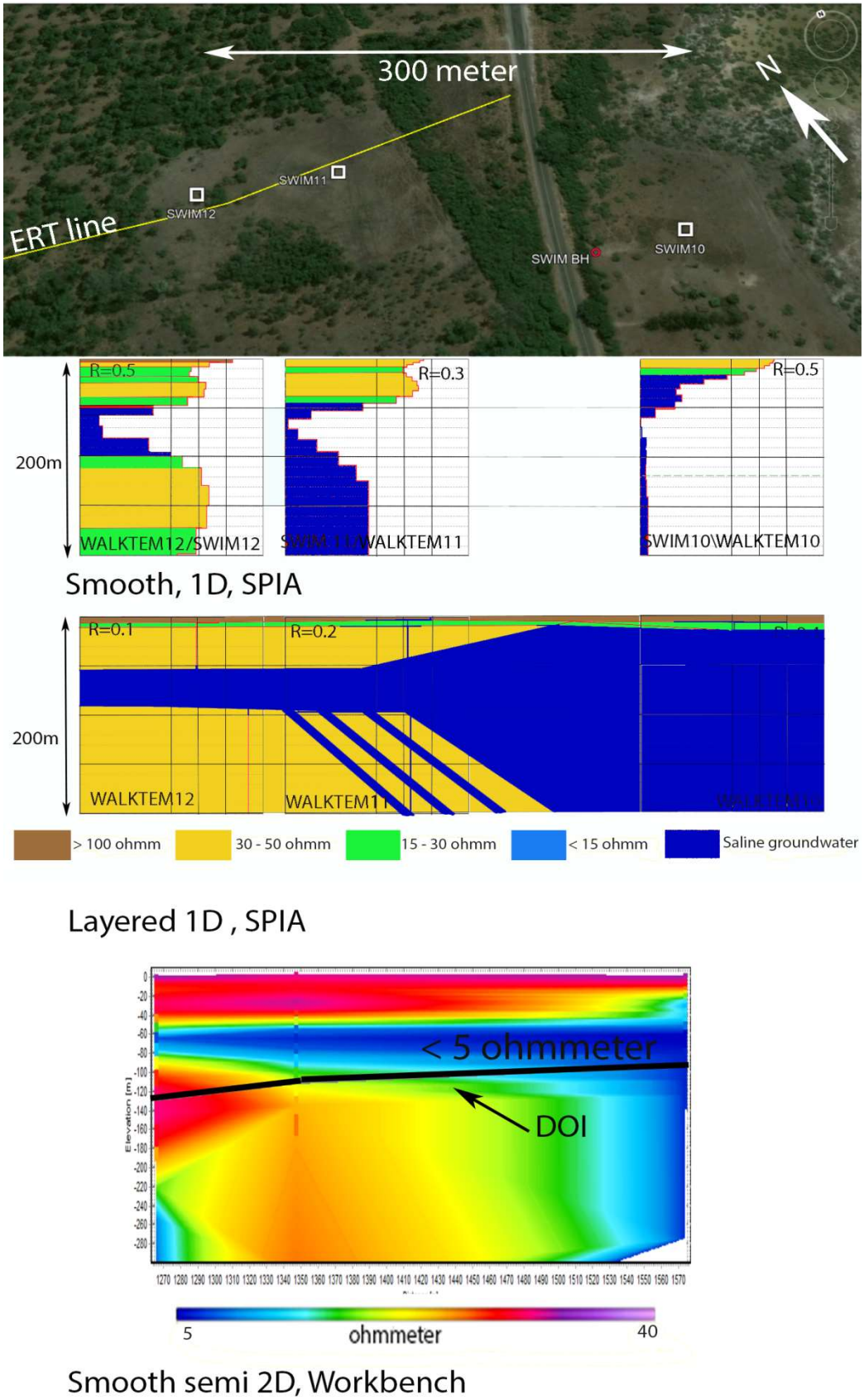


Figure 49. WalkTEM profile close to the SWIM borehole perpendicular to the coast, smooth inversions (SPIA), Layered (SPIA) and semi 2D smooth (Workbench).

The inland propagation of saline water (< 5 Ωm) is restricted to the shallow aquifer, reaching (at least) up to the Zonge sounding TDEM18 (Figure 50). To what extent this is progressive saline intrusion due to groundwater abstraction is not known; this would require additional monitoring on water conductivity and groundwater gradients on the east side of the road.

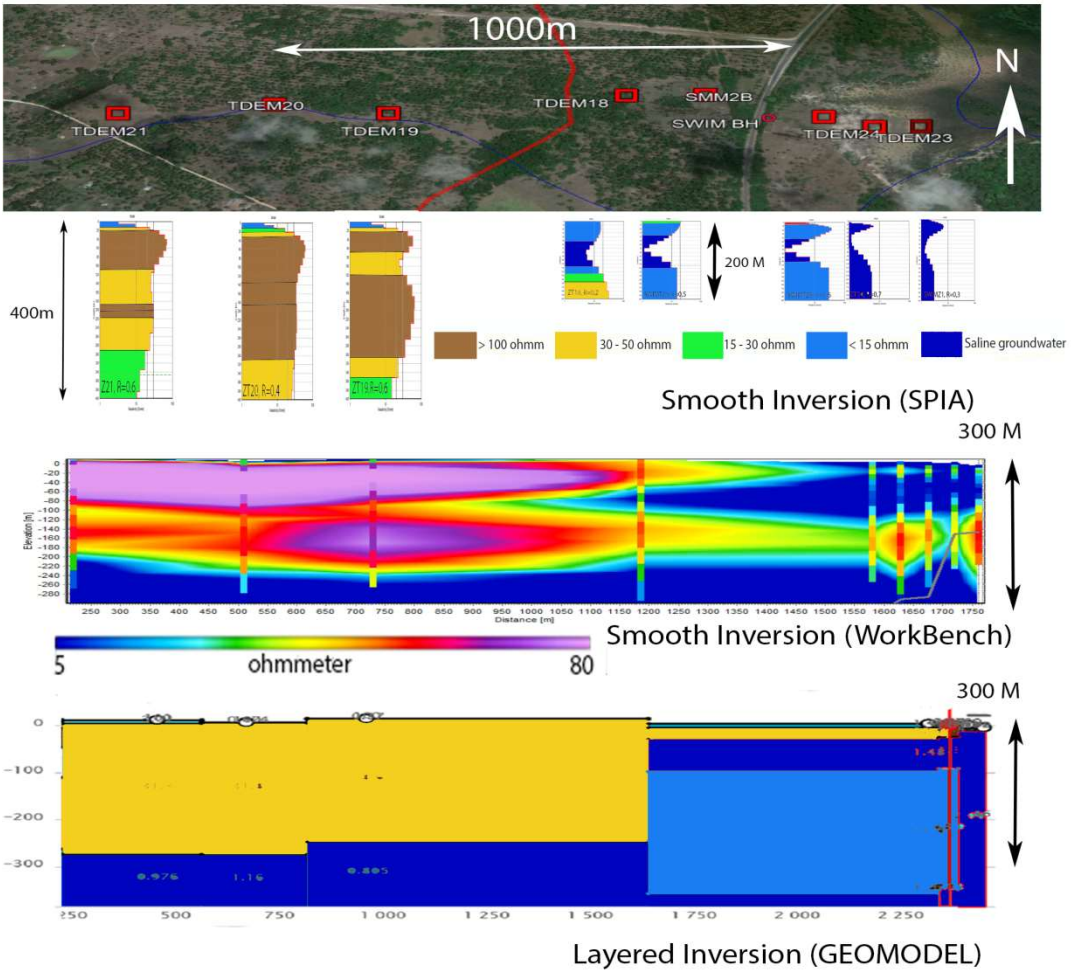


Figure 50. Zonge profile perpendicular to the coast, smooth inversions (SPIA), semi 2D smooth inversion (workbench) and layered inversion (GEOMODEL).

The deep aquifer carries fresh water (Zonge TDEM18 and WalkTEM SWIM12), becoming brackish just west of the main Ukunda to Ramisi road in WalkTEM SWIM11. East of the road the salinity of the deep aquifer is not completely clear: the WalkTEM sounding SWIM10 indicates saline water all across the depth interval, but the three Zonge soundings east of the SWIM borehole indicate resistivities of more than 10 ohmm, reducing to 5 ohmm further east. Since the DOI of Zonge is larger than WalkTEM, the deep WalkTEM data may be incorrect and it is not impossible that the deep aquifer still has some brackish or even fresh water as also suggested in the smooth (Workbench) inversion profile in Figure 51. This may indicate deep brackish groundwater outflow under the Ocean as 'submarine groundwater discharge' (SGD).

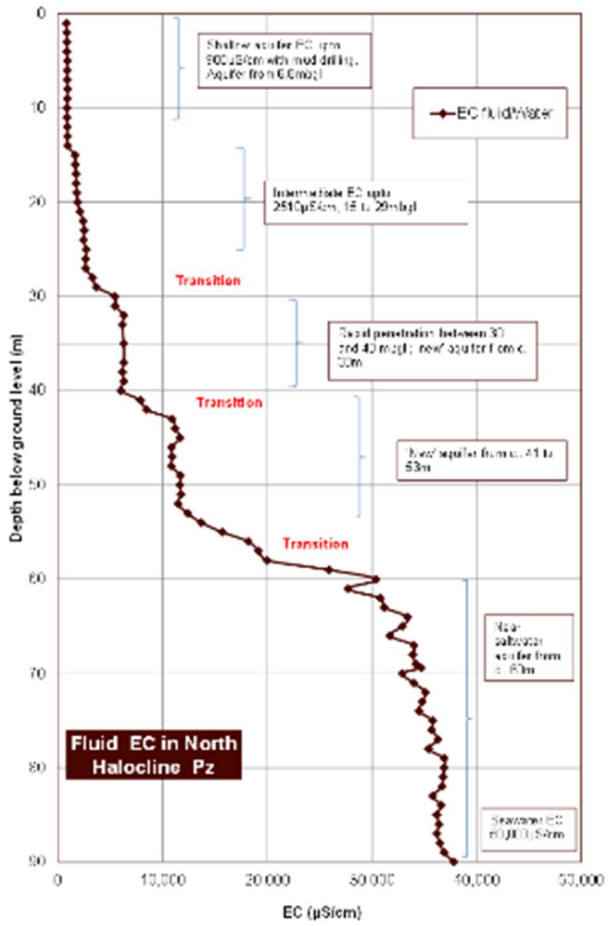


Figure 51. EC variation with depth while drilling the SWIM BH. The borehole was drilled entirely within Pleistocene coral limestones (data courtesy of Base Titanium Ltd/Mike Lane, Rural Focus)

In Chapter 7 the comparison between the different used geophysical equipment and measurements will be discussed in more detail.

5.6 Additional WalkTem soundings outside the project area

On the request of Rural Focus and Base Titanium Ltd, 7 additional WalkTEM soundings have been carried out outside the project area at 2 locations to assess the local saline/fresh groundwater interface. The area was more agricultural with irrigated sugar cane fields. Because very limited additional information was available, only smooth inversions were calculated.

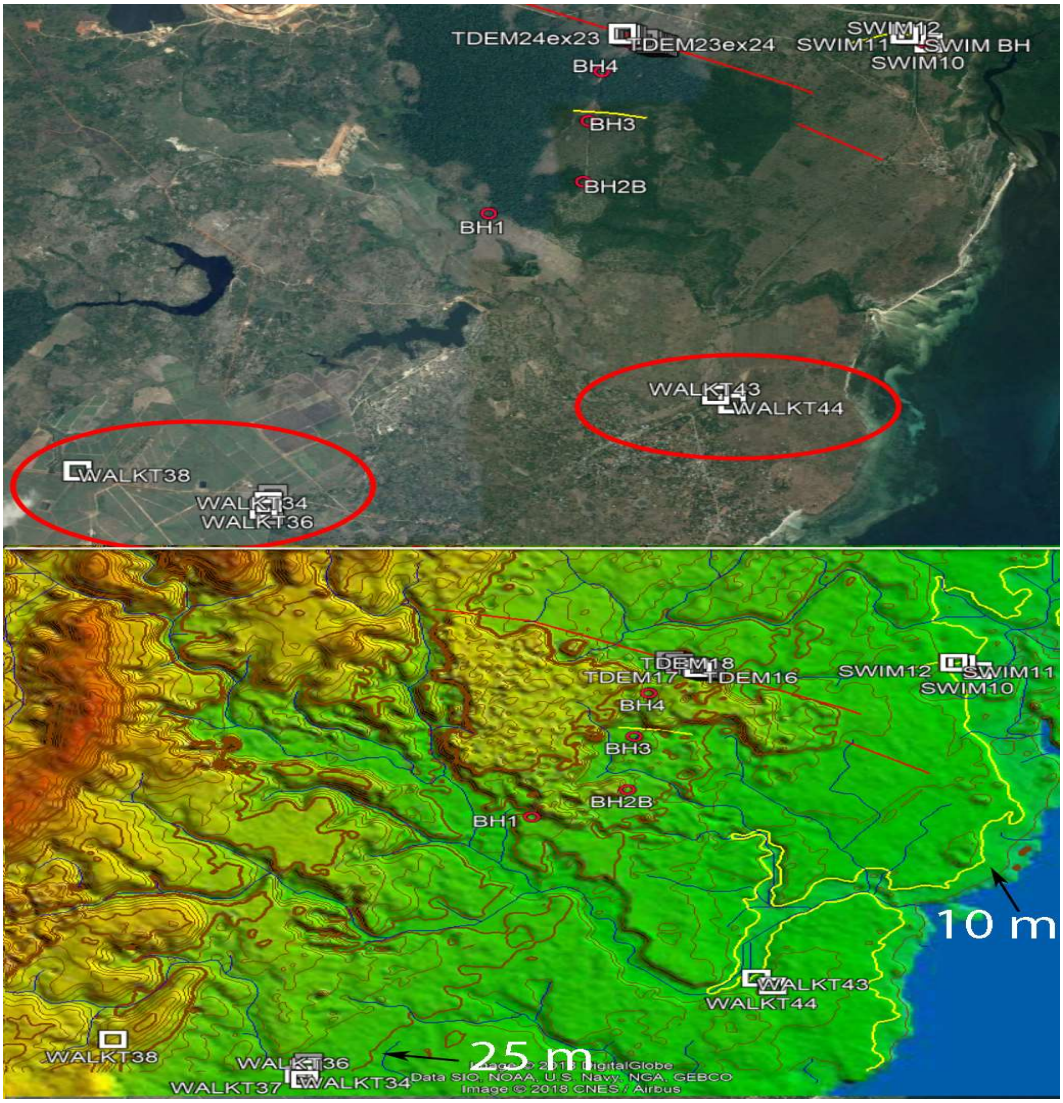


Figure 52. Location of the additional WalkTEM measurements

5.6.1 Vingujini, WalkTEM 43, 44

The first location was northeast of Vingujini, close to borehole GD33. At this borehole it was observed that the water from the borehole became more and more saline over recent years. The monitored water level (Figure 53) shows a dropping trend towards levels even below mean sea level.

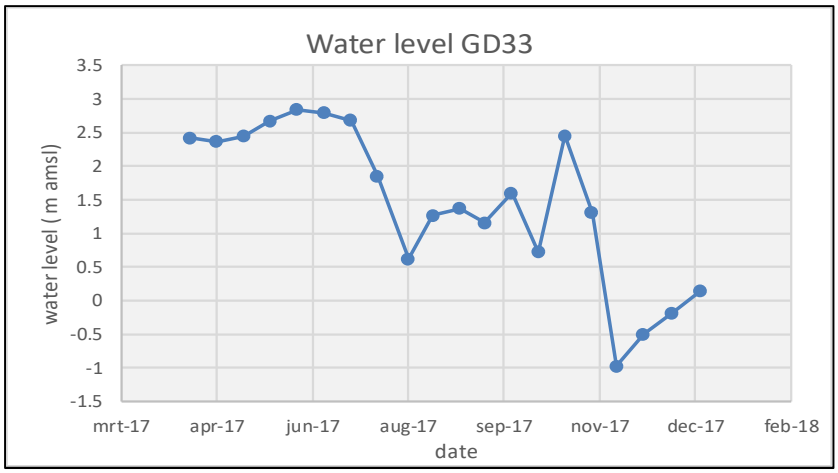


Figure 53. Measured water level (in meters above mean sea level) in Vingujini GD33

Two soundings were done, numbers 43 and 44. Sounding 43 was close to the borehole and a major (Mukurumudzi) river valley to the west. Geologically, the borehole was drilled (30,3 m) in coral limestone (see Table 1). Sounding nr. 44 was taken on the other side of the main road towards the coast. The locations are given in Figure 54, the results in Figure 55.

Table 1. Borehole GD33 drilling information

Date works started	-	5/01/2011 – 12/01/2011
Total depth	-	30.35m
Water struck level	-	13m
Water Rest level	-	11.33m
BH drilled diameter	-	355mm (14")
Geological Strata	-	Coral limestone
Conductivity measurements (taken at the respective depth intervals)		
22m	-	685micro-siemens/cm
26m	-	680 micro-siemens/cm
30m	-	860 micro-siemens/cm



Figure 54. Vingujini additional sounding locations

Despite the limitation of only two soundings, the decrease of resistivity towards the coast is obvious. The elevation (Google Earth) is at 14 m asl. From this it may be concluded that saline groundwater has intruded up to this location, 1,3 km from the coastline. The possibility that groundwater wells become more saline in this part of the coast area is a significant potential threat. Comparable to the SWIM borehole site, the propagation of saline water is limited to the shallow aquifer. The sounding WalkTem 43, close to the river valley indicates also deeper saline groundwater at 190 m (if this is not a low resistive shale or clay layer).

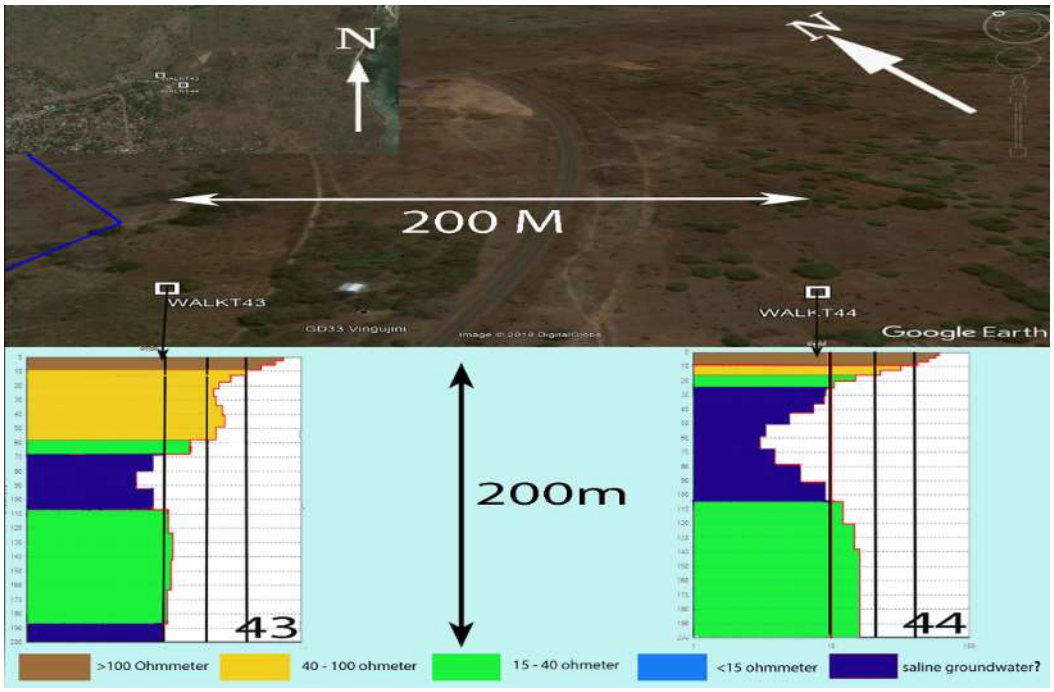


Figure 55. Results Vingujini

5.6.2 Milalani, WalkTem 34 - 38

The second location was more inland, 1700 m west of Milalani, near the valley of the Lukungwi River, within a paleo channel (Ferrer *et al.*, 2019). The elevation is at 25 masl. In this area a lot of groundwater is being pumped by KISCOL for sugar cane irrigation. The locations are given in Figure 56, the results in Figure 57.



Figure 56. Milalani, additional sounding locations

WalkTem soundings 34, 35, 36 and 37 were conducted in and near the Lukungwi river valley. For referencing, one additional sounding (38) was conducted 2 km to the west, at Kidzumbani at an elevation of 70 masl. Sounding 36 was close to an existing borehole. All soundings, except WalkTem 38, are supposed to be in the paleo channel. WalkTem 38 may be beyond the western edge of the paleo channel, on Pliocene Magarini Formation overlying fresh Mazeras (pers. comm. M. Lane). The results that are presented in Figure 57, indicate salinization from north to south. The reference sounding nr. 38 reveals much higher resistivities (> 100 ohm), consistent with the different geology.

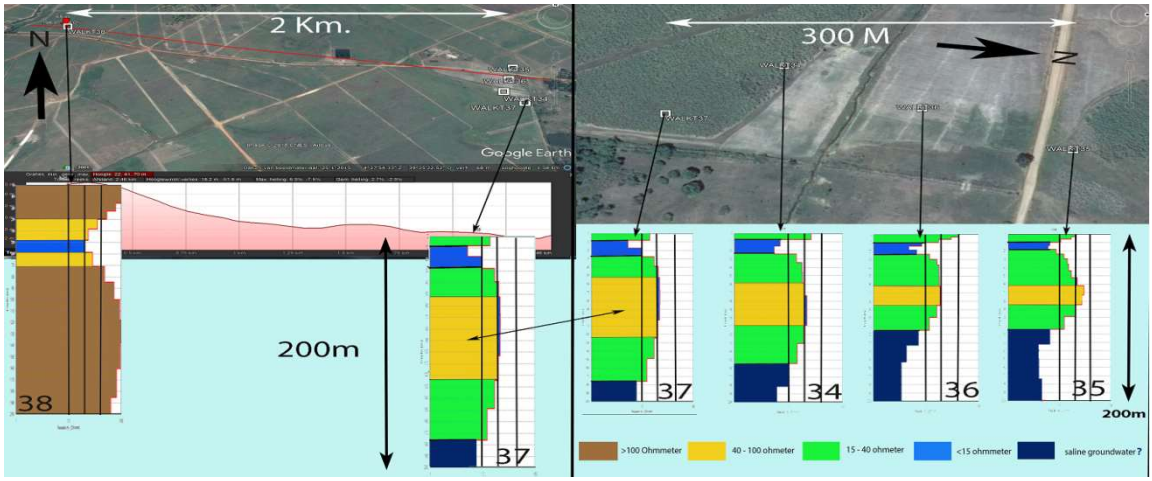


Figure 57. Milalani additional WalkTEM sounding results

Without additional information from boreholes and groundwater quality, the low (deep) resistivities could also be clay/shale layers. The consistency of the low restistivity pattern from WT35 to WT37 intrusion of saline water from north to south is the most likely explanation. This means that the paleochannel contains connate saline groundwater from an earlier geological period. The saline groundwater situation may also be related to groundwater abstractions in nearby large KISCOL sugar cane estates. For ISGEAG this was only a one-day exercise and we don't have the information to further assess the situation in more detail.

5.7 Conclusions

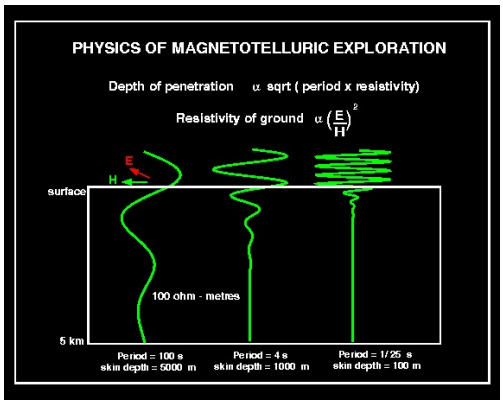
Overall conclusions and discussion on the results in relation to the use of time Domain Electro-magnetics (TDEM) and the WalkTEM equipment more specifically during the Kwale field campaign is being discussed in paragraph 8.1.6 of Chapter 8.

6 Application of Audiomagneto-telluric (AMT) Soundings

6.1 Introduction of Audiomagnetotellurics (AMT) method

In the Audio magneto telluric (AMT) method, the electrical conductivity structure of the subsurface is imaged by using the Earth's natural electromagnetic (EM) fields as a source. Berdichevsky & Dmi-triev 1976). It is a higher-frequency magneto telluric technique for shallower investigations with less depth of penetration than the broad band magneto telluric, and often take only about one hour to perform (but deep AMT measurements during low-signal strength periods may take up to 24 hours) and use smaller and lighter magnetic sensors. Most of the energy in the audio frequency EM spectrum (1 to 10 000 Hz) is due to the energy released in lightning discharges. This energy propagates all over the world within the Earth–ionosphere waveguide (Garcia & Jones 2002) and forms the source field for the AMT method.

The primary incident EM fields propagates vertically downward as planar in geometry and travel diffusively in the earth so that high frequency (short wave- length) waves penetrate a relatively short distance, while low frequency (long wavelength) waves reach greater depths (Figure 58; (a) Penetration of EM waves (adopted from Karen Rae) and Figure 58 (b) Conductivity of rocks (adopted from Richards 2018)). Apart from the frequency, the depth of penetration of an electromagnetic field also depends upon the electrical conductivity of the medium.



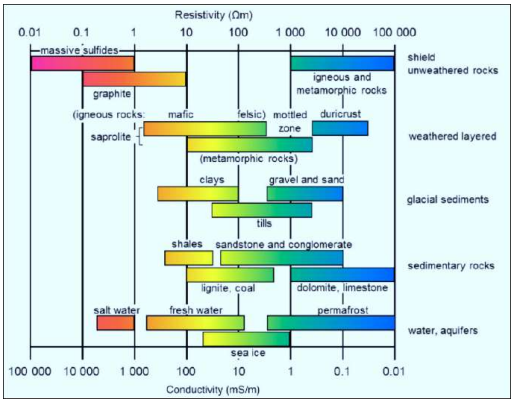


Figure 58. (a) penetration of EM waves (adopted from Karen Rae), and Figure 58. (b) Conductivity of rocks (adopted from Richards, 2018)

Typically, AMT involves simultaneous measurements of two surface components of the electric field (Ex and Ey), made using short potential dipoles grounded at each end and three components of the magnetic field (Hx, Hy and Hz) measured using induction coils or fluxgate magnetometers at shorter periods (<1 s). These electric and magnetic fields are acquired as time series (Figure 59) that require Fourier transformation to the frequency-domain before the determination of the transfer functions between the horizontal components of the magnetic (H) and electric (E) fields.

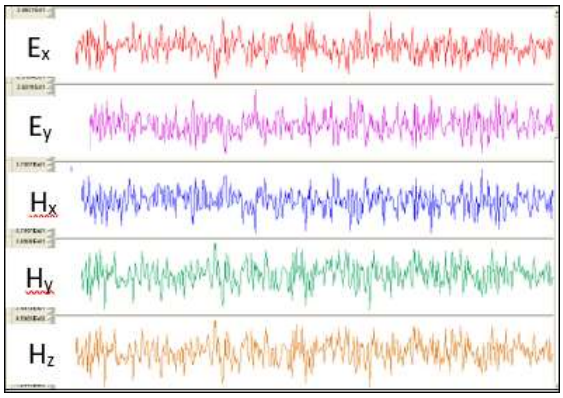


Figure 59. Graphical display of the time series of the electric (Ex, Ey) and magnetic fields (Hx, Hy, Hz) as recorded using phoenix MT equipment

The transfer functions normalize the measured electric field response for the strength of the surface magnetic field in the frequency domain. A linear relationship exists between the measured horizontal components of the EM field (magnetic and electric field components. By assuming plane wave excitation, orthogonal components of H and E are linearly related through a complex impedance tensor Z (Cagniard 1953).

At varying frequency, the complex off-diagonal impedances Zxy and Zyx plots graphically as apparent resistivity and phase curves.

6.2 Field Set up

Two sets of MTU-5A equipment from Phoenix geophysics limited that comprises of a data logger, magnetometers (magnetic sensors), electrodes and a GPS was deployed for AMT data collection. See also Figure 60 below.


Figure 60. AMT/MT equipment from Phoenix Geophysics Ltd (electrodes, gps unit, sensor coils, cables and MTU-5A unit).

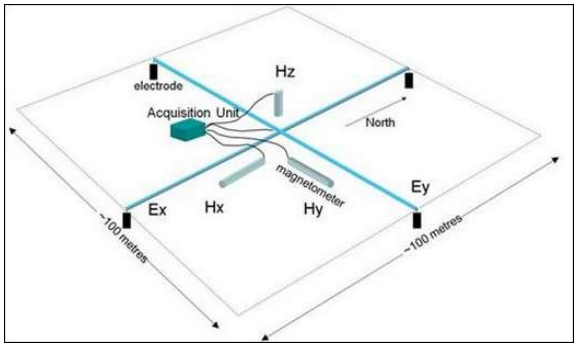


Figure 61. Layout for AMT recording (adopted from OPEN energy)

Equipment installation for measurements:

- The porous electrodes were installed in shallow moistened holes to ensure that there is conductivity between the ground and the pot. When installed, the electrodes form four quadrants with the data logger and the battery at the intersection. Three sensors (Hx, Hy and Hz) are installed in these quadrants with careful leveling and accurate orientation to ensure that they are orthogonal to the electrode lines (Figure 61). Before data collection, confirmation of existence of sufficient conductivity between the electrodes and the ground is performed with an Ohmmeter. In Kwale survey, most of the measurements fell below the 2000 Ωm level, the recommended upper limit. On retrieval, the contact resistance was re measured since it was expected to change immediately after electrode installation. The values of the contact resistance are important during data processing.
- The equipment used (MTU-5A), has capabilities for both AMT and MT data acquisition depending on the acquisition parameters set. For AMT, High pass filters and AC coupling was activated for detection of high frequency signals >1Hz .The data was set to be recorded in only 2 bands with band 2 (1-3KHz) at 2 time slots and band 3 (< 1KHz) at 1 time slots which is adequate for the acquisition period of 1hour. Longer time slots require longer acquisition periods.

6.3 Calibration

Before each data acquisition campaign or survey, the data logger (box), and the sensors (magnetic coils) must be calibrated beginning with the box and then the sensors to ensure that field measurements are traceable to the standard measurements obtained from the calibration of the box and the sensors. Calibration files are very important during data processing.

6.4 Data Processing and Quality

- Acquired data is stored in a compact flash card that is programmed with a standard (STARTUP.TBL) file that is loaded with acquisition parameters and the details of the box serial no and the coils used together with their calibration files.
- On retrieval, the time series data stored in the compact flash is transferred into a PC for archiving and processing using SSMT2000 software from phoenix geophysics. With SSMT2000, the contents of the parameter files are viewed for confirmation and editing.
- The next stage is to process the data to produce Discrete Fourier Transforms (DFTs) from the raw time series data. This converts data from time series to yield frequency domain estimates of apparent resistivity and phase
- The final stage in SSMT2000 involved the processing of DFTs into cross powers. The cross powers are saved as plot files for graphical viewing in MTEditor program from phoenix geophysics limited
- MTEditor merges the cross powers for graphical display of one-dimensional curves. This enables the viewing of different characteristics of the soundings, such as apparent resistivity, phase, impedance, strike direction, coherence, and so on, across the full frequency range acquired. It also provides the ability to remove individual crosspowers from the calculations, so that poor quality data can edited out by masking.
- After all the edits are completed, the data is stored in EDI (Electronic Data Interchange) format that is the industry-accepted format. In this format the data is ready for forward modelling /inversion and interpretation
- Electricity transmission infrastructure and human settlement in the survey area stood as the most common potential sources of interference in the data especially at acquisition frequency of 50 Hz. To mitigate this, sounding sites were located at least 300 m from the power lines and the home states and a line frequency filter of 50 Hz that matches the Kenya power line frequency was activated to reduce the interference.

6.5 Exploration depth.

Audio Magneto tellurics (AMT) utilizes a limited frequency band in the audio range, generally from 0.1 Hz to 10,000 Hz and its penetration is governed by the following equation (after Nabighian 1991).

$$\delta \approx 503\sqrt{(\rho/f)} \quad (m)$$

At this bandwidth, high-resolution inversion modeled resistivity results of up to 1 km depth can be achieved. In the Kwale survey, most of the soundings achieved a penetration depth of between 500 m and 700 m at 32 Hz and 16 Hz sounding frequencies.

6.6 Data Analysis

Upon successful completion of processing, the EDI files are used as the input source for the WinGLink's Data analysis program, an MT Tools program used to edit and analyze individual stations as standalone datasets.
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 inhomogeneities can have a severe influence on the interpretation, ρa-curves are shifted upward or downward giving a wrong resistivity model.

6.7 Results

In Kwale survey, AMT soundings were executed along three profiles labelled as BH3, BH5 and SWIM, refering to the existing boreholes. The AMT sounding stations were located on the same spots as the TDEM stations on each profile to allow for comparison and static shifting of AMT data in case of distortion of AMT data due to cultural noise. The choice of the trend of the traverses was decided based on the geological structures and the location of the three boreholes. The station spacing that was achieved was not regular along the profiles due to the need to avoid home states, power lines, fences and other sources of cultural noise encountered within the survey area. Landowners also declined to offer access permission in their farms, which made it impossible to collect data between the BH5 and the SWIM boreholes. BH3 transect was interfered by a road and an underground power cable that run along the road.

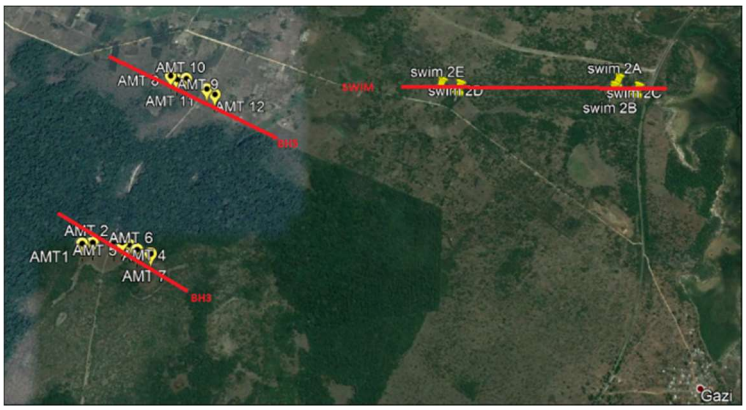


Figure 62. Google Earth image showing the trend of the three AMT profiles

All the transects trended perpendicular to the line of the three boreholes which gave the opportunity to constrain the models with the borehole logs from the wells as well as allow for forward modelling.

The final results are based on 1D inversion models with constrains from the borehole logs from the adjacent boreholes. The1D models from individual AMT data sets along a traverse are combined to produce a 2D pseudo section along the profiles in an attempt to capture the variation of resistivity both laterally and vertically along the traverse. On interpretation, the responses of the geological sections along each profile are first compared with the theoretical (expected) responses of such sections and finally the hydrogeological implication of the resistivity layers as depicted in the 2D pseudo sections.

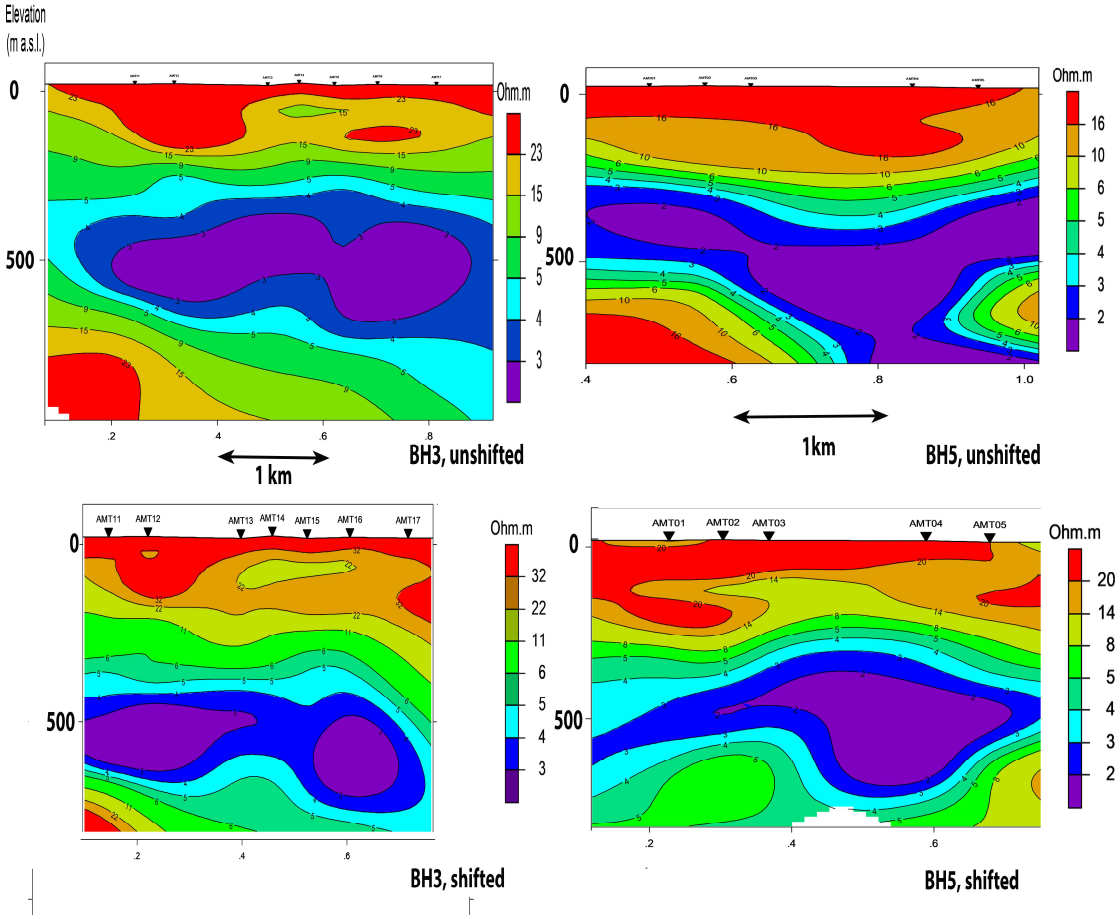


Figure 63. Results of shifted and unshifted AMT profiles of BH5 and BH3

6.7.1 BH3 Profile

This profile is adjacent to borehole BH3 and trends in the WNW-ESE direction (Figure 63) and traverses a region that is covered by recent alluvium soils that is composed of Siliceous sands and dead plant material. Seven AMT stations (AMT01-AMT07) were deployed along this profile at approximate station spacing of about 50 m with acquisition period of about an hour. Smooth and layered inversion models of individual data sets indicate a variation in the resistivity with depth.

Geological logs retrieved from BH3, the adjacent borehole indicates the presents of corals and sandstone at a depth of about 40 m. This coincides with the moderate to high resistivity signature that seems to be thinning towards AMT station 17. However, thickness appears poorly estimated between AMT stations 11 and 13 due to the larger spacing between the data points occasioned by the avoidance of an underground electricity cable that runs along the road to BH3.

6.7.2 BH5 profile

Pseudo section from this traverse revealed resistivity variation similar to the other two profiles especially in the first three layers where the sequences of occurrence is in the same order, however the layers exhibit more thickness than in the other profiles. The landowners and the presence of a relatively busy road, home states and a power line occasionally interrupted acquisition of data in this profile. All these notwithstanding, the resistivity layers still coincided with the geological logs from BH5, the borehole adjacent to the profile, but with exaggerated thicknesses.

6.7.3 SWIM profile

The profile is adjacent to the monitoring Swim borehole and trends in the W-E direction with its eastern end being right on the sea front (Figure 64). Five AMT sounding stations (Swim 2A, 2B, 2C, 2D and 2E) defines the profile that crosses Ukunda-Ramisi road between AMT stations Swim 2D and 2E. The profile lies almost at sea level on exposed corals and sands. The unshifted and shifted results are shown in Figure 64.
In the constrained results (Figure 65) at 40 m below sea level, a conspicuous lowest resistivity layer with a dipping boundary is prominent on the seaside of the traverse. This boundary is likely to be the freshwater-seawater interface formed by the receding freshwater front due to intruding seawater.

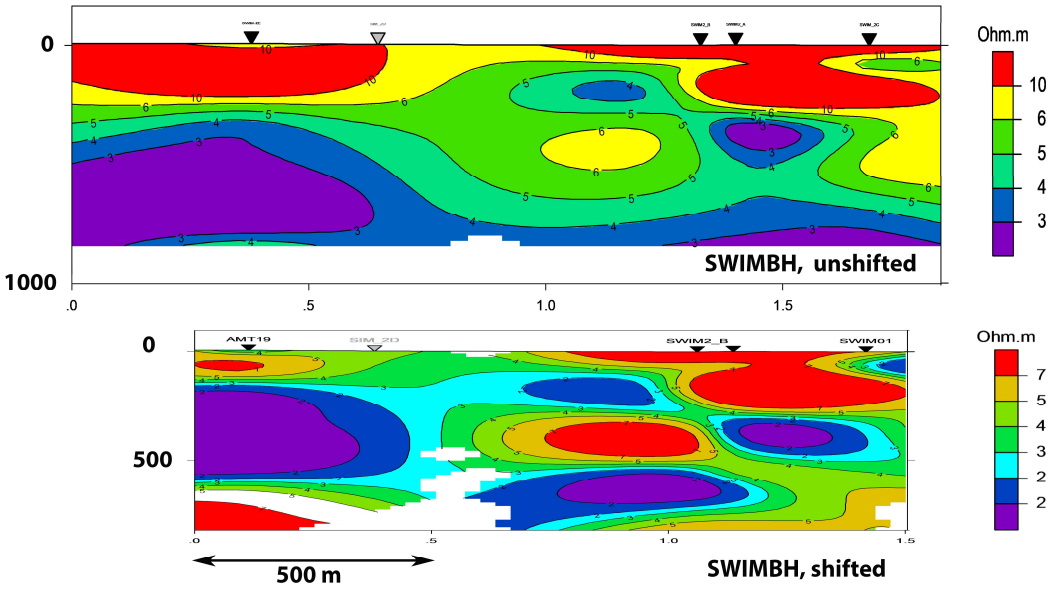


Figure 64. AMT shifted and unshifted results at SWIM borehole transect

6.1 Conclusions

AMT soundings and profiles derived from these soundings can give insight in the resistivity distribution up to very large depths if they are combined with additional information from TDEM soundings and Boreholes. Without this extra information AMT can lead to misleading interpretations.

Even with extra information, the resolution remains low and formation resisitivities and depths are only indicative. In Kwale, the AMT models could be fitted to the Base borehole logs, but only when they were heavily constrained (see smoothed and heavily contrained KenGen solutions in Figure 65).

In Kwale, the most important observation from the AMT soundings is the consistent low resistivity of the deeper layers. Because AMT needs to be shifted with TDEM soundings the question could be “why apply AMT?” AMT can be shifted with TDEM soundings with a smaller exploration depth. Loops sizes for really deep TDEM soundings can be 200 m or more and require powerfull transmitters.

With instruments like WalkTem, a DOI of 300 – 500 mtr could be in reach. Deeper measurements require larger loop sizes and extra transmitters or can be combined with AMT. The choice is depending on the availability of equipment, software and skills. One should also keep in mind that AMT is more sensitive to artificial noise (motorways, powerlines, fences urbanization etc) because the natural source signal is actual within this noise. Not every location is suitable for AMT soundings.

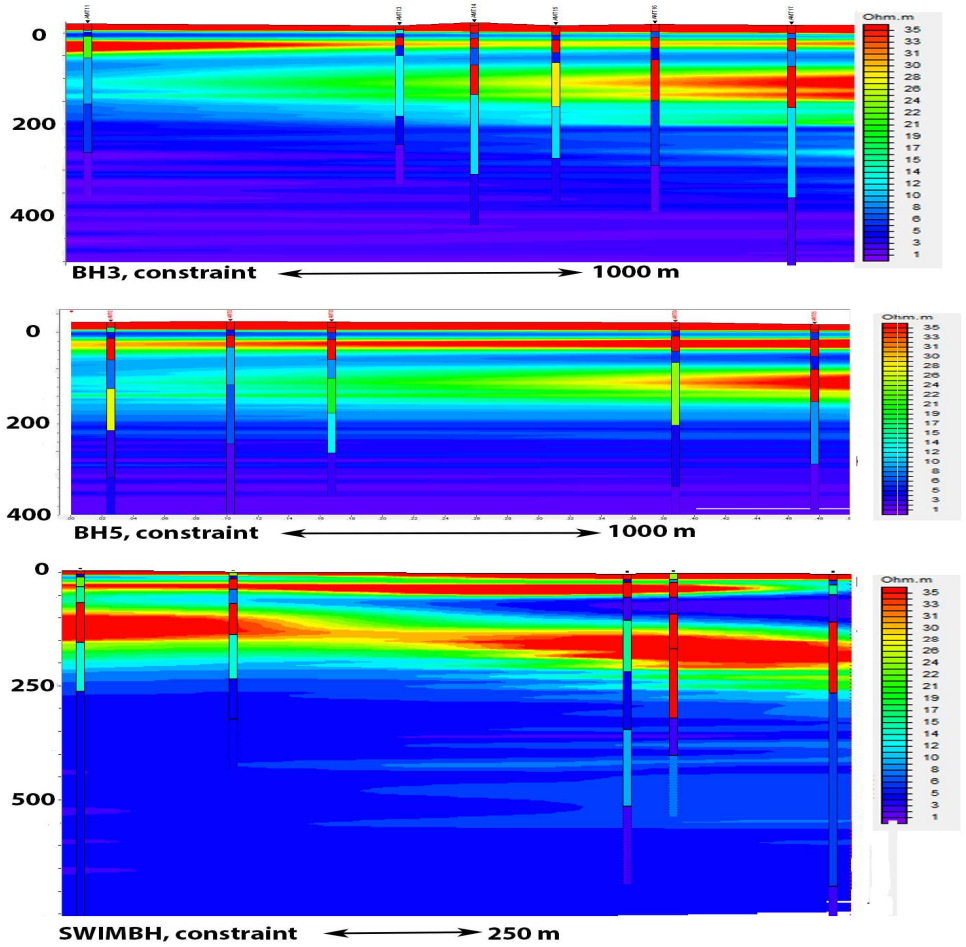


Figure 65. Constrained models of BH3, BH5 and SWIM borehole (source: KenGen)

7 Comparison of the resistivity methods

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

In Kwale, VES soundings, ERT tomography, TDEM and AMT soundings were applied on three transects. The location of the transects was based on existing information kindly provided by Base Titanium Ltd.. The transects are shown in Figure 66. VES soundings were carried out near Base boreholes 3 (BH3) and 5 (BH5) and close to the SWIM borehole.

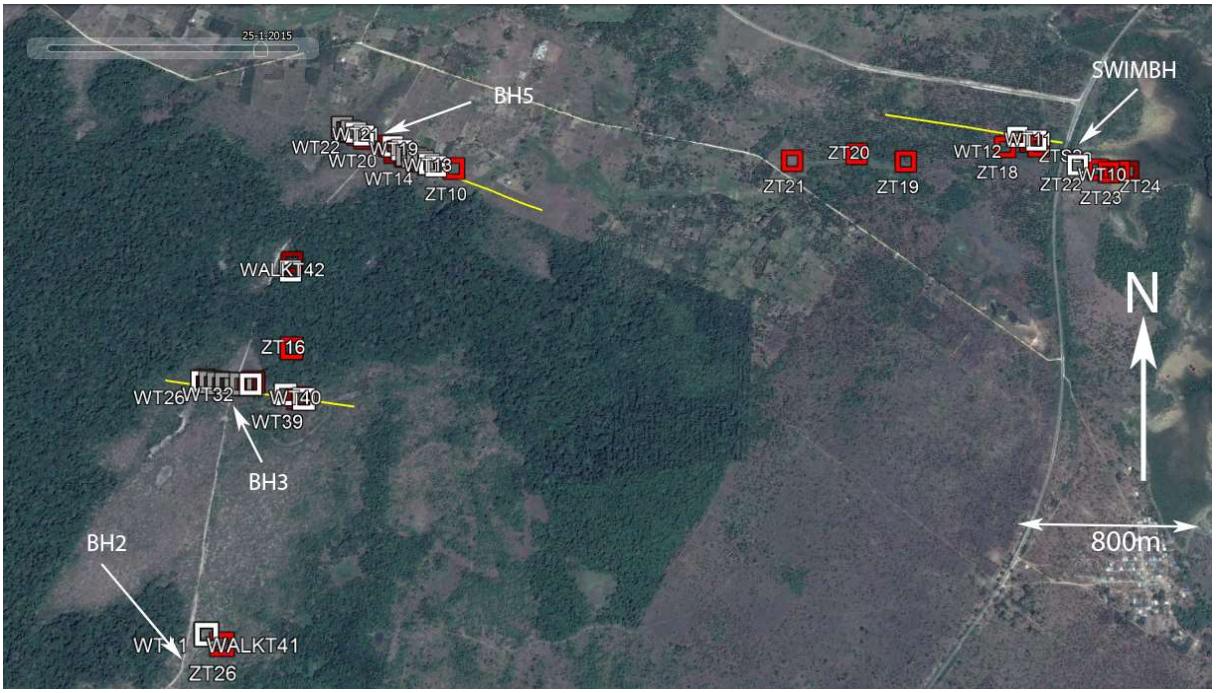


Figure 66. Location of ERT tomography (yellow), TDEM WalkTEM (white squares) TDEM Zonge (red squares) AMT soundings were carried out near the Zonge TDEM measurement points (red squares).

The results of each of the methods were presented and discussed in previous chapters. In this chapter the outcomes of the methods are compared holistically. Because of the information that is available at BH 3 (both geological and electrical logs) and because these methods are independent of the geophysics done within ISGEAG, the evaluation of the applicability of the various methods (VES, ERT, TDEM and AMT) is mainly focused on the BH3 transect (Figure 67).

7.1 Comparison of methods and results

In the study area Base BH3 gives the best information on the actual geology: reliable geology from the dual rotary drilled production borehole and vertical resistivity distributions from the electric log carried out in the piezometer borehole (BH3piez), 50 m north of the production borehole. In the first part of this section the performance of TDEM, ERT and VES is illustrated by mutual comparison of the individual soundings near BH3. Next, the results of the various methods are visually combined for comparison, for the three transects BH3, BH5 and SWIM.



Figure 67. Map showing sounding locations near BH3 (both production and piezometer BHs). The ERT3 transect is shown in green, the Zonge TDEM soundings in red, the WalkTEM TDEM soundings in white and the AMT soundings as small white circles. The location of VES5 is the blue flag southwest of BH3, with the VES orientation shown as a yellow line. The white line south of BH3 is the (unused) line of the existing ERT LRBS9

In Figure 68 on the next page, the electric logs are combined with the geo-logs. The long normal resistivity log gives the best estimate of the formation resistivity, because of its penetration depth. At this early stage, It can be concluded that the formation resisitivities are rather low for sandstones, corals and limestones.

The Spontaneous Potential (SP) log normally reveals information on formation boundaries, but the SP log from the BH3 piezometer hole does not clearly show layer boundaries.

The electrical conductivity of the groundwater was measured during drilling and was typically around 600 µS/cm (at 25°C), which is equivalent to a resistivity of 15 ohm-m. For sandstones, the formation factor can be 5 – 10 (or more), depending on the secondary porosity and cementation of the formation matrix. According to Archie's Law, formation resistivity would therefore be at least 100 ohm-m, which is clearly not the case in the BH3 data. This could be due to the presence of conductive minerals in the sandstone matrix itself or the relatively thin conductive clay/shale layers that influences formation resistivity.

From the logs, two low resistivity zones can be distinguished: the Pleistocene (Kilindini) sands and clays between 20 and 30 mbgl; and the zone between 50 and 75 mbgl, consisting of Jurassic Mtomkuu shales, Kambe Formation limestones and shales at the top of the Mazeras Formation. The second thin low resistivity zone divides higher resistivity layers of shelley quartz sandstone, marking the top of the Mazeras Formation.

For the comparison, the unconditioned inversions of TDEM (WalkTEM and Zonge), the ERT3 tomography, 'shifted' AMT soundings and the unconditioned inversion of VES5 are used.

In Figure 69, the VES 5 sounding close to BH3 is compared with the results of the electrical log and the TDEM WalkTem 26. The depth of investigation (DOI) of the VES is limited to 50 - 60 m. Beyond that depth the interpreted layer parameters are very uncertain and correlated.

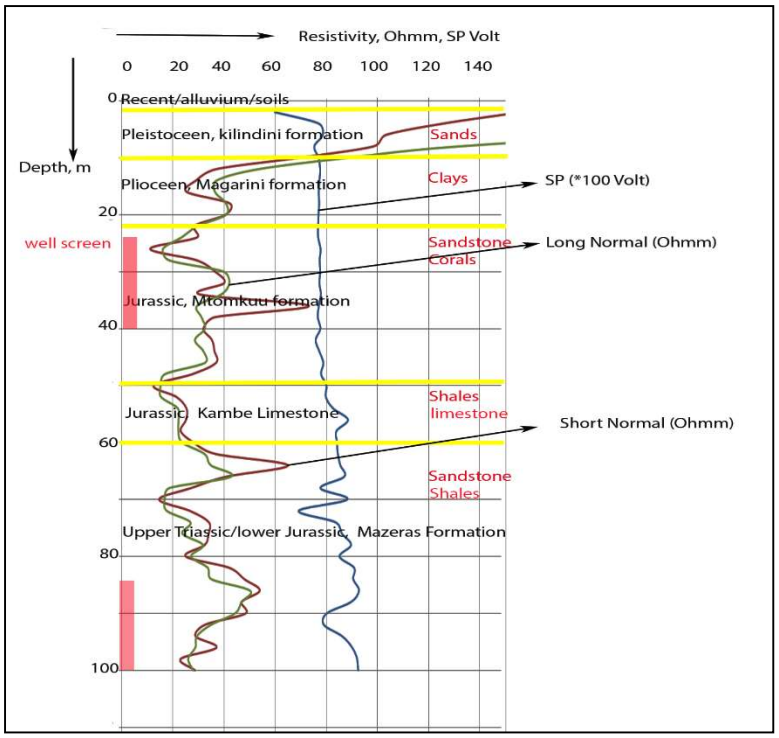


Figure 68. Layer interpretation from the electric log (Short and Long Normal resistivity; and SP). BH3Piez and BH3 screen positions are also shown (data courtesy of Base).

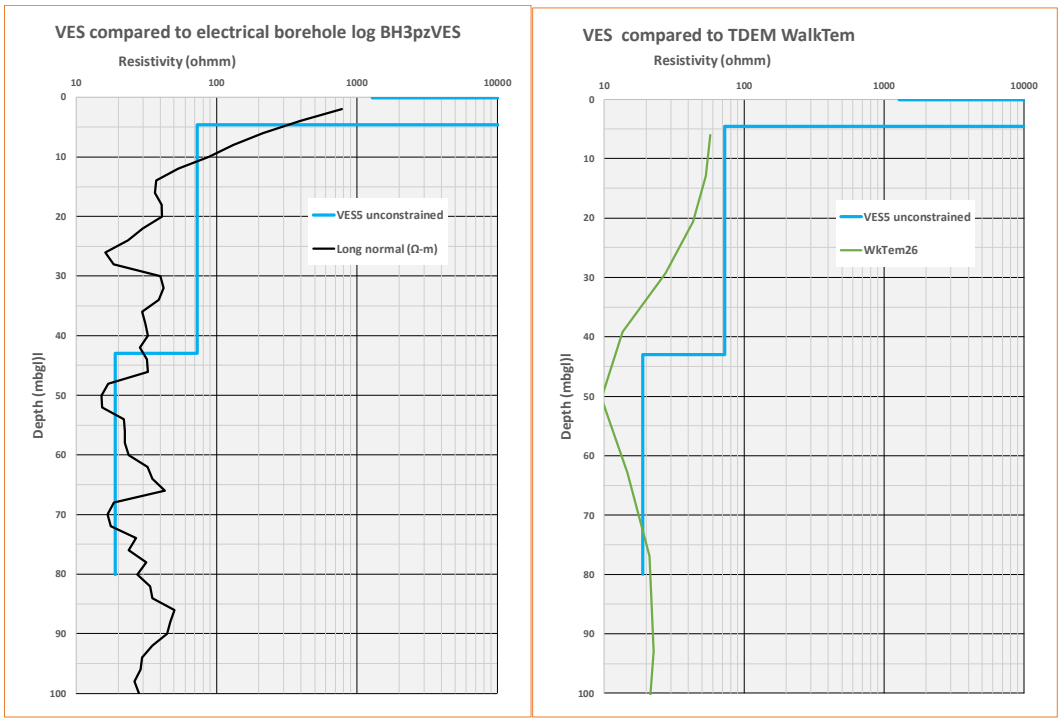


Figure 69. Comparison the electric log from BH3 with VES5 (left) and the WalkTEM26 smoothed model (right).

In VES 5, the Pleistocene clay at 10 - 20 m is not encountered. The comparison is weak, probably because the VES location is 240 m southwest of BH3. The WalkTEM soundings make it clear that the shallow clay layer is absent to the west of BH3. This is shown in the figure to the right, where the VES5 layer model is compared with the most westerly WalkTEM, no. 26 (smoothed model). Neither the WalkTEM nor VES5 indicate the shallow clay. The VES only just discerns the low resistivity Jurassic shales at 43 m and the high resistivity top layer (the shallowest 4.5 m, with a resistivity of 17.000 Ω-m). The TDEM instrument cannot "see" the true resistivity of the top layer because its high resistivity does not generate any induction.

In Figure 70, the WalkTEM TDEM and Zonge TDEM unconstrained smoothed inversions are compared. In a standard smooth inversion, 20 layers are divided over the depth of investigation or over a fixed depth. The midpoint of each of the 20 layers is used in this line visualization. The Zonge models in the middle of Figure 69 are based on the frequency of 32Hz and at the left a combination ofthe frequency's 4Hz, 16Hz and 32Hz data sets are presented. Walktem automatically combines all the used frequency's in one sounding.

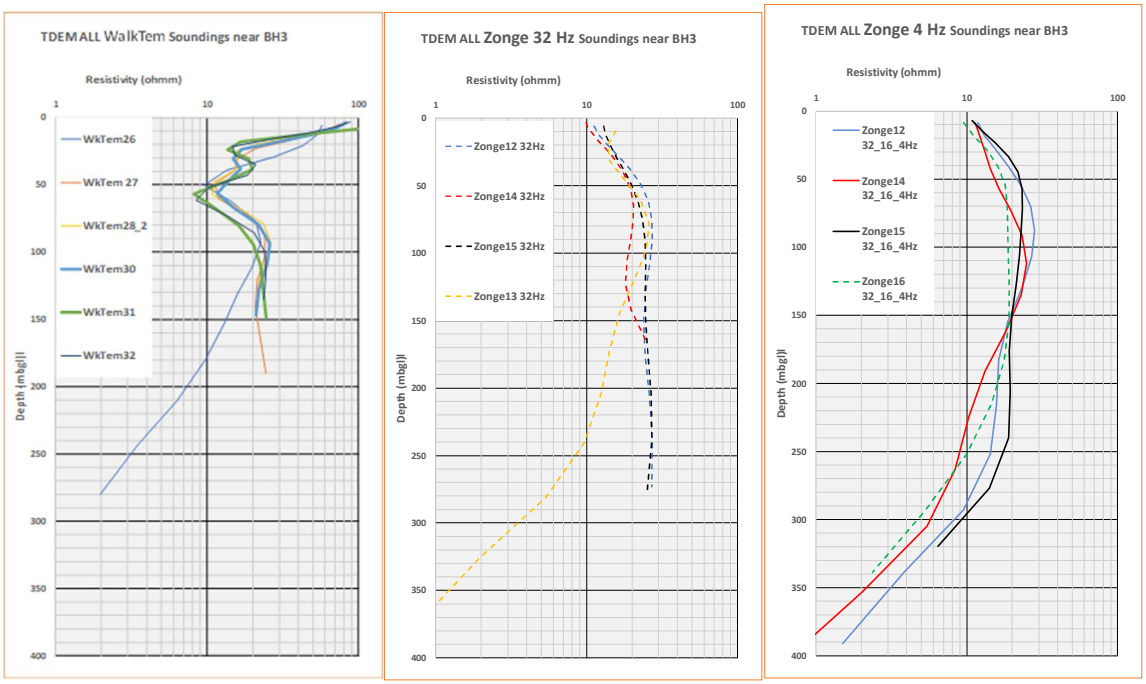


Figure 70. WalkTEM (left), Zonge 32Hz (middle) and Zonge 4Hz (right) smooth model resistivities near BH3. The curves are cut-off at their calculated DOIs.

The resistivity pattern of the WalkTEM soundings is clear and consistent with the drilling information; the DOI is limited to 150 m due to the use of a relatively small loop size and transmitter. The Zonge 32Hz soundings have less resolution and are not consistent with the drilling information; the DOI is variable, from 160 – 300 m. The pattern of all the 4 Hz Zonge soundings is consistent beyond a depth of 250 m, showing a gradually decreasing resistivity to 1 ohm-m at 400m.

In Figure 71, the three types (WalkTEM, Zonge 32 and 4 Hz) are compared directly. The WalkTEM clearly delineates the two low resistivity zones comparable to BH3 and at the correct depths. The WalkTEM model also detects the high resistivity top layer, which is important for getting the proper inversion result.

The Zonge 32Hz sounding gives no proper results for the first 100 m: it does not show the clay and shale zones and the high resistive top layer is missing. Even when this top layer was added as a constraint, the results were still not useful. The instrument lacks resolution, due to the limited number of early time windows in combination with the loop size (100 X 100m), with a corresponding transmission delay time.

The deep Zonge 4Hz results cannot be verified with the borehole information. It holds important information on the deeper layers, however. The DOI is calculated at around 400 m. Beyond 250 m the resistivity gradually decreases to very low resistivities (1 ohm-m), which may indicate saline water or (saline) clays with a very low resistivity at depth. This is consistent with this locality, where the seafront is 4.5km to the east and where saltwater is known to have intruded inland (Tole, 1997).

In Figure 71 the borehole resistivity log is compared with WalkTEM 31 smoothed and layered models. There is a difference in the depth of the first low resistivity layer, but this could be due to lateral differences between the borehole and the sounding.

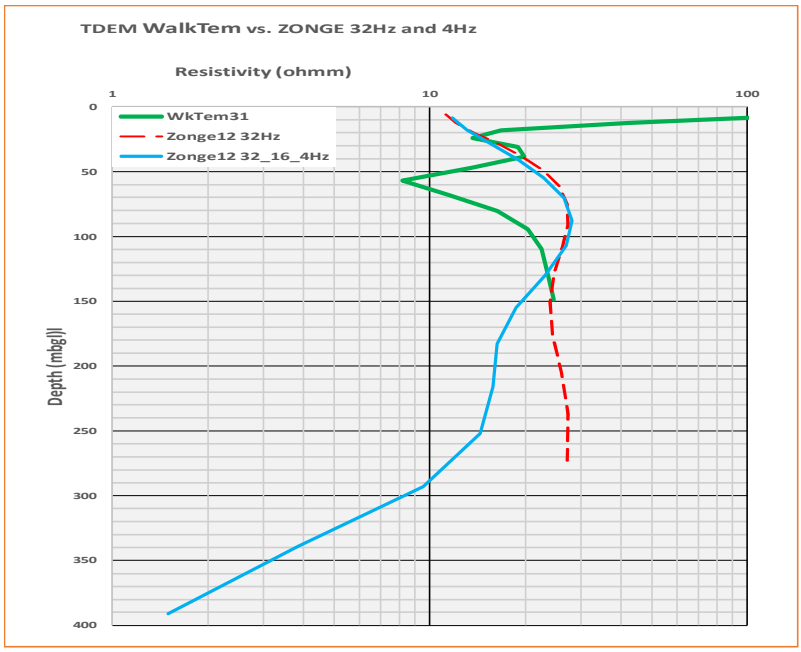


Figure 71. Comparison of the WalkTEM and Zonge sounding results

In Figure 72 the borehole resistivity log is compared with WalkTEM 31 smooth and layered models. There is a difference in depth of the first low resistivity layer, but this could be due to lateral change between the borehole and the sounding.

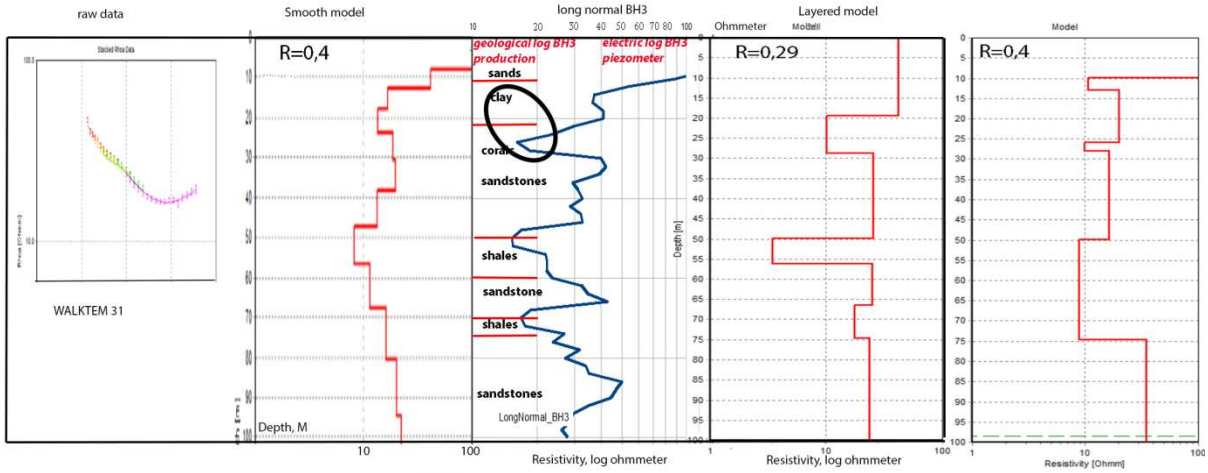


Figure 72. WalkTEM 31, 125 m north-northeast of BH3 inverted with a model based on the borehole log. From left to right: TDEM measured data, the smoothed model, the lithology and LN resistivity from the BH3 electric log and two versions of interpreted layer models.

In Figure 73 below, the results and methods of ERT and TDEM are compared. In this figure the ERT transect cannot accurately locate the two low resistivity layers because of the lack of resistivity contrast and because of the missing data points due to correction (see apparent resistivity on the corrected data). The center of the low resistivity zone found in the smooth inversion (without constraints) is indicated by the blue band.

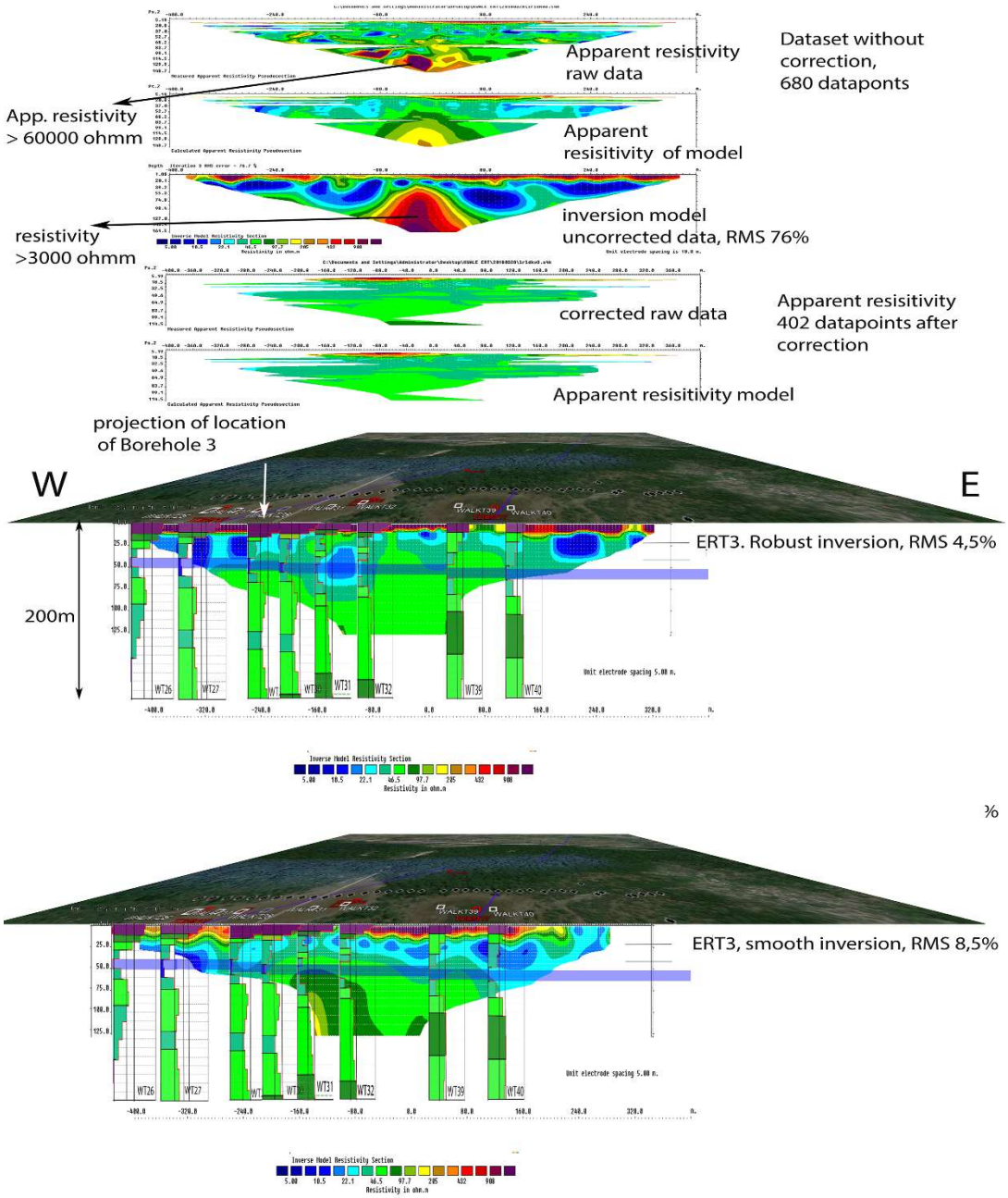


Figure 73. ERT3 compared to the WalkTEM soundings near BH3. The bottom two images give the combined ERT and WalkTem results.

The effect of missing data on the inversion of ERT3 is obvious; in the west and east part of the tomograph the low resistivity layer becomes thicker because of the interpolation, while in the middle the deep high resistivity layer and the missing data points at medium depth misinterpret the location of the low resistivity layer. At the top of this figure the uncorrected dataset is presented; the inversion of this set with apparent resistivities of 60,000 ohm-m yield tomographs with RMS errors of 60%. It is important when ERT data are presented to give the RMS error, the percentage correction and the maximum and minimum calculated resistivities. Without these data, the results cannot be judged properly.

In Figure 74, Figure 75 and Figure 76 below, all the results for ERT, TDEM and AMT measurements at BH3, BH5 and the SWIM site are compared (scaled according to the DOI). At the bottom of each figure the results are projected onto each other, using the same colour scale (to the extent possible, since the different inversion programs use different colour criteria). For the SWIM borehole, the projection of the method is given separately in Figure 77.

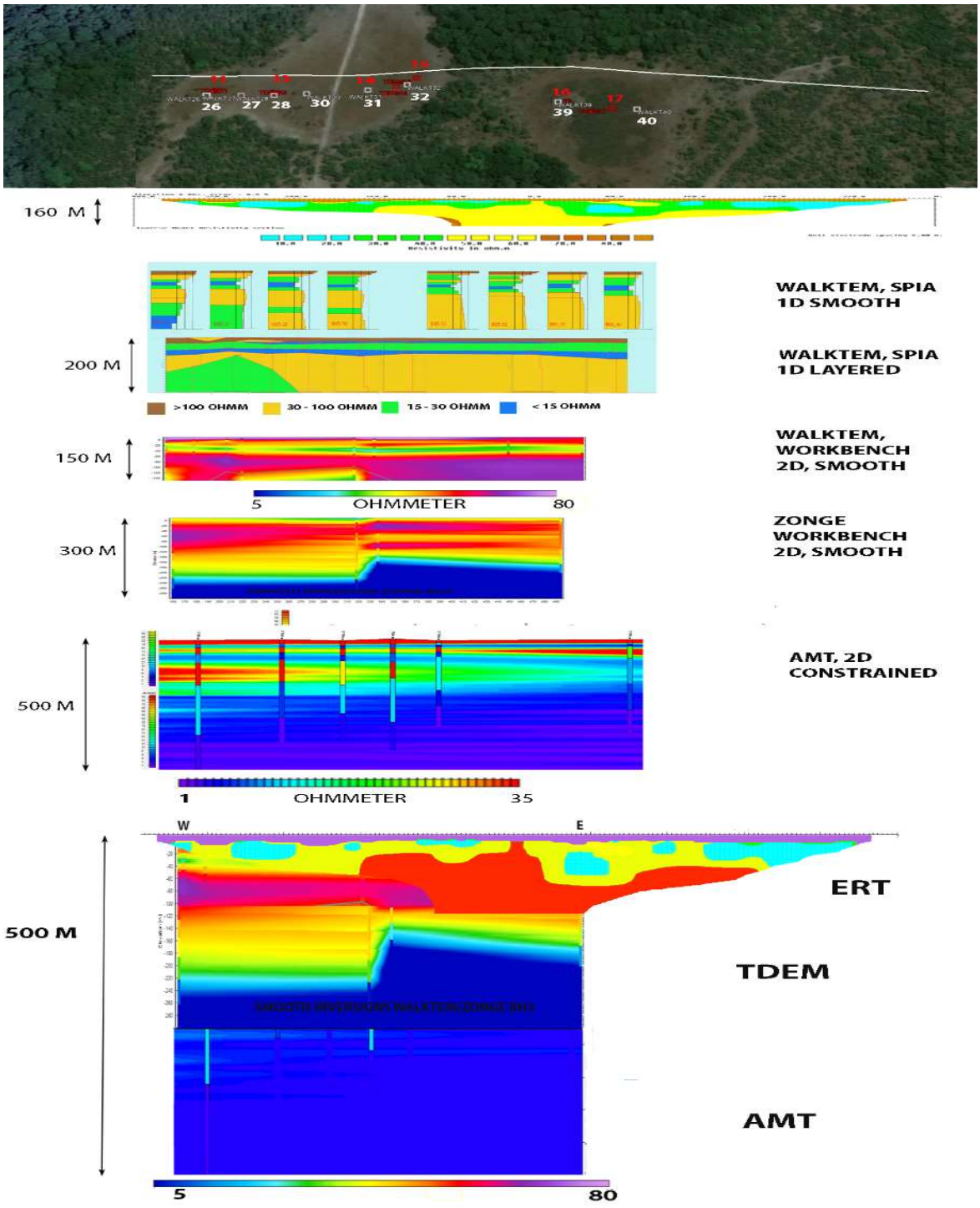


Figure 74. Comparison of ERT, TDEM and AMT interpretations at BH3.

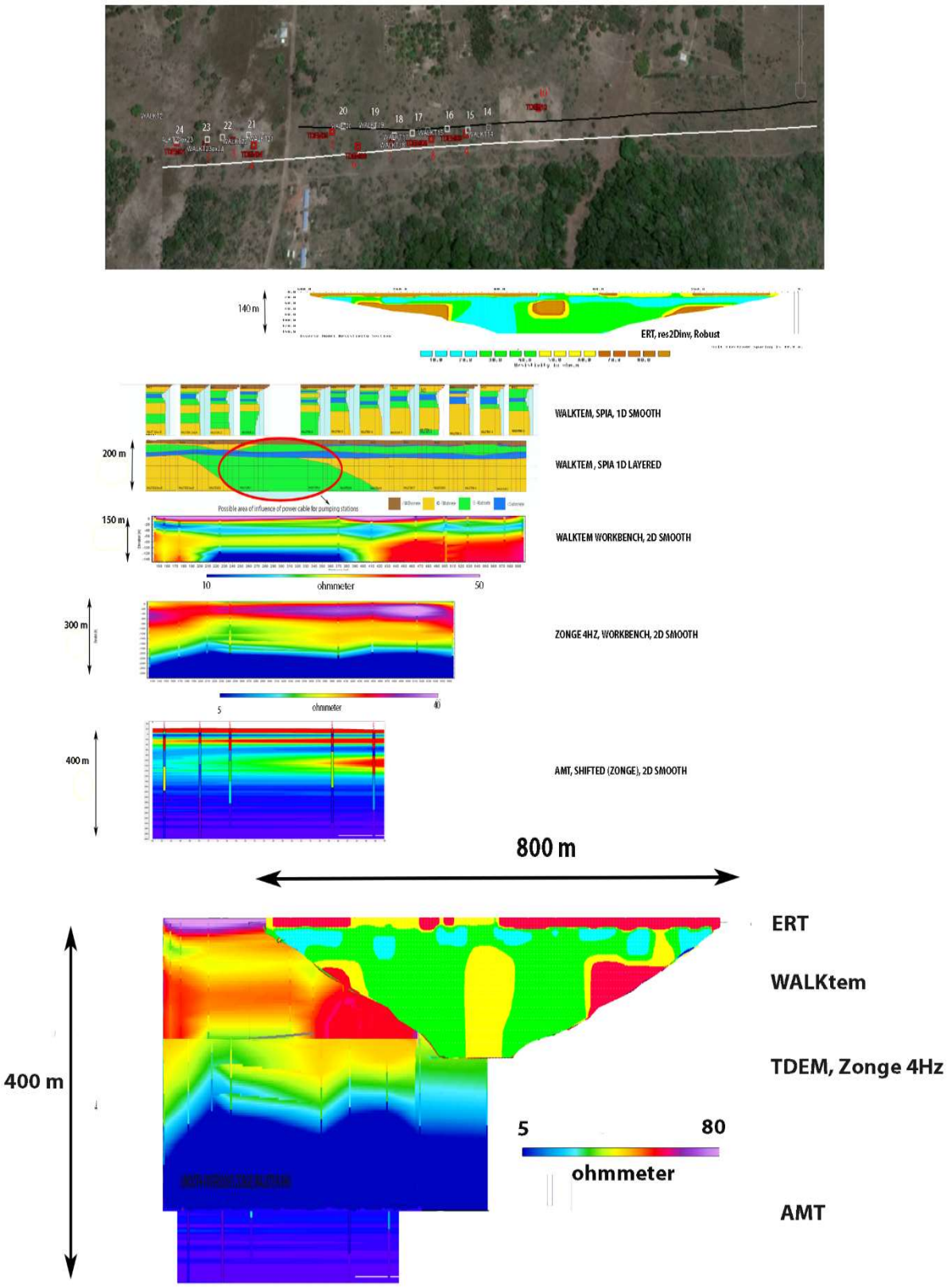


Figure 75. Comparison of ERT, TDEM and AMT interpretations at BH5.

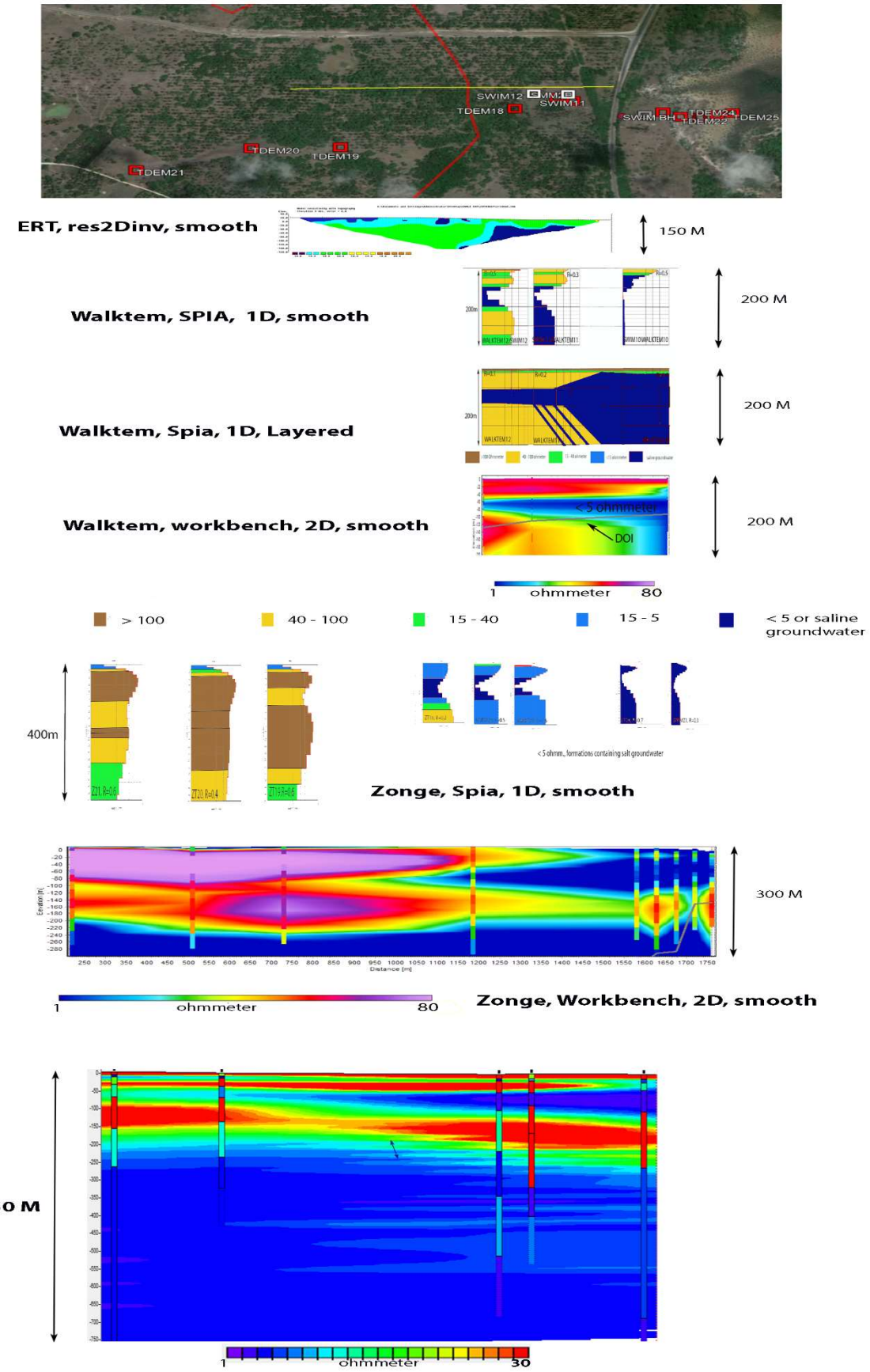


Figure 76. Comparison of ERT, TDEM and AMT interpretations across the SWIM site.

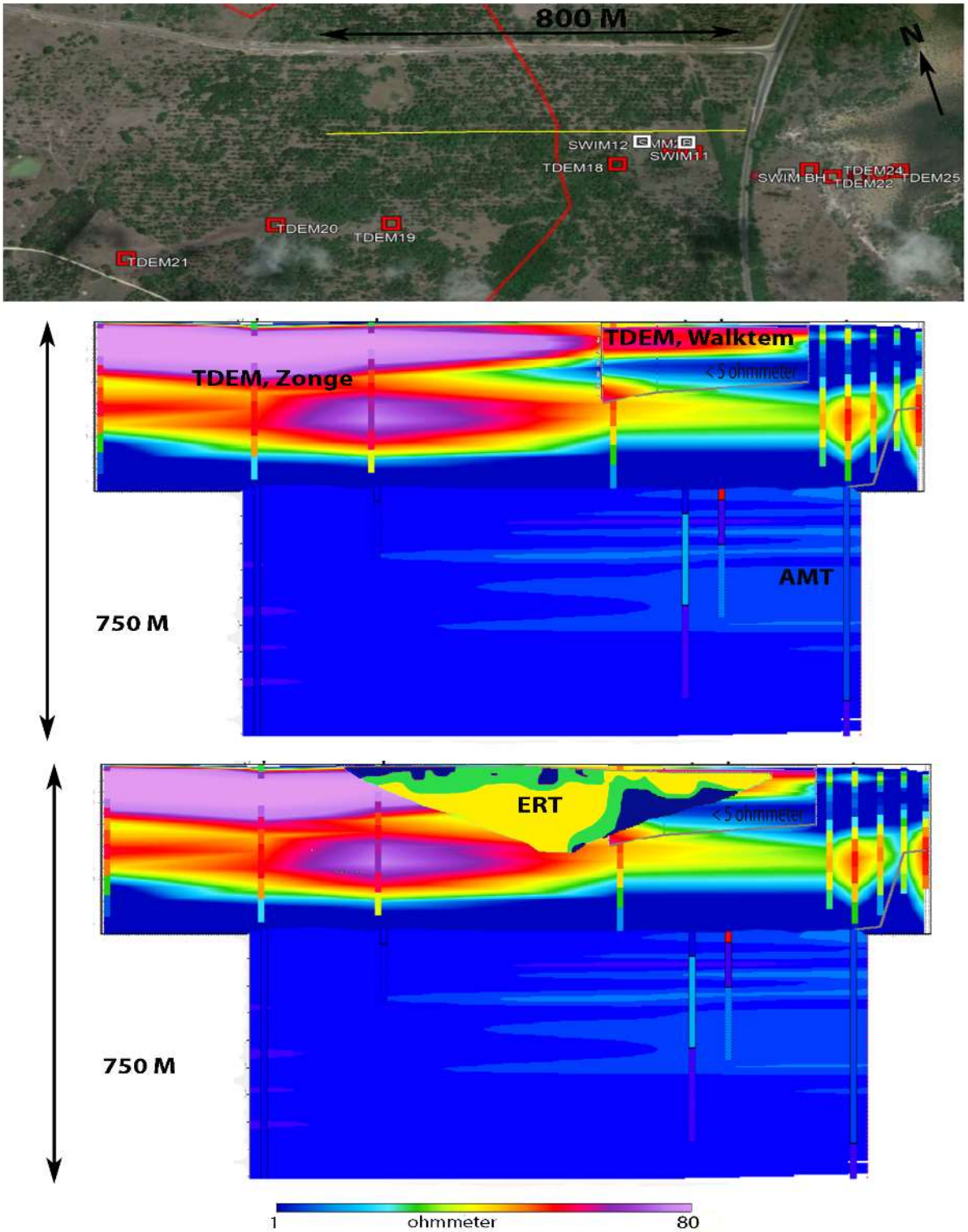


Figure 77. Projection of ERT, TDEM and AMT inteerpretations at the SWIM borehole.

From the comparison of the methods at BH3, BH5 and the SWIM site, it is concluded that at BH3 and BH5 the ERT method worked poorly due to the dry topsoil and the low resistivity contrast.

When reporting ERT results, it is important to provide not only the tomograph, but also essential technical information: the electrode configuration, the RMS error (%), the type of inversion, the percentage correction and the minimum and maximum calculated resistivities. Without such information a tomograph can be misleading.

The TDEM WalkTEM instrument gave the best resolution in the low resistivity range at relatively shallow depths (<150 m). Care should be taken with datapoint selection for inversion. In retrospect, looking at the results, we conclude that any future TDEM surveys using the WalkTEM, the optimum set-up would be a combination of a small (40 X 40 m) and a larger transmitter loop (100 X 100 m) and will give the best results (i.e. the best resolution and the greatest DOI). The 40 X 40 loop WalkTEM measurements combined high and low moment soundings with separate delay times, and gives the best resolution for shallow and intermediate depths (<150 m).

Data collected by the TDEM ZONGE instrument used (a ZT30 transmitter and GDP32 receiver; and 100 X 100 m loops) did not always obtain adequate resolution. This Zonge set-up lacks data points close to the ground surface and therefore the inversion lacks information on shallow layers. The Zonge 4Hz data, however, gave useful information about the decreasing resistivity between 150 and 300 mbgl, which is consistent with the AMT results. At the SWIM borehole, due to better resistivity contrast and a more conductive top layer, the results were better for all the methods.

With the AMT data, both shifted and unshifted inteerpretations discriminated the low resistivity values below 200 m. As with the Zonge TDEM, the AMT method lacks contrast for the shallow layers.

One important observation is that automatically smoothed 2D inversion profiles with software like Workbench and Winlink do not always give useful interpretations, while changing lateral interpolation constraints heavily influences the 2D profiles. These types of software should be applied with care. When the number of soundings is limited, it is better to generate profiles by hand from the 1D inversions.

In the next Section an attempt is made to combine the best of all methods into one tentative hydrogeological profile from the coast and within the Base wellfield.

7.2 Synthesis related to conceptual hydrogeology

A general conceptual profile is presented in Figure 78 on the next page. The profile is compared with the existing conceptual hydrogeology. It is clear that the resistivity profile generally agrees with the existing concepts, but there are also differences and new issues, which are further discussed in this section.

In Figure 79 a tentative, combined cross section is presented, based on TDEM soundings on a transect running from the coast (SWIM borehole) inland towards borehole 5 and from there to the southeast, along borehole 3 towards borehole 2. The section crosses a lineament twice. This lineament coincides with sharp bending of the Kidongoweni river, a dip in elevation (from the DEM) and is also visible as an anomaly on a map of earlier FDM airborne research (Carruthers 1985). Note that where the lineament crosses in the south, the change is only based on one single sounding, WalkTem 41 close to borehole 2.

The conclusions so far based on this profile include:

- Three layers of low resistivity were distinguished:
- shallow Pleistocene clays (not continuous) at depths between 15 and 30 m bgl;
- Zone of Jurassic shales at 50 – 70 m bgl;
- Deep zone of probably saline rock at 200 – 250 m bgl;
- The shallow clay layer is not continuous, while the second layer is found in all soundings, correlating with the zone of Jurassic shales (and Limestones) in the geological logs. This shale layer may be displaced by a fracture or a fault. The third low resistivity zone, as the result from the 4Hz Zonge soundings, is showing low resistivities in the deep underground indicating deep saline or brackish water that may correspond with Maji ya Chumvi beds (*or Mariakani sandstones) underlying the Mazeras sandstones.*

The thicknesses of the Mazeras are believed to be (pers. comm. M.Lane):

- 360m beneath the Shimba Hills;
- 270m beneath the Central Dune and the Base process plant;
- 180m between the fault immediately east of the mine site and the fault between BH5R and BH5E Pz; and
- <180m east of BH5E Pz.

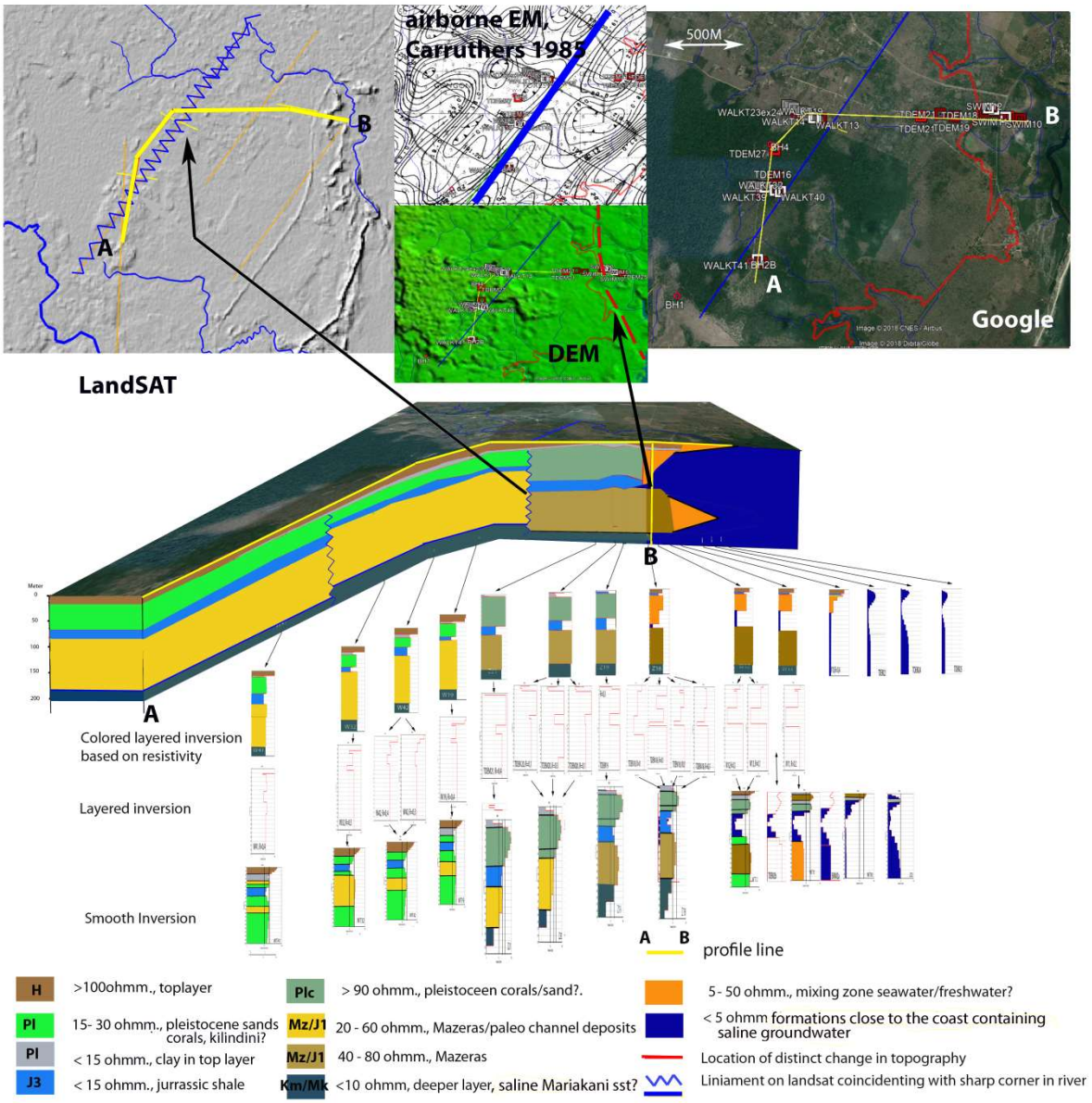
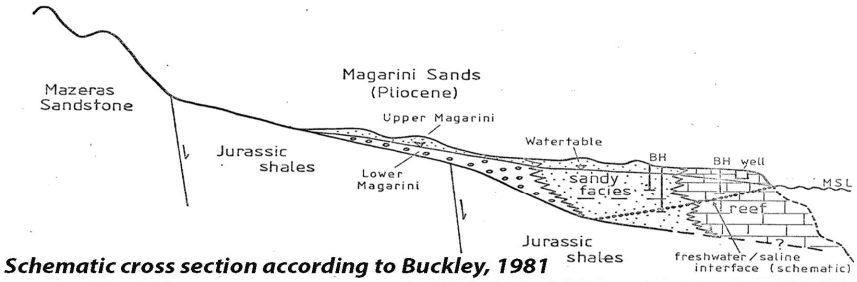
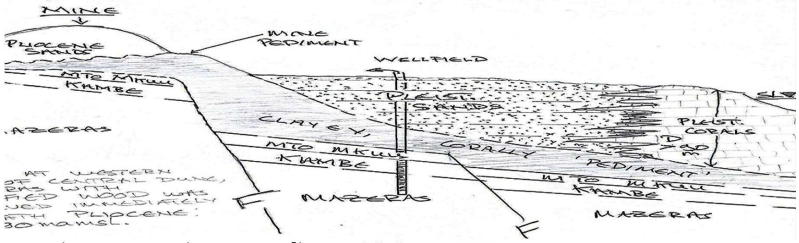


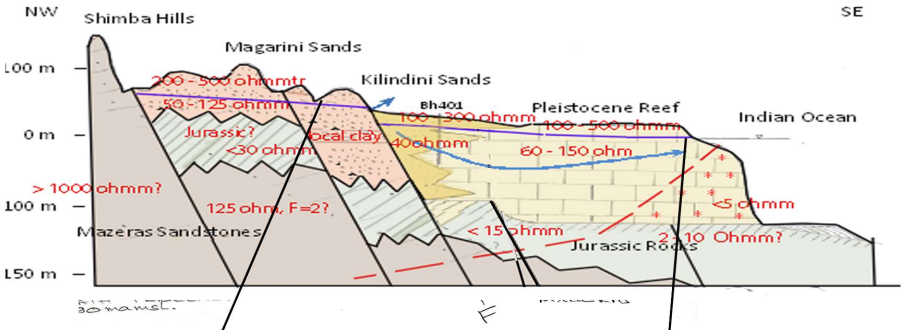
Figure 78. Tentative hydrogeological cross section along the Base boreholes and from Borehole 5 towards the Coast (SWIM borehole)



Schematic cross section according to Buckley, 1981



Schematic cross section according to M. Lane, 2018



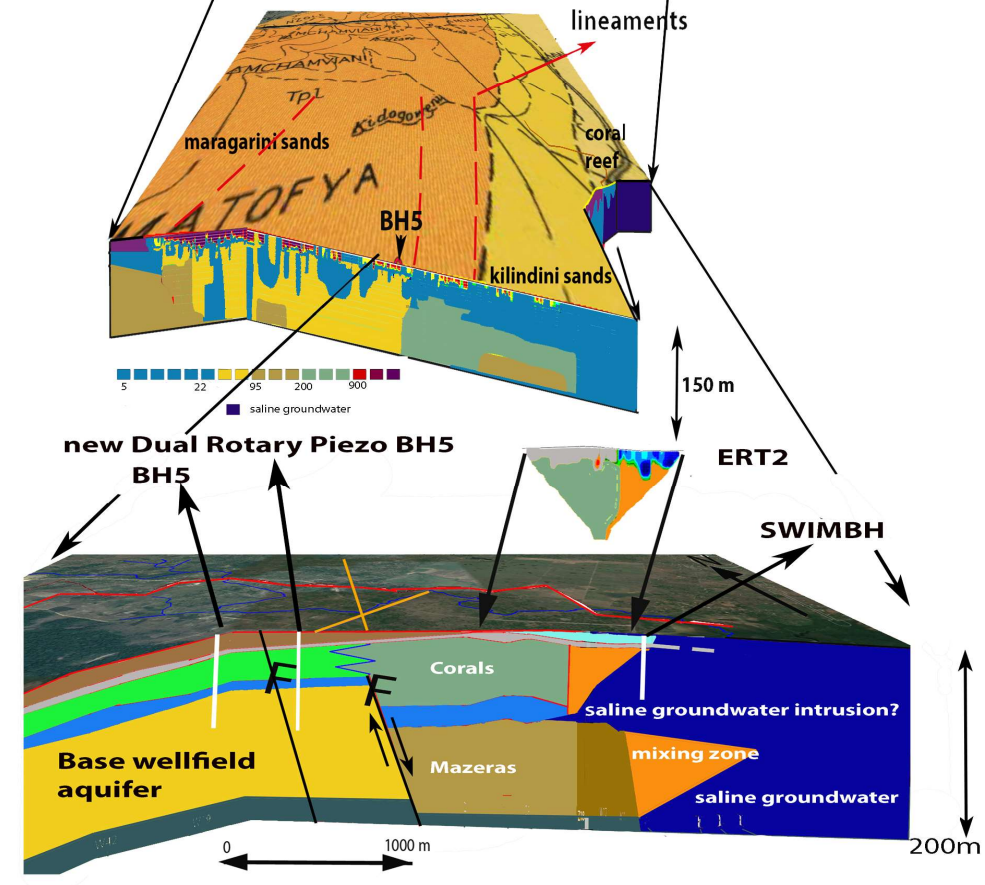


Figure 79. Conceptual cross-section compared with existing conceptual models.

7.2.1 Further considerations related to the conceptual hydrogeology

Mazeras resistivity

The resistivity of the Upper Mazeras sandstones is much lower than expected and as assumed in previous geophysical programmes in this area; GSK (2005) assumed values of 125Ω-m, whereas both downhole logging and ISGEAG programme geophysical measurements indicate that actual resistivities are <60 ohm-m, and in the Base boreholes as low as 20-30ohm-m. Closer to the coast, the Mazeras resistivity seems to be slightly higher (though only in the few Zonge soundings).

The water conductivity (in the Base Titanium boreholes) ranges from 500 – 700 µS/cm which is between 15 – 20 in ohmm. The formation resistivity depends on the porosity and can be calculated with the law of Archie in a simplified from: Formation resistivity = Formation factor * Water resistivity. In unconsolidated sediments the formation factor ranges between 1 and 5, for (fractured) sandstones this factor is expected to be much larger. For fractured sandstone with this type of groundwater, a resistivity of at least 75 ohmm should be expected, which is not the case at the considered boreholes.

This means that the matrix of the aquifer is either conductive or that the productive layers are relative thin or a combination of the two. Other explanations are possible. For example: the line of the Base boreholes is located in a somewhat divergent geology within the Mazeras or they are located in an old valley cutting into the Mazeras, mainly filled with sediments of the sandstone itself and on top of which the younger Jurassic (Mtomkuu/Kambe) were formed. At one location outside the fieldwork area higher resisitivity's are encountered within the Mazeras (see also paragraph 5.6)

It is clear that the combined data of the TDEM soundings deserve additional, more detailed analysis which was not yet done in this ISGEAG campaign. This analysis should focus on additional resistivity patterns in the depth zone of 100 -300 m. At first glance (in particular near Borehole 5) there might be a zone of relatively high resistivity at approximately 250m, before the resistivity reduces at greater depth. This should be confirmed/rejected by further analysis of the TDEM data.

The SSW-NNE fault lines

There is clear existing information indicating a major fault zone directly east of the Base wellfield, as also illustrated in the conceptual profile in Figure 78 and Figure 79. The TDEM-based profiles near Boreholes 3 and 5 do however not clearly indicate major vertical displacements in the depth of the top Mazeras. This finding is a bit complicated by the possible influence of the powerlines: some distinct lateral changes are visible in the Mazeras resistivity results (profile BH5), but they may have been caused by powerline interferences.

In the BH5 profile, a tentative fault is indicated in the existing (re-interpreted) ERT line LRBS1 (RFL) at approximate 300 m east of Borehole 5, which is confirmed by the recent drilling of a Base dual piezometer monitoring borehole in that area. The most eastern WalkTem sounding on the profile may still have been west of that fault, explaining why the fault was not detected in the profile. Unfortunately, the execution of additional TDEM soundings further east (as originally planned) had to be stopped due to social problems with the community. Additional TDEM soundings, going over the fault zone and related to the new piezometer BH drilling data could clarify this issue.

SWIM Borehole profile

The conceptual model at the coast, near the SWIM borehole, recognizes a distinct difference between the shallow and deep aquifer, separated by a confining aquiclude. At the SWIM borehole, the aquiclude seems to consist of a low permeability Pleistocene coral limestone rather than Jurassic shales or limestones. It is assumed that the underlying deep aquifer (at approximately 110/120m bgl is the Mazeras sandstone Formation, but this has not been confirmed by drilling data.

The deep aquifer carries fresh groundwater, becoming brackish in eastern direction. The Zonge soundings east of the Ukunda-Ramisi road even suggest that there may be outflow of brackish water under the Ocean as 'submarine groundwater discharge' (SGD).

The shallow aquifer in the SWIM borehole profile consists of Pleistocene coral limestone, consistent with the reconnaissance soil map (Michieka *et al.*, 1978). The interface between fresh and saline groundwater in the shallow aquifer is clearly delineated by the ERT, TDEM and VES methods. The inland propagation of the interface coincides with the change in topography at 10m amsl (above mean

sea level). For effective monitoring of the evolution of saltwater intrusion, Base is strongly advised to construct an additional (dual piezometer) monitoring borehole near the present tip of the intrusion wedge in the shallow aquifer, inland from the current SWIM location, 350m due west of the main road, opposite the SWIM borehole. This borehole should be planned to fully penetrate the Pleistocene material, and all Jurassic material down to the top of the Mazeras sandstone in order to confirm solid geology at depth and much enhance the conceptual model.

Regional saline intrusion

Assuming a 'first guess' causal relation of saline intrusion being related to the 10 m asl topography line, lateral intrusion is to be expected in the red shaded area in Figure 80. Of course, the development of the fresh groundwater heads and gradients, influenced by groundwater abstraction and recharge actually determines if the intrusion propagates further to the west. The risks of progressive salinization should be managed by further understanding from additional geophysics (e.g. additional TDEM or even airborne TDEM like SkyTem), exploratory drilling and a well-managed monitoring system.



Figure 80. DEM with the location of the extra measurements and in shaded red the area below the 10 m asl for tentative saline intrusion. ERT lines are indicated in white, lineaments in blue.

Vingujini and Milalani salinization

As discussed in the TDEM chapter, seven additional WalkTEM soundings were carried out south of the Forest, at Vingujini and west of Milalani. These were carried out to assess the local saline/fresh groundwater interface (for the locations see Figure 78 above). Saline groundwater was indicated at both locations: near Vingujini (WT43 and WT44) in the shallow aquifer and in the deeper aquifer near Milalani (WT34 – 37). Both locations are further inland than the proposed intrusion zone below the 10m contour. The question, therefore, is how to explain salinization at these two locations?

To this end a comparison was made with the results of the airborne 'INPUT' (INduced PUlse Transients) EM investigations from 1977 (Austromineral, 1978) (Carruthers, 1985). See also Box 3, next page.

From this comparison, the most likely cause of salinization near Vingujini is lateral and recent (later than 1977) propagation of saline intrusion through the shallow aquifer from the coast towards

Vingujini. This means that the whole area east of Vingujini would contain saline/brackish water, which can easily be verified by additional fieldwork (e.g. WalkTEM soundings).

The group of WalkTEM soundings at Milalani (WalkTEM 35 – 37) found low resistivities , which suggest saline palaeo-groundwater as the source or, alternatively, deep (saline?) shales. The location is known to be in a palaeochannel. The INPUT map suggests an even more complex system of buried river valleys (palaeochannels). A relatively large valley seems to have the direction NNE-SSW, but this really should be confirmed with additional WalkTEM soundings, because it is only based on the very low-resolution INPUT measurements and their similarity to the recent TDEM soundings. It may also be an interference effect from the known/possible faults, which adopt the same orientation. It should be kept in mind that INPUT is based on apparent resistivity and not true resistivity from the inversions. Shallow layers could influence the image despite the very basic corrections that were applied (see Box 3).

Box 3: The Milalani case related to Airborne TDEM in Kwale in 1970s

In 1977, airborne TDEM was executed in Kwale by Austromineral (and discussed in Carruthers, 1985). With this so-called INPUT system, six time windows were measured, (ranging from 0,3 – 1,9 milliseconds). This window is compared to the WALKTEM measurements in this area with a depth of 150 m. However, the real DOI was not clear because the altitude of flight was not given and it was not clear if an altitude correction was applied on the data. In Figure 81 the results or responses of a late time windows are given, corrected for shallow disturbances by using window 2 (Carruthers, 1985). This response is than contoured and colour-filled. Dark blue colour is related to high responses, thus low resistivity. Red colours indicate low response and high resistivity. These responses are related to the apparent resistivity and not to the formation resistivity. However, when the WalkTEM soundings are compared with this map, a similarity in the distribution of the resistivity can be observed.

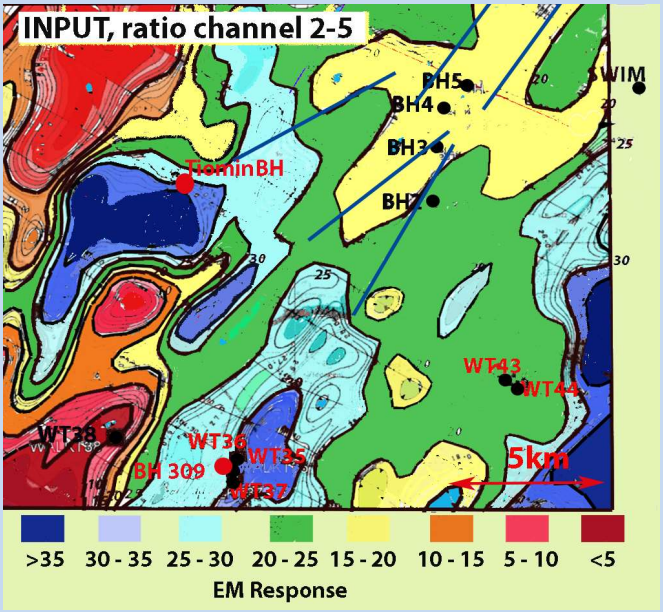


Figure 81. Results from airborne TDEM 'INPUT' survey 1977 and WalkTem sounding near Vingujini (WT43,44), west of Milalani (WT34 -37) and near Kidzumbani (WT38)

WT38 corresponds with the high INPUT resistivity. The WalkTem soundings WT34-37 (west of Milalani), all indicate deep saline groundwater (or, but unlikely, thick clays/shales), comparing very well to the blue, low response INPUT zone.

Despite the time lag and the difference in resolution, the results of the WalkTem measurements remarkably correspond with this airborne survey. As a consequence, the salinity (or thick shales?) near Milalani is suspected to be sourced from connate saline groundwater from a paleochannel.

Near Vingujini, WT43 and WT44 indicated (shallow aquifer) salinity, increasing in eastern direction towards the coast. The INPUT map (green area) does not show low responses in that area. Therefor it is concluded that WT43 and WT44 indicate recent, lateral saline groundwater intrusion from the ocean.

7.2.2. Conceptual hydrogeology and geology: the sub-regional context *(contribution by Mike Lane (Rural Focus / Gro for GooD)*

This closing section discusses the geological and hydrogeological conceptual models described above in the broader sub-regional contexts, drawing on a very broad range of data collected by Base Titanium Ltd in the period 2003 to 2018; and from the findings of the Gro for GooD research project (Groundwater Risk Management for Growth and Development; https://upgro.org/consortium/gro-for-good/) from 2013-18. This holistic view considerably advances the previous understanding of the geology and hydrogeology of the broader study area.

This section clearly shows that the combination of information from different sources improves and increases the understanding of aquifer systems, if that information is accessible, of good quality and interpreted with the appropriate skills. It also shows that in this area, instruments such as the WalkTEM can significantly contribute to making sense of these data. However, what this summary makes very clear is that additional measurements and research are necessary, as well as the continued existence of a smart monitoring network; finally, in the context of sensible water resources management, catchment protection including balanced soil conservation programmes need to be implemented. The complexity of the system combined with high and increasing demands for groundwater (for domestic, agricultural and industrial uses) and the potential danger of salinisation of this precious resource call for continuous monitoring and careful management.

Groundwater is a very significant component in water supply in Kwale County, supplying water to over 58% of the County population in early 2019 (NDMA, 2019). In the area east of the Shimba Hills, a number of aquifers have been described (Gro for GooD/Base, 2019, in press).

- A shallow unconfined aquifer located in Pleistocene coral limestones adjacent to the sea. This is heavily exploited by shallow wells and boreholes. Yields can approach 15m3/hr in parts of the aquifer, which is karstified[5] in places. In the southern palaeochannel (see below), the Msambweni public water supply well on the shoreline has been pumped at 27m3/hr.

- A shallow unconfined aquifer in Pleistocene sands and corals, which is also heavily exploited by shallow wells and boreholes. This aquifer unit lies between the eastern edge of the Coastal Hills and the intercalated western edge of the corals; yields can exceed 6m3/hr.

The two Pleistocene units are heavily exploited for domestic and commercial uses and are already affected by saline intrusion in some places (Tole, 1997); many of the Coast hotels and apartment complexes rely on water from the coral limestone aquifer to supplement piped water from the Tiwi aquifer (located north of Ukunda and covering an area of approximately 30km^2). Parts of the Tiwi aquifer have recently been found to have become salinized (Oiro *et al*, 2019). Abstraction by South Coast hotels is uncertain, though an estimate based on a novel approach combining Google Earth, Trip Advisor and the Manual for Water Supply Services in Kenya (MoWI, 2005) suggests that actual abstraction in 2017 was about 3,270m^3/d (Ferrer *et al*, 2019a).

Many rural households in Kwale County rely on handpumps to abstract water from these shallow aquifers for domestic and other uses. Average daily abstraction from 'smart' handpump-equipped boreholes (Thomson *et al*, 2012) varies widely between wet and dry seasons. A large data set from 2014 and 2015 showed that average daily handpump abstraction was 1.4 to 1.6m^3/d, ranging from 0.7 to 2.1m^3/d in wet and dry seasons respectively; extrapolation suggests that mean daily abstraction from the 300 hand pumped boreholes and wells in the broader study area is approximately 450m^3/d (0.16MCM/yr) (Thomson *et al*, 2018). Public water supply abstraction from the Pleistocene coral aquifer borehole at Vingujini, the shallow well at the Msambweni water supply compound and a third borehole elsewhere in the Msambweni area is reported to amount to 340m^3/d (0.12MCM/yr; MWI/KCG, 2017).

[5] "We may define karst as comprising terrain with distinctive hydrology and landforms that arise from a combination of high rock solubility and well developed secondary (fracture) porosity." Page 1, Ford *et al* (2007).

The ISGEAG WalkTEM measurements 43 and 44 shows that saline intrusion is occurring below Vingujini, confirmed by the recent increasing electrical conductivity of water from the public water supply borehole located there (since early 2016); in May 2018 the electrical conductivity of water from this borehole was 2,397µS/cm, up from ECs typically <1,000µS/cm in 2014-15[6].
Msambweni Town lies in the eastern part of the southern palaeochannel aquifer system (see below), though wells in the Town are not salinising at present; ECs in a shallow well in the western part of the Town are ~700µS/cm[7].

The Pliocene Magarini Sands host a poor aquifer; these sands make up the Coastal Hills which include the deposit mined by Base Titanium; this aquifer is unconfined and exploited by a few shallow wells and boreholes, and hosts a few small springs. Groundwater test yields are low (<2m^3/hr). Water quality is often poor, with waters typically of low pH and containing excessive concentrations of iron, and sometimes manganese[8].

The ISGEAG WalkTEM 38 measurement suggests that the Pliocene has a resistivity of >100Ω-m. Beneath the Pliocene at this location (Kidzumbani, 4.3km west of Mililani Centre), lower resistivity material occurs, initially 40-100Ω-m then falling to <15Ω-m; this may represent either the 'clayey pediment' that underlies the Pliocene at the Base mine; or a local occurrence of Jurassic shales or clays overlying the deeper Mazeras sandstone.

The Shimba Hills themselves are made up of the Lower Jurassic Mazeras sandstone (grits and coarse sandstones with occasional silicified wood). It forms a semi-confined or confined aquifer exploited by a number of boreholes; there are a few relatively deep wells in this unit. This aquifer in isolation is relatively poor, with test yields from two to 10m^3/hr.

ISGEAG's WalkTEM 38 measurement (at Kidzumbani) suggests that 'fresh' Mazeras sandstone has resistivities of ~100Ω-m, considerably higher than the fractured/faulted Mazeras encountered in the Gongoni Forest Base production borehole (see below).

Underlying the Coastal Hills and extending an unknown distance eastwards is a sequence of fractured and faulted Jurassic sediments that hosts a deep confined or semi-confined aquifer (typically from 60–120m bgl). This unit comprises the Mtomkuu Formation (shales, sandstones, limestones and silty clays), the Kambe limestone (classic grey, marine limestone) and the Mazeras sandstone. Boreholes drilled to ~110mbgl fitted with ~30m of high-capacity screens are capable of yields up to 230m^3/hr. The best part of this aquifer sequence is the upper-most 40m of the Mazeras, which is fractured and weathered. Between the Jurassic sediments and the Pleistocene sands a 10 – 25m thick coral-clay bed which acts as an aquitard separating the two aquifer systems. The deep aquifer is recharged by water moving laterally from the Shimba Hills and is at least partly fault-controlled. Catchment management measures to prevent soil erosion and minimise overland flow are required (soil degeneration will decrease recharge and intensify flooding downstream) to maximise recharge and help protect this aquifer from over-exploitation.

The ISGEAG geophysics programme results considerably improve our understanding of the complex groundwater system in this area, in particular in relation to the following:

a) *The geophysical and inferred hydrogeological characteristics of the major aquifer unit, the confined or semi-confined Jurassic sedimentary succession.*

The thickness of the combined Jurassic sediment sequence has been defined with reasonable accuracy; it extends from about 50 to 200-250m bgl. The top 20m comprise 'Jurassic shales' (in fact constituting both the Mtomkuu shales and sandstones, and the Kambe limestones). The remainder of the sequence comprises an intermediate resistivity layer (40-80Ω-m) from 70 to 125m bgl; and a lower resistivity zone (20-60Ω-m) from 125 to at least 200m bgl. The intermediate resistivity layer corresponds with the high-capacity fractured and weathered upper part of the Mazeras, which forms the best aquifer unit in the sequence; fresh, competent, unfractured Mazeras forms the remainder of the Jurassic succession.

[6] Base Titanium data.
[7] Gro for GooD data.
[8] Base Titanium data.

This is different to the conceptual geological model developed by Gro for GooD, which estimates that beneath the Base wellfield the thickness of the Mazeras is not more than 270m, while to the east (beneath the SWIM borehole) it is no more than 180m thick.

Beneath the Mazeras (200-250m bgl), a very low resistivity zone (<5Ω-m) is discriminated; this could either be salinised Mazeras sandstone, or the underlying Triassic Karoo sediments; in southern Kenya this is represented by the Mariakani Sandstone, an Upper Triassic sequence comprising fluvial feldspathic sandstones with shale lenses and mottled sandstone at its base. The Mariakani outcrops west of the Shimba Hills and is not known for being a high capacity aquifer (yield range from two to occasionally >10m^3/hr). The Mariakani is between 1,800 and 2.400m thick (Caswell *et al*, 1953). The horizontal resistivity profile (the top of the Mariakani and the bottom of the Mazeras) suggests that this is a geological, and not a geochemical boundary.

b) The characteristics of the aquitard that separates the shallow and deep aquifers.

The 'Jurassic shales' (50-70m bgl, resistivity <15Ω-m) act as a leaky confining bed, and in the eastern part of the Gongoni Forest area is continuously distributed. It is not universally 20m thick, however. In some parts of its range, however, it is also water-bearing. Where continuous and impermeable, these shales prevent direct recharge (and pollution).

c) The presence of hitherto 'hidden' SSW-NNE oriented faults between the mine site and the shoreline.

Caswell *et al* (1953) describe SSW to NNE oriented faults west of the Shimba Hills, but none east of the Hills in the study area. Gro for GooD geological fieldwork determined that at least three faults not described by Caswell *et al* occur east of the Hills; the first of these forms the valley of the upper Mukurumudzi River, west of the mine. The second and third lie east of the Base mine site; these are located immediately east of the mine site; and between BH5 and the BH5 replacement dual piezometer borehole. All are oriented SSW to NNE, which is parallel to the fault systems west of the Shimba Hills and roughly parallel to the coast; all are downthrown to the SSE at 2 to 3°.

ISGEAG's analysis discriminated both of the faults east of the mine site in the re-worked ERT profile along the northern edge of the Gongoni Forest; however, a further three faults may also exist (the putative faults are located 840, 1450, 2500, 3200 and 4200m from the western end of the profile, where BH5 is at +2860m). The first and fourth of these are broadly identical to the faults identified by Gro for GooD; the existence of the fifth possible ISGEAG fault is confirmed by the difference in observed geology in the BH5 replacement dual piezometer and the SWIM borehole. In the replacement piezometer, dirty grey Mtomkuu shaley sandstone was encountered from 50 to 58m bgl, and grey Kambe limestones from 58 to 92.8m bgl; at the SWIM borehole, Pleistocene coral limestones were encountered from ground level to 90m bgl. The only explanation for the difference is the putative 4200m fault, which crosses the northern Gongoni Forest boundary at about WGS84 554200E 9512300N (elevation approximately 26m amsl); this is approximately 1.9km SSW of the SWIM borehole and 1.0km east of the replacement piezometer.

Two further putative faults lie east of fault east of the mine site, but west of BH5; there is no objective evidence that these exist on the ground, but there is no evidence to contradict their existence, either.

The significance of the faults lies in their role in facilitating recharge from the west, from the Shimba Hills themselves and the fault that underlies the upper Mukurumudzi River.

d) The nature and depth of saltwater intrusion across the near-shore zone (SWIM borehole); and at an abstraction borehole located about 1.4km west of the shoreline.

A broad range of measurements (VES, WalkTEM and Zonge TDEM and AMT) have mapped the horizontal and vertical distribution of saltwater intrusion in the vicinity of the SWIM borehole in considerable detail.

Base has previously determined that electrical conductivity and bromide concentrations have increased in water from the public water supply borehole at Vingujini since early 2016. ISGEAG's WalkTEM

measurements WALKT43 and 44, to the NW and SE of the borehole objectively confirm that saltwater intrusion had indeed taken place at Vingujini as of March 2018.

e) The occurrence of a low resistivity zone within the Milalani wellfield that conforms with the broad conductivity patterns discerned in a 1977-flown TDEM survey.

An isolated investigation of the characteristics of the material within the southern or Milalani palaeochannel found the unexpected occurrence of relatively shallow saline (or low resistivity) aquifer material. Along a north-south transect approximately 300m long, low resistivity material (<10Ω-m) was observed in four WalkTEM measurements, ranging from ~115m bgl (below ground level) at the north end to ~175m bgl to the south.

In 2013, a Kwale International Sugar Company Ltd (KISCOL) borehole (BH 309) was drilled in the northern part of the WalkTEM transect, drilled to a depth of 86m and tested at 240m^3/hr. Electrical conductivities encountered across four separate struck water levels (10-72m bgl) ranged from 100 to 228µS/cm. (see Box 3 for the location of BH 309).

ISGEAG analysis of a 1977 airborne TDEM survey demonstrated that this low resistivity zone was mapped at that time, so it is unlikely that low resistivity values at this location is due to groundwater abstraction from BH 309. (Little groundwater abstraction data for KISCOL boreholes is available in the public domain.) The possibility that localised brackish zones exist is in part confirmed by the relatively poor quality water encountered in a 2003 exploratory BH drilled by Tiomin at WGS 548256E 9511068N (~60m amsl); BH D was 85m deep and tested at 13m^3/hr, and produced water with an EC of 1,859µS/cm[9]; it is located in the vicinity of the high EM response zone (30 to >35) due west of BH2 in Box 3 above (indicated as TIOMIN BH).

Beneath the Msambweni and Kinondo areas an indurated sand and coral sequence overlies Mazeras sandstone at depth. These indurated sediments occur in hitherto undescribed palaeochannels that extend from the west towards the coastline aligned approximately NNW to SSE. These are believed to have evolved between the early Cretaceous and the start of the Pliocene. Boreholes constructed in the western part of the Mililani palaeochannel encounter a high capacity semi-confined aquifer in which ~100m deep boreholes have been tested at discharge rates approaching 250m^3/hr.

The Jurassic and indurated sand and coral aquifer systems are hydraulically connected and underlie a total area of not less than 85km^2. Abstraction from this aquifer system is limited to the wellfields that help to meet KISCOL and Base water needs. Across the period during which the ISGEAG field programme was carried out, aggregate abstraction by these two water users was estimated to be ~5,200m^3/d (1.9MCM/yr).

Recharge to this entire aquifer system has recently been calculated using a simulation model (Ferrer *et al*, 2019b). The model used the soil water balance method and was calibrated against water level, abstraction and climate data from 2014 to 2017; the following recharge volumes were calculated:

Table 2. Recharge to the Msamweni aquifer 2010 - 2017

Year:	2010	2011	2012	2013	2014	2015	2016	2017
Rain:	1,022	1,406	987	1,154	1,715	1,757	867	1,442
Recharge:	71	160	50	86	156	169	58	224

NOTES:
Synthesised spliced catchment rainfall based on data from Shimba Hills Centre, Msambweni and Kwale Agricultural Stations; mm/yr. Recharge as MCM/yr.

Mean annual recharge is approximately 122MCM/yr. However, we know that recharge is immensely variable, and conforms with findings in other countries that recharge is associated not only with actual

[9] Base Titanium data.

rainfall, but with rainfall intensity (Kolusu et al, 2018; Seddon et al, 2016; Jasechko et al, 2015; Jasechko et al, 2014; Taylor et al, 2012; Owor et al, 2009) and soil type.

Similar high rainfall intensity recharge events have been observed in the study area; an example is shown in Figure 82 below.

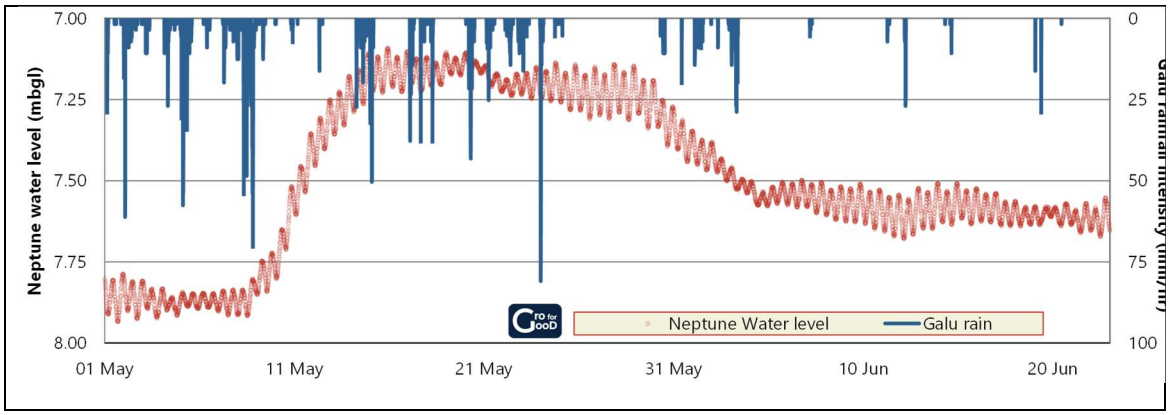


Figure 82. Water levels and rainfall intensity in the Galu area, May – June 2017

The Gro for GooD project established a water resources monitoring network across an area of 400km^2. Two sites are located in the Galu area, approximately 7km NE of the SWIM borehole. The Neptune shallow Pleistocene coral limestone aquifer monitoring site is a locked, unused well located 600m from the shoreline; a digital water level logger was installed in the well, set to record water level data every 15 minutes. A Maplin automatic weather station is installed at a house located 420m north of the well. The weather station reports rainfall intensity, among other climatic parameters, every five minutes across the period 1st May to 30th June 2017. The Pleistocene coral limestone aquifer in the Galu area is similar to that at the eastern edge of the ISGEAG study area.
This station is situated at about the 10m contour line and would lie on the edge of the red shaded zone of Figure 78 had the map covered the Galu area. Electrical conductivity in this well ranged from 2,400 to 2,650µS/cm in 2016-17 (n = 42), so it is only marginally brackish[10].

The shallow well is clearly within the zone of tidal influence, as can be seen in the Figure above, including showing neap and spring tide periods.

Rainfall in the first seven days of May 2017 totalled 173mm and did not lead to discernible recharge. However, on 8th May 174mm of rain fell in a single day, leading to a very swift increase in water level elevation. Water levels rose from 7.92m bgl at 12:02hrs on the 8th to 7.09m bgl on the 15th at 22:17hrs. This 0.83m water level increase took place over a 7.43day period. The Pleistocene coral limestone is known to be karstified in places, with very high vertical and horizontal hydraulic conductivities. The early wet period (1st to 7th May) was insufficiently intense to exceed the limestone's capacity to absorb and distribute recharge water; however, the very intense rainfall event exceeded the aquifer's ability to distribute water and so a recharge 'spike' was observed.

After the recharge peak however, continued but less heavy rainfall fell (>10mm) on the 14th, 16th, 17th, 20th, 21st, 22nd and 23rd), but water levels started to decline. The ability of the aquifer to absorb the recharging rainfall was greater than the recharging rainfall's ability to fill it, leading to a natural groundwater recession.

The Kambe limestone is a fractured marine limestone between the Mtomkuu and Mazeras Formations. It forms a confined aquifer which has been encountered and screened in three boreholes (at Bumamani, Magaoni and Fihoni). At depths of 60 to 110m, this aquifer in isolation yields >15m^3/hr, though at present it is not exploited at anything close to this level of abstraction.

[10] Gro for GooD data.

It is becoming clear – from properly-supervised boreholes and careful sample collection – that the thickness of the Kambe formation increases north of the Gongoni Forest. Boreholes drilled south of the Gongoni Forest apparently do not encounter the Kambe at all

ISGEAG analysis has not been able to discriminate the resistivity difference between the Kambe and the Mtomkuu formations, so have treated them as a single layer with a resistivity of ~15Ω-m; the two units appear to have such similar resistivities that it is impossible to model them as separate lithological units.

The Mtomkuu Formation comprises two different units (Rais-Assa, 1988):

- The Lower Mtomkuu Formation lies unconformably on the Kambe Formation. The basal part contains Mazeras and Kambe pebbles, and suggests intense erosion.
- The Upper Mtomkuu is less developed than the Lower, and is made up primarily of marine shales.

Elsewhere in this discussion, the 'Jurassic shales' have been treated as the aquitard separating the shallow unconfined aquifer from the deep semi-confined aquifer. However, in some parts of the Gongoni aquifer system, the Mtomkuu constitutes a useful aquifer in its own right; although no boreholes have been constructed only in the Mtomkuu, a significant aquifer unit in this material was encountered in BH3 from 32 to 46m bgl (calcareous sandstone and siliceous pebbles 32-40m; and fine-grained fractured and weathered sandstones 40-46m).

7.2.2 Discussion and unknowns

One of the significant uncertainties that remains – and interest in which has been re-ignited by the ISGEAG geophysical measurements and a re-appraisal of dual-rotary and fluid rotary flush drill data – is the true distribution of palaeochannel deposits in the ISGEAG study area and the broader area as well. Gro for GooD have determined that a large palaeochannel exists in the Milalani area and a smaller one in the Kinondo area. These are oriented SE to NW; the southern palaeochannel is approximately 5.4km across, while that at Kinondo is about 3.1km across. The palaeochannels terminate abruptly against the SSW to NNE fault located immediately east of the mine site.

However, there is significant scope for ambiguity in the interpretation of lithological data, even from dual-rotary drilled boreholes.

8 Conclusions and lessons learned

The Kwale experiment shows how skilled applications and integrated interpretation of multiple measurements and methods can help to provide a better insight into the groundwater system than any of these methods in isolation. In this case this leads to a better understanding of the location of the fresh and saline groundwater interface, as well as the geometry and lateral extent of both aquifers and clay layers.

The excellent documentation from existing Base boreholes and previous surveys was crucial for the improved understanding of this groundwater system. This is why we once again advise paying more attention to ensuring that the quality and availability of consultant's survey and borehole completion reports in Kenya is improved. These technical documents should be easy to acquire to minimise repetition of work, while the information in the reports themselves should be complete, correct and reproducible in a way that the data can be of use in future programs and so help to develop a better insight into the hydrogeology of an area. This ongoing process of gaining and increasing knowledge is fundamental for sensible and sustainable groundwater exploration.

8.1 Conclusions

There are multiple conclusions that can be drawn from the geophysical fieldwork executed in Kwale, and can be divided into a number of different topics, including: general approaches, methodology and geology, as well as aspects specifically related to VES, ERT, TDEM and AMT measurements and interpretations.

8.1.1 General conclusions

Borehole siting reports often lack essential information; sometimes they even contain mis-interpretations that conflict with basic methodological assumptions. In general, reports (even thorough ones) are extremely difficult to obtain and do not contribute to the understanding of the local hydrogeological conceptual model, which is essential to achieving sustainable groundwater exploration in the context of sensible water resources management. It is therefore recommended that the standard model report for any hydrogeological related assessment be adhered to and improved. Advice and recommendations are provided in Annex 2 of the ISGEAG Final (End term) Report (March 2019).

It is important to take the time to explain the purpose of the research to local communities and land owners, in order to obtain permission to access land. Share the report with relevant stakeholders after the research is completed.

8.1.2 Methodology

In Kwale, it is clear that the TDEM WalkTEM instrument gave the best results in terms of resolution. An important aspect is that the instrument calculates the inversion directly on the screen, immediately after data acquisition. This very much improved the efficiency of the surveys indeed. Establishing the depth of the fresh/saline groundwater interface can be done very quickly using the WalkTEM soundings.

The TDEM Zonge and AMT methods were poor in terms of resolution but gave useful information about the deeper layers, particularly the Zonge 4Hz soundings. With the WalkTEM, deeper soundings can be made if the loop size is increased. With an extra transmitter, depths of interpretation up to 800 m deep should be possible. This was not, however, experimented with in the Kwale case.

A combination of several transmitter loops with TDEM instruments like the WalkTEM, combined with the right software (SPIA), can give a combination of both shallow and deep inversion results at high

resolution. The use of the AMT method would not be necessary in this case. The quality of the inversions of AMT resistivity data is strongly dependent on the quality of the TDEM data.

The ERT, VES (and HEP) methods were difficult to execute because of the high resistivities of the dry sandy top layers, directly overlying low resistivity layers. Due to the problem with electrode contacts (because of the high resistivity top layer), high resolution ERT protocols (i.e. Dipole Dipole and Gradient arrays) could not be applied. Even with the Wenner array, a lot of 'bad' data points had to be deleted.

For the TDEM and AMT methods, less labour is required compared to VES soundings and ERT profiles. However, the interpretation of the data is less straightforward and instrumentation is more complex and expensive (especially the older generations of instruments). The interpretation of 1-D individual soundings (VES, TDEM, and AMT) all assume horizontal layering.

The application and interpretation of all the methods should be done with appropriate skills and experience. Conclusions reached should be based on multiple soundings and profiles. Inversion results should be combined with all additional information that is available (such as lithological and electrical logs) to develop a meaningful conceptual geological/hydrogeological model. The VES (and HEP) methods are relatively cheap, easy to use, simple and straight forward; however, they have limited resolution and exploration depth, and are of more limited utility in understanding the hydrogeological system. Finally, using inversion and interpolation programs, particularly those that use the option of automatically generating 2-D profiles, can give misleading results

8.1.3 Geology related

The first shallow clay layer in Kwale, which seemed discontinuous, can locally prevent shallow aquifer recharge. The second, the Jurassic confining layer, seems to be more or less continuous. Recharge to the second (deeper) aquifer system will mainly be indirect, from the outcrop area to the west. The deeper (Mazeras) aquifer seems to be discharging to the ocean, so saline groundwater intrusion is not yet an issue at this location. The shallow aquifer may be particularly vulnerable to increased saline groundwater intrusion, because of over-abstraction from the shallow aquifer, although currently limited evidence is available that this occurring in this location. Fresh groundwater water in the deep Karoo sandstones is expected to depths of >200m; deeper layers may contain saline water.

The surprisingly low resistivity of the Mazeras aquifer is not what would be expected of sandstone containing fresh groundwater. The reason for this could be due to a matrix consisting of conductive minerals within the sandstone; or that water bearing layers are restricted to thin layers which are beyond the resolution capabilities of the geophysical methods used. Borehole logging data seems to point to a combination of these two. The low resistivities of the Mazeras formation could also be related to a NNE-SSW oriented paleo channel associated with and connected to the palaeo channels as referred in the STOTEN paper (Ferrer et al, 2019).

Additional TDEM WalkTEM soundings south of the study area at Vingujini showed clear evidence of saline groundwater intrusion, probably due to extensive groundwater exploitation. More (saline) groundwater mapping with the WalkTEM, or even airborne TDEM (SkyTEM) is strongly recommended.

Near Gazi (at the SWIM borehole), at least one additional dual-piezometer monitoring site is recommended further inland from the current SWIM location, 350 m due west of the main road and opposite the SWIM borehole; A dual-piezometer installed in this area will monitor saltwater intrusion more effectively than the current single monitoring point.

8.1.4 Chapter 3: Conventional methods (VES)

- Referencing VES measurements to reliable borehole information clearly shows the limitation of electrical resistivity methods. The interpretation of unconstrained VES soundings is restricted to models with four to five layers. Due to equivalence, VES soundings cannot accurately discriminate the many sub-layers without recourse to additional geological information, such as borehole lithological or electric log data.
- The effective exploration depth of VES in this dry sandy area is practically limited to approximately 60–70m; this is even less than the 'rule of thumb' that penetration depth is 1/6 the electrode separation distance, AB. Beyond this depth the inversed layer parameters are

uncertain; and at greater depths still, parameters (both resistivities and thicknesses) are comparatively meaningless.

- In VES layer models with more than three layers, the parameter values can be 100% correlated. This interpretation problem can only be tackled by restricting one of the parameters to a 'realistic' value from independent geological data.
- The measured apparent resistivity field curve data were not 'shifted' (smoothed), which many Kenyan consultants routinely do. 'Standardized' shifting/smoothing of the field curve can lead to erroneous interpretations. Shifting should always be done with care, and based only on the correct information; for example, by when lateral changes that are clearly indicated from multiple double potential readings. This issue (smoothing) is an important subject for discussion and further research.
- If field data are shifted, it is extremely important to include the original, unshifted raw data in the report, so that they are available for any future re-interpretation.
- The possible interference effects of the power lines (both above and below ground level) at BH5R and BH3 were not investigated.
- The proper calibration (and correct operation) of resistivity equipment is an important issue that should be better addressed in Kenyan groundwater survey practice.
- In the ISGEAG Kwale campaign three different DC resistivity instruments were used: an ABEM SAS1000 (AMREF), a Scintrex SARIS (Manken Consultants) and an ABEM Terrameter LS (Jos Hansen Ltd). Of the three instruments, the 24V SARIS and LS are superior. They can generate sufficient current to obtain useful readings up to (at least) a 250 m electrode spread (AB/2). In this dry area the 12V SAS1000 was not able to generate useful measurements beyond an electrode separation of 80m.
- Our (first) experience with the new ABEM Terrameter LS (only the VES application was used) led to some interesting conclusions:
    - The instrument was found to be 'too user-friendly', making flexible operation quite difficult; in order to measure alternative current electrode separations, we needed to by-pass the fixed menu provided in the instrument;
    - The instrument gives measuring standard deviations for the potential and current electrodes separately, which we found helpful in tracing electrode contact problems;
    - The instrument calculated the standard deviation within a single measurement cycle which makes it at least twice as fast as instruments such as the ABEM SAS4000 which for ERT measurements is a significant advantage;
    - The instrument can generate very high voltages, which can be useful in difficult conditions;We were not able to explore the very promising capacity of the instrument in making ERT measurements.

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

- ERT is an integrated combination of multiple VES measurements (and therefore a much better alternative than 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 along the same alignment; and when using smaller electrode distances (shorter profile lines with a higher resolution but with decreased exploration depth);
- In this region, with very high resistivity at t ground surface (i.e. dry sand), the application of the ERT method is difficult due to poor electrode contact, especially with long cables and electrode distances. In these areas the Wenner array is often the only configuration that is applicable; while this configuration typically has poorer resolution, it is less sensitive to lateral changes;
- 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 match these requirements;
- Multi-channel instruments (like the ABEM SAS 4000 or ABEM LS) can speed up the measurement and increase the number of measurements made, if good electrode contact can be established;
- Because of its excellent lateral resolution, when choosing the most appropriate electrode configuration for a given area (e.g. Dipole, Gradient, Schlumberger, Wenner), the ERT method can give insight into both vertical and lateral resistivity changes and the depth to the saline groundwater interface;

- Coupling with powerlines and galvanic protected buried iron pipes can influence the quality of the data especially when the profiles orientate parallel to these anthropogenic features;
- ERT software generates nice coloured images, but this is not where the interpretation process ends. Actually, it is where it starts; it is a process of trial and error together with the elimination of incorrect field data, the application of different inversion constraints and alternating with forward modelling, which together achieve the best fit into a hydrogeological conceptual model;
- In ERT tomographs, the % RMS error, the protocol and inversion program used, the type of inversion and the amount of data reduction/correction should be indicated ted.

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

- The WalkTEM instrumentation is a great improvement in conducting TDEM soundings over earlier instruments; the system is relatively small and portable, easy to operate, generates inversions directly on the screen, and has high resolution of both very shallow and deep layers at the same time;
- In sedimentary areas (as encountered in Kwale), under the given circumstances (high resistivity top layer), the application of TDEM is expected to be more successful than in Basement areas, because EM systems are more sensitive to conductors (low resistivity layers). However, a lack of resistivity contrast can limit the results. Compared with DC systems, the optimum resistivity range in which TDEM operates is restricted; however, TDEM systems can accurately discriminate low resistivity zones beneath high resistivity zones, due to the high resistivity contrast. The depth to zones containing saline groundwater are an excellent target for the TDEM method;
- As with VES, the interpretation assumes horizontal layering. Lateral changes (vertical contrasts in resistivity) in the vicinity of a TDEM sounding will give disturbances, but much less so than with VES because of the smaller footprint (a 40 X 40 m loop rather than several hundreds of metres of linearly-aligned cable)
- In dry areas where the exploration depth of VES and ERT is limited by high surface resistivities, the TDEM system is very useful;
- 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 discriminate low resistivity layers with an accuracy of less than 5 m. The lower the resistivity (the higher the contrast), the better the depth resolution. The resolution becomes poorer in high resistivity areas, especially when the resistivity increases with depth (as in Basement terrain);
- In most of the TDEM systems, the first ten meters are not measured, due to delay times needed to shut off the transmitter. With the WalkTEM this problem has been overcome; by using the dual moment option, information for shallow depths is also collected;
- For a proper application of TDEM, good skills and experience in interpretation are needed; the operation protocol is a good deal less straightforward than with VES instruments (such as Terrameters). Useful soundings are not always directly recognized from decay curves. For very deep soundings, stronger transmitters are needed. The WalkTEM has very much improved over earlier instruments in this regard;
- Instrumentation is more sensitive, expensive and sometimes more complicated to control;
- Inversion, and inversion software, are more complicated than with VES interpretation;
- Higher resolution 2D profiling can be carried out by conducting multiple soundings along a profile line. Such protocols are used in airborne TDEM systems such as the SkyTEM, where the instruments, hanging below a helicopter, conduct many soundings along straight flight-lines;
- TDEM is an EM method; galvanic coupling with metal (fences, pipelines, and powerlines) can be severe. However, no electrodes are needed, which makes it very suitable in areas with a high resistivity top layer, like Kwale.

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

- The AMT method is less labor intensive than both VES and ERT. However, the setup must be done with great care. Adjusting the system and taking measurements as well as data validation has to be done with careful professional judgement. In the fieldwork area, a calibration should be executed for the magnetic sensors in a relatively magnetic noise-free area;

- Because AMT is a passive system that uses natural sources (thunderstorms, solar winds), no transmitter is required; this makes the instrumentation relative light and compact, compared with TDEM, ERT and VES methods. There are also AMT systems available that use their own transmitter (Controlled Source AMT);
- Application of AMT in noisy areas (power lines, urbanization etc.) is very limited and relatively intense data sampling is required.

8.2 Lessons learned

Besides conclusions drawn from the geophysical program executed in Kwale, some important lessons were learned during the on-the-job training component. Some of the major lessons learned are listed below:

- Memorandums of Understanding (MOUs) with project partners should be signed well in advance of starting the fieldwork mission. Final payment should only be made at the end of the fieldwork and when all the data and interpretation have been delivered.
- The project plan should allow for ample time for mutual interpretation and reporting. This was a severe challenge, particular in the co-operation between the KenGen and Dutch experts. Mission time was mainly spent on conducting measurements in the field, logistics, data quality analysis and building a database. Project time for combined inversion and mutual interpretation of the many data sets collected was inadequate. Subsequent and protracted email communication proved to be an ineffective way to resolve this deficiency. Ample time for conjunctive learning and discussion would not only improve the results and the reporting, but it would also reinforce the role and knowledge of local partners.
- File names, stations names and numbers should be unambiguous and GPS coordinates should be adopted according to international standards and reciprocal with Google-Earth (WGS84).
- Before the start of the fieldwork, the field location should be visited for a reconnaissance and a thorough social grounding by a field hydrogeologist, a social worker and local community leaders

References

ABEM (2010). Terrameter SAS 4000 / SAS1000 Instruction manual. ABEM Instrument Sweden. http://www.guidelinegeo.com/wp-content/uploads/2016/03/Manual_Terrameter.pdf

Adams, B., 1986. Tiwi Aquifer study. British Geological Survey and Ministry of Water Development.

Alle, I.C., Descloitres, M., Vouillamoz, J-M., Yalo, N., Lawson, F.M.A., Adihou, C. A., 2018. Why 1D electrical resistivity techniques can result in inaccurate siting of boreholes in hard rock aquifers and why electrical resistivity tomography must be preferred: the example of Benin, West Africa. Journal of African Earth Sciences 139 (2018) 341-353.

Austromineral (A. Horkel ed.), 1978. Geological Survey and Results of Mineral and Base Metal Prospecting in the Coastal Belt South of Mombasa (Kwale-District). Kenya-Austria Mineral Exploration Project: Rept. Ill, 106 pp., Vienna 1978.

Austromineral, 1980. Groundwater exploration in Taita Hills and Mombasa South areas. Unpublished report to Ministry of Water Development and Natural Resources, Nairobi.

Buckley, B.S., 1981. Report on a Visit to Assess Groundwater Potential of the Kenya Coast of Malindi (Including Proposals for the South Coast Groundwater Resources Project). Institute of Geological Sciences (IGS), Wallingford, UK.

Carruthers, R.M., 1985. Report on geophysical studies relating to the coastal aquifer of the Mombasa district, Kenya. British Geological Survey, Natural Environment Research Council, report RGRG 85/4.

Caswell, P.V., 1953. Geology of the Mombasa-Kwale Area. Geological Survey of Kenya. Rept., 24 (1952), Nairobi 1953.

Ferrer, N., Folch A., Lane M., Olago D., Odida J., Custodio E., (2019). Groundwater hydrodynamics of an Eastern Africa coastal aquifer, including La Niña 2016-17 drought. Science of the Total Environment, 661 (2019), pp. 575-597.

Ford DC & Williams P, 2007, Karst hydrogeology and geomorphology (Revised edition). John Wiley & Sons.

Gichaba, C.M., Anyumba, J., Eloso G.F., 1992. Groundwater potential in Kidiani area, Kwale district, Kenya. Atti Ticinesi Scienze della terra, 35 (1992), 231-272.

Groen, M., Rolf, H.L.M., Omiti, A., Cosmas, R., 2018. ISGEAG, 1st Technical Report, geophysics near Kajiado town, 1st technical report within the ISGEAG VIA-Water, project managed by Acacia Water, The Netherlands. Final Report, August 2018. Accessible via: https://www.samsamwater.com/projects/81/data/synthesis_report_Technical_Report_Kajiado_town_AUG2018.pdf

Gro for GooD/Base Titanium Ltd, 2019, Drought and Recovery in 2016-17 in the South Kenya Coast. A Study of Climatological, Surface Water, Groundwater and Socio-Economic Conditions in Msambweni Sub-County through a Drought and Recovery Cycle. In press.

Groundwater Survey (K) Ltd, 2005. Borehole Drilling and Completion Report, Msambweni Area, Kwale, South Coast. Prep. for: Tiomin Resources Inc., Report No. 05/1054, June 2005, Nairobi.

Hetu, R., 1978. Interpretation Report: Airborne EM Survey with Barringer "INPUT" System of Area 6 (Tiwi Aquifer). Unpublished Report 77–18. Terra Surveys Ltd. For Ministry of Natural Resources, Mines and Geology, Kenya.

Horkel, A.D., 1984. Notes on the geology and mineral resources of the southern Kenyan coast. Mittel Österreichische Geologische Gesellschaft. Accessible via: *https://www2.uibk.ac.at/downloads/oegg/Band_77_151_159.pdf*

Jasechko S, Birks SJ, Gleeson, Wada Y, Fawcett PJ, Sharp ZD, McDonnell JJ & Welker JM, 2014, The pronounced seasonality of global groundwater recharge. Water Resources Research, Vol. 50, pp. 8845–8867

Jasechko S & Taylor RG, 2015, Intensive rainfall recharges tropical groundwaters. Environ. Res. Lett., Vol. 10, 7pp

Kolusu SR, Shamsudduha M, Todd MC, Taylor RG, Seddon D, Kashaigili JJ, GY, Cuthbert MO, James PR, Sorensen JPR, Villholth KG, MacDonald AM & MacLeod DA, 2018, The El Niño event of 2015-16: Climate anomalies and their impact on groundwater resources in East and Southern Africa. Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-516.

Loke, M.H. (1999). Manual RES2Dinv/mod ver.2.2 Rapid resistivity inversion/forward modelling; Freeware courtesy of M.H.Loke, *http://geom.geometrics.com/pub/GeoElectric/Drawings/Res2Dinv.pdf*

Michieka, D.O., van der Pouw, B.J.A., Vleeshouwer, J.J., 1978. Soils of the Kwale-Mombasa-Lungalunga area, quarter degree sheets 200, 201 and 202. Kenya Soil Survey Project, Reconnaissance soil survey report no. R3, Nairobi. Including soil map. Ministry of Water and Irrigation, 2005, Practice Manual for Water Supply Services in Kenya. Nairobi, October 2005.

MoWI/KCG (Ministry of Water and Irrigation/Kwale County Government Water Services, Infrastructure Development and Public Works), 2017, Water Security and Climate Resilience Project – Phase 2 Consultancy Services for Preparation of Kwale County Water Supply Development Master Plan Draft Water Supply Development Master Plan Volume I: Report Version 0. Prep. by Egis Eau, Nairobi.

Mumma, A., Lane, M., Kairu, E., Tuinhof, A., Hirji, R., 2011. Kenya, Groundwater Governance Case Study. World Bank Water Papers, *www.worldbank.org/water*

NDMA (National Drought Management Authority), 2019, Kwale County Drought Early Warning Bulletin February 2019.

Oiro, S., Comte, JC., 2019. Drivers, patterns and velocity of saltwater intrusion in a stressed aquifer of the East African coast: Joint analysis of groundwater and geophysical data in southern Kenya. Journal of African Earth Sciences 149 (2019) 334–347

Oosterom, A.P., 1988. The Geomorphology of Southeast Kenya. Doctoral Thesis, Agricultural University, Wageningen. 227 pp., 34 tbs, 32 figs, 160 refs, 1 map (1: 500 000).

Oteri, A.U., 1991. Geophysical investigations of sea water intrusion into the Cainozoic aquifers of South Coast Kenya, a review. Department of Geology, University of Nairobi, Journal of African Earth Sciences, Vol. 13, No. 2, pp. 221-227.

Owor M, Taylor RG, Tindimugaya C & Mwesigwa D, 2009, Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin. Environ. Res. Lett. Vol. 4, 6 pp

Pedersen, J.B., Schaars F.W. et al. (2017). Mapping the fresh-saltwater interface in the coastal zone using high-resolution airborne electromagnetics; a case study where AEM is used to map saltwater intrusion as well as the outflow of fresh water to the sea. EAGE, First

Break, Volume 35 I, August 2017.
https://pdfs.semanticscholar.org/179e/c27d9a0929855b6c4fab5158063b266d15a7.pdf

Post, V.E.A., Groen, J., Kooi, H., Person, M., Shemin Ge., Edmund, W.M., 2013. Offshore fresh groundwater reserves as a global phenomenon. Nature, Vol.504, December 5, 2013.

PWN, Artesia, (2013). Hydrological application of Airborne TDEM in the dunes along the Dutch Coast; some summarizing slides. PWN, Artesia and partners. http://www.artesia-water.nl/wp-content/uploads/Hydrological-application-of-airborne-TDEM-SkyTem-along-the-Dutch-Coast-.pdf

Rais-Assa, R., 1988. Stratigraphy and geodynamics of the Mombasa Basin (Kenya) in relation to the genesis of the proto-Indian Ocean. Geol. Mag. 125, 141–147.

Rolf, H., (2017a). Geophysical surveys for Sponge City project Kajiado, Kenya; field investigations carried out in February 2017 for the VIA Water funded projects Sponge City and ISGEAG, projects managed by RAIN Foundation and Acacia Water. Technical report SamSamWater Foundation, the Netherlands. Accessible via:
https://www.samsamwater.com/projects/81/data/Geophysical_technical_report_FINAL_09AUG2018.pdf

Rolf, H. (2017b). VES soundings Kajiado Town; technical Interpretation and inversion results of all available VES soundings in and near Kajiado Town up to April 2017. Technical report SamSamWater Foundation, The Netherlands.
Accessible via:
https://www.samsamwater.com/projects/81/data/VES_soundings_Kajiado_Town.pdf

Rolf, H., 2019. VES soundings ISGEAG Kwale, technical interpretation. Technical Interpretation and inversion results of all VES soundings conducted in the VIA-Water ISGEAG project, Kwale field campaign April 2018. SamSamWater Foundation, Netherlands. (in prep.).
Accessible via: https://www.samsamwater.com/projectdata.php?projectid=86

Seddon D, Taylor R, Kashaigili J, Todd M & Cuthbert M, 2016, Episodic groundwater recharge in a semi-arid environment - assessing the impact of the 2015-16 El Niño in Central Tanzania. Abstract n°1869, 43rd IAH Congress, 25-29th September 2016, Montpellier, France.

Tahal Group, 2012, Consultancy Services for Water Supply Master Plan for Mombasa and other Small Towns within the Coast Province, final water resources report. Coast Water Service Board & Ministry of Water and Irrigation, WaSSIP project, August 2013.

Tahal Group, 2013, Consultancy Services for Water Supply Master Plan for Mombasa and other Small Towns within the Coast Province, full feasibility report. Coast Water Service Board & Ministry of Water and Irrigation, WaSSIP project.

Tahal Group, 2013, Consultancy Services for Water Supply Master Plan for Mombasa and other Small Towns within the Coast Province, preliminary design report. Coast Water Service Board & Ministry of Water and Irrigation, WaSSIP project, August 2013.

Taylor RG, Todd MC, Kongola L, Maurice L, Nahozya E, Sanga H & MacDonald AM (2012): Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. Nature Climate Change, Vol. 3, pp. 374–378.

Thomson P, Hope R and Foster T, 2012, GSM-enabled remote monitoring of rural handpumps: a proof-of-concept study. Journal of Hydroinformatics, vol. 14 no. 4, pp. 829-839.

Thomson P, Bradley D, Katilu A, Katuva J, Lanzoni M, Koehler J & Hope R, 2018, Rainfall and groundwater use in rural Kenya. Science of the Total Environment, No. 649, pp. 722–730.

Tole, M.P., 1997. Pollution of groundwater in the coastal Kwale District, Kenya. School of Environmental Studies, Moi University, Eldoret, Kenya. Sustainability of Water Resources

under Increasing Uncertainty (Proceedings of the Rabat Symposium S1, April 1997. IAHS Publ. no. 240, 1997. 287

Wright, E.P., 1985. Visits to Kenya, Malawi and Zimbabwe, 21 April to 12 May 1985, 'back to office report'. WD/OS/85/16 June 1985

Zohdy, A.A.R. et al.,1974. Application of Surface Geophysics to Groundwater Investigations. Techniques of Water-Resources Investigations of the USGS, Chapter D1. *https://pubs.usgs.gov/twri/twri2-d1/pdf/TWRI_2-D1.pdf*

Annexes

Annex 1: Coordinates and raw field data of the Soundings

The raw measured data and WGS84 locations of all TDEM, ERT and AMT soundings are available on the SamSamWater website as:

raw_data_ISGEAG_Kwale_31032019.7z

The raw measured data of the ISGEAG Ves soundings are given in Annex 2.

Annex 2: Coordinates and raw field data of the VES Soundings

Coordinates VES sounding locations (WGS84)	
VES 1	4°24'29.50"S 39°30'21.69"E
VES 2&2A	4°24'28.67"S 39°30'19.33"E
VES 3	4°24'28.53"S 39°28'42.21"E
VES 4	4°24'26.03"S 39°28'37.43"E
VES 5	4°24'26.03"S 39°28'37.43"E
VES 6	4°24'23.82"S 39°28'35.13"E

Measured VES sounding field data ISGEAG Kwale

- apparent resistivity in Ωm, - unshifted raw data - in red: reading standard deviation larger than 1%

*) VES 4 SARIS Wenner was executed twice

**) VES5 Standard devations LS from potential electrodes

VES1		VES 2		VES2A		VES3		VES 4								VES 5		VES 6			
SAS1000 Schlumbg		SAS1000 Schlumbg		SARIS Schlumberger		SAS1000 Wenner		SAS1000 Wenner		SARIS Wenner *)		SARIS Schlumberger		LS Schlumberger		LS Wenner		SARIS Wenner		SAS1000 Wenner	
AB/2	Rho	AB/2	Rho	AB/2	Rho	AB/2	Rho	AB/2	Rho	AB/2	Rho	AB/2	Rho	AB/2	Rho	AB/2	Rho **)	AB/2	Rho	AB/2	Rho
1.6	33	1.6	1642	1.6	2025	1.2	4350	3	3960	15.0	1485	1.6	3588	2.4	1804	1.2	10150	9.0	1070	1.8	10802
2	27	2	9554	2	2024	2	4841	6	3164	15	1486	2	3827	3	1759	2	11625	12	465	2	11551
3	23	3	1716	3	1958	2	4576	9	2493	21	799	3	4037	6	1306	3	13356	15	297	3	9832
3	19	3	1504	3	1696	2	4635	15	1330	21	798	3	4081	8	1000	5	14250	18	185	6	4200
4	16	4	1269	4	1372	3	4606	18	996	30	251	4	3847	10	751	8	12152	24	90	6	4260
5	17	5	1011	5	1131	4	4287	24	556	30	251	5	3431	13	715	12	4270	30	75	9	1580
6	18	6	755	6	821	5	3866	30	221	45	68	6	3007	13	591	18	2503	36	73	9	1580
8	16	8	488	8	445	6	3883	36	113	45	65	8	2393	18	443	30	158	42	55	12	746
8	19	10	255	10	269	8	3203	42	93	60	50	10	1923	24	185	36	121	51	54	12	741
8	18	13	76	13	128	9	3254	51	84	60	48	13	1240	32	54	42	93	60	82	15	496
10	18	13	144	16	59	12	1425	60	76	90	35	16	1327	42	29	51	60	75	60	18	395
10	20	16	57	20	20	15	890	75	52	90	38	20	723	56	32	60	49	90	64	24	238
13	20	20	32	20	52	18	490	90	12	120	29	25	351	75	19	75	51			24	177
13	25	25	23	25	40	24	175	120	105	120	28	25	670	100	17	90	44			30	263
16	28	32	23	25	31	30	81	150	36	150	24	32	158	133	18	120	38			30	226
16	22	40	21	32	71	36	56	180	165	150	25	45	65	178	27	150	25			36	225
20	22	50	19	32	32	36	56	240	297	180	22	40	232	237	24	180	25			42	105
20	26	63	2	32	78	42	23	316	78	180	19	50	124			240	21			51	156
25	15	63	3	40	48	42	18			210	14	63	58			300	24			60	324
25	14	80	5	40	27	51	15			210	22	80	40							60	247
25	14	80	14	50	61	51	26					80	53							75	199
32	18	100	8	50	14	60	38					100	33								
32	17			63	112	60	46					130	27								
32	14			63	38							160	26								
40	3			63	30							200	15								
50	4			80	61							200	17								
				80	8							250	13								
				100	3							250	23								
				130	2																
				130	2																
				160	1																
				200	5																











KENGEN
Kenya Electricity Generating Company Ltd.
Olkaria | Off Moi Southlake Road.
P.O BOX 785 20117 | Naivasha | Kenya
Tel: 0725921886, +254 711 037085
www.kengen.co.ke

SamSamWater Foundation
Westzijderveld 101 R
1507 AA Zaandam
The Netherlands
phone +31 (0)6 44 988 559

Wiertsema & Partners
Feithspark 6 9356 BZ Tolbert
Postbus 27 9356 ZG Tolbert
Telefoon (0594) 51 68 64
Fax (0594) 51 64 79
www.wiertsema.nl

Amref Health Africa in Kenya,
Wilson Airport, Lang'ata Road,
P.O. BOX 30125-00100,
www.amref.org

Acacia Water
van Hogendoornplein 4
2805 BM Gouda
The Netherlands
Telefoon: 0182 – 686 424
Internet: www.acaciawater.com
Email: info@acaciawater.com