Hydrogeophysical characterization of groundwater conductors and storage geological structures through Audiomagnetotelluric and Electrical Resistivity Tomography methods

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Abstract

Geophysical-structural and hydrogeophysical studies were carried out using the Magnetotelluric (MT), Audiomagnetotelluric (AMT) methods and Electrical Resistivity Tomography (ERT) technique, which allowed a better understanding of the Caxambu groundwater regarding the structures geometrical parameters. For processing the MT and AMT data, the robust Egbert code (Ebert, 1997) and for inversion ModEM algorithm (Egbert et al. 2017) were used. For the ERT data, processing and inversion had done by a commercial 2D and 3D software. The AMT and ERT results produced a joint model called Resistivity Cube, which integrated and emphasized at different depths the region's structures found. The results generated by the three methods were interpreted together based on the previously geological studies developed by CPRM (1999) and Pedrosa-Soares et al. (2018). The results can provide the ideal management of the hydric reserve avoiding the indiscriminate water use that can lead to shortages. This study is of public interest that may support the development and organization of hydromineral planning, management and conservation in the short, medium and long terms. Given the current urban occupation, potential contamination factors and other aspects with a potential influence on its characterization as a natural and socio-economic resource, a policy under the demand for water may be developed for the conscious use of these water sources.

Introduction

For water resources mapping, it is not the groundwater itself that is the target, but the geological situation in which the water is inserted. Geophysics plays an important role in the characterization of rocks for groundwater studies. Electrical and electromagnetic methods proved to be particularly applicable to hydrogeophysical studies. The properties of geological formation are important for hydrogeology, such as porosity and permeability of rocks, and they can be correlated with signatures of electrical resistivity.

The work focuses on the Water Circuit located in the south of Minas Gerais, in the city of Caxambu. Known for its hydromineral wealth, water fountains are important for the city's supply, economy and tourism, as they have medicinal and therapeutic properties. In the middle of the Serra da Mantiqueira, the Water Park Tourist Complex integrates ten municipalities.

Geotechnical, Geological and hydrological studies developed by Pedrosa-Soares et al. (2018) and CPRM (1999) in the region had obtained a greater understanding of the processes that involve the formation and characterization of hydrothermal founts.

This research aims to deepen the knowledge regarding the storage and conductive structures of water based on geological-structural mapping studies developed by UFMG and the UERJ teams. The work objective is to obtain responses of these structures behavior in the subsurface and to understand the geometric parameters of the structures (dimension, depth, dip angle), circulation dynamics, natural and/or induced discharge and to map the possible conductor that supplies the region.

With AMT and ERT within Water Park, it was possible to verify the influence of Bengo's Brook and characterize the shallow conductive structures up to 300 m according to the salinity that the water sources present. From these two results, it was possible to integrate them in the developed technique known as the Resistivity Cube. Out of the Park, the AMT and MT results complement each other, imagining up to 5 km in depth. They showed the behavior of the fault and fracture system, their dependence of Caxambu Shear Zone, how this Zone affected on the upward interaction between the deep conductors found in the MT and the conductors.

The study is of public interest because the city depends on this natural resource for local supply and the indiscriminate use of water can lead to a reserve shortage. Thus, the information obtained generates information for the community and local managers on how to conserve and preserve the hydromineral instance, in the short, medium and long terms, given the current urban occupation and potential contamination factors of the sources/wells.

Theory

- **The Magnetotelluric Method**

The MT method, according to Tikhonov (1950) and Cagniard (1953), is based on the electromagnetic induction principle, where electromagnetic waves are generated by physical phenomena in the atmosphere and vertically focus on Earth's surface.

The induction of electric current on Earth occurs generating a secondary electromagnetic field. Horizontal (Hx and Hy) and vertical (Hz) magnetic field components are measured at the surface in a frequency range of 10^{-4} Hz to 10^4 Hz by induction coils and the components of the electric field (Ex and Ey) by non-polarized electrodes.

The Audiomagnetotelluric method is an MT method variation where, in this case, the frequency used is between 10 Hz and 100 kHz, which is very applied on groundwater studies (Vozzof 1991).

The most important method parameter is the Impedance Z. In the frequency domain (ω), the horizontal electric E(ω) and magnetic H(ω) fields can be related through the complex 2x2 impedance tensor Z(ω):

$$\begin{pmatrix} Ex\ (w) \\ Ey\ (w) \end{pmatrix} = \begin{bmatrix} Zxx(w) & Zxy(w) \\ Zyx(w) & Zyy(w) \end{bmatrix} \begin{pmatrix} Hx\ (w) \\ Hy\ (w) \end{pmatrix} \quad (1)$$

From each impedance tensor component, the apparent resistivity (Eq. 2) and phase (Eq. 3) can be calculated.

$$\rho_a = 1\omega\mu|E_x|^2|H_y|^2 = 1\omega\mu|Z_{xy}|^2 \quad (2)$$

$$\Phi = \arctan \frac{Im\ (Z(w))}{Re\ (Z(w))} \quad (3)$$

Which ω is the frequency,μ is the magnetic permeability.

- **ERT technique**

Electroresistivity is a shallow resolution method and also provides contrast information of the resistivity between subsurface layers, consisting of the application of an artificial current (I) source in the ground through the electrodes in a contact line (Telford et al 1990). The procedure objective is to measure the electrical potential difference (ΔV) between two points, associated with induced electric currents and it is based on Ohm's law (V= RI). The basic equation for calculating apparent resistivity (ρ) for any electrode configuration (Kearey et al. 2013) is:

$$\rho = \frac{\Delta V}{I} \left\{ \frac{2\pi}{\frac{1}{ra} - \frac{1}{rb} - \frac{1}{RA} + \frac{1}{RB}} \right\} \quad (4)$$

The most common electrode arrays used are Wenner, Schlumberger, and Dipole-Dipole.

Geological Characterization

Caxambu is located at Minas Gerais South part, between two narrow valleys formed by those rivers Cachoeirinha and Bengo. It occupies a small part of Mantiqueira Hill and with Alto Parnaíba Arch and Verde River Depression constitute the local scenario. Thus, all hydromineral parks that are part of the Minas Gerais Water Complex are located in floodplains of the Rio Verde Depression.

In synthesis, Caxambu is over an area marked by tectonic events responsible for intense ductile deformation (Machado and Endo 1993; Ebert et al. 1993).

All the region’s rocks are fractured in different degrees. Those fractures have a preferred orientation to ENE/WSW, NS, NW/SE, SE/NW. Considering the various present lithotypes, quartzites are those with the highest fractures density, followed by gneisses and shales (Pedrosa-Soares et al. 2018).

The local geology is complex and it is represented by the presence of gneissic rocks of the Archean/Paleoproterozoic basement and the succession of metasedimentary rocks (shales, gneisses and quartzites) of the Andrelândia Mega Sequence (Hasui 1982). The local geology composition can be seen at the Figure 1.

- **Hydrologic and Hydrographic study**

The Water Park of the municipality of Caxambu is located at Bengo Brook. This is part of the hydrographic unit called the Cachoeirinha sub-basin, which is part of the Baependi River basin (Pedrosa-Soares et al. 2018).

From studies carried out by CPRM (1990) in this area, there are the predominance of fractured and intergranular aquifers distributed along the main drainages. NE-SW direction failures and fractures condition a large part of the drainages that form this sub-basin.

The recharge of these two types of aquifers occurs mainly by rainfall infiltration in the areas with higher topography and flows into subsurface to the local base level that is marked by the Bengo’s Brook channel (Pedrosa-Soares et al. 2018).

Along the Caxambu hill, the drainage shows an annular pattern, with an inflection of the Bengo stream. The hill also represents the main recharge area. Justified by the presence of alkaline intrusion that is the most significant means of circulation and mineralization of the waters captured in the Park (Carmo et al. 2006).

The hydrochemical results and the Carbon-14 dating carried out by Pedrosa-Soares (2018) presented that the water has a deep circulation, old and meteoric origin, past rainwater, associated with thousands of years. From the isotopic studies also carried out, there are two groups of water sources with different characteristics. They indicate the existence of two groundwater circulation domains, whose compartmentalization and isolation can be explained by anisotropy and lithostructural heterogeneity along the Caxambu Shear Zone. Thus, the group I include the sources Dona Leopoldina, Dom Pedro, Viotti, Mayrink 1, Mayrink 2, and Mayrink 3 and are considered less salinized. The second group includes the most salinized sources: Duque de Saxe, Venâncio, Ernestina Guedes, Dona Izabel, Beleza, and the Geiser. These sources can be seen at Figure 2.

Data acquisition and Processing

- **Field Planning**

The data survey consisted of two phases: the first one within Water Park, in the city of Caxambu, and the second one outside of it, in its countryside. Each one of these phases had different goals and approaches. The first one, within the Water Park, the main objective was to investigate shallow geological structures with 50 m resolution and detail level. In this case, the fieldwork consisted of acquired ERT and AMT profiles. For both methods, four profiles were raised, which three of them were dip (P1, P2, and P3) and one strike (P4). For the ERT were using stainless steel electrodes; the spacing of 5 m between them; and Wenner, Schlumberger, Dipolo-Dipolo and Mixed arrangements.

For the AMT method, the data acquired with 50 m spaced stations and cross arrangement, totaling 18 stations within the Hydric Complex. The length of the electrics dipoles Ex and Ey, north/south and east/west, respectively, were 52 meters; the electrodes used, as well as in the ERT method, were stainless steel. The frequency range used was from 10 Hz to 100 kHz divided into three bands.

The second part consisted of a survey outside the Water Park, in Caxambu countryside. Three dip profiles were acquired applying MT and AMT methods. The main objective of this survey was to verify the existence of deep conductive structures with the MT that, possibly, can feed the Water Park sources and its interaction with the shallow conductors investigated by the AMT. The spacing ranged from 300 m to 500 m and field arrangement was cross-shaped.

The Figure 3 exhibits the acquired profiles inside (in green) and outside (in blue) the Park. The red line is the Verde River drainage which cuts all dip profiles, been Bengo Brook the most important in the area.

- **ERT data treatment**

The 2D and 3D ERT data were treated using a 2D and 3D commercial processing and inversion softwares, respectively. On them, the spikes were removed and the data that had a lot of associated noise and that would affect the result were evaluated. After this adjustment and data processing, topography insertion, the inversion was made using Occam Inversion Methodology. This methodology aims to obtain the most smooth model with predict and observed data fitted.

Concerning 3D data, it was generated from 2D profiles raised parallel to each other, P2 and P3.

- **MT data treatment**

To obtain the impedance tensor was used the robust Egbert code (Egbert, 1997), which is a technique analogous to the least-squares estimate. Egbert's robust method minimizes the differences between observed and predicted values and assigns weights to errors that vary within an iterative process until convergence is achieved.

After processing the data, it is necessary to know how the subsurface structures behavior with regard to dimensionality. The method used for dimensionality analysis was Phase Tensor (Caldwell et al 2004 and Booker 2014).

The Figure 4 shows the Dimensionality Analysis applied to AMT data acquired inside the Park, while the Figure 5 represents the Dimensionality Analysis on AMT and MT data, respectively, surveyed outside the Park.

After this Dimensionality Analysis treatment part, was necessary to retrieve apparent resistivity data through the impedance phase curves using the Rhoplus algorithm (Parker and Booker 1996). Then the inversion was performed using the three-dimensional magnetotelluric inversion algorithm of Egbert et al. (2017), called ModEM.

- **Resistivity Cube**

This Cube could been developed after the ERT and AMT results are obtained. The main objective was to generate sections for each profile based on the union of previously obtained results. Therefore, the ERT was more evident for presenting a better resolution in shallower depths, discretizing shallow structures e throughout the session emphasizing the AMT to image higher depths. This technique could be applied because the parameter used in both methods is the same: resistivity.

Results

The results of ERT 2D (Figure 6) and 3D (Figure 7) produced models at a depth of up to 40 m. The Wenner, Schlumberger, Dipole-Dipole and Mixed methods were applied and the results were compared with each other. The final model identifies the shallow conductive layer filled with fluvial, colluvial and alluvial sediments from Caxambu Hill that can reach up to 18 m in the vicinity of the Tourist Complex. There is a shallow circulation of water that follows a likely NE/SW direction, orthogonal to the survey and perpendicular to the principal direction of the fault and fracture system of the local aquifer system. The region of the Park suffers excellent influence from the alkaline intrusion present in the Morro and, therefore, this region has great transmissivity and percolation of fluid.

The AMT inside the Park has mapped up to approximately 300 m of depth (Figures 8, 9 and 10). On these result were possible to verify the structures found in the ERT with higher resolution in depth. The conductive river/colluvial layer next to Bengo's Brook was identified. Subvertical fractured zones have been found corroborating with the local geology that are considered the primary means of percolating fluid. NE/SW direction water circulation was also considered, which is mainly influenced by alkaline intrusion and faults and fractures that also follow NE/SW direction.

The Resistivity Cube (Figure 11) was obtained through the development of a Python code and consequent integration of the ERT and AMT results. Due to the greater sensitivity in mapping shallow structures of the ERT, it became more evident superficially and the profile was complete with the information obtained with the AMT. Thus, it was also possible to verify the same structures previously identified in the ERT and AMT: such as the alluvial/river conductive layeres; the system of faults and subvertical fractures probably composed of lithologies with quartzitic, schistous and gneissic facies; and the NE / SW direction of the most superficial water circulation of the observed conductors.

The 3D AMT results obtained in the Countryside of Caxambu showed a conductive layer filled with fluvial sediments less thick than the layer identified near the Water Park (Figure 12). Subvertical structures were also seen in the models, which are considered to be the main upward circulation paths of the deep paleowater. This result reached about 800 m in-depth and such a grouping of faults could be, considering the lithostratigraphy of Andrelândia Mega Sequence, formed by (i) Biotite gneiss with intercalations of shale biotite, quartzites, amphiboles and phyllites; (ii) Biotite Gneiss, Muscovite schist, quartzite, limestone-silicate rocks, amphiboles and metraultramafic rocks; and (iii) the rocks of the Archean/Paleoproterozoic basement consisting of banded or migmatitic orthogneisses, amphiboles, greenschist sequences and metaultramafic rocks (Pedrosa-Soares 2018).

The models obtained with the 3D Magnetotelluric reached out 5 km in depth, mapped deep structures that may be the source of feed for the Caxambu fissural aquifer (Figure 13). These MT profiles are associated with large subvertical conductive structures embedded under the gutters of local streams and streams. These structures correlate with the extensive feature of the Caxambu Shear Zone, which is made up of brittle - fault and fracture - and brittle-ductile zones. Therefore, the AMT and MT results show that Bengo's Brook, its distributors and Mombaça Stream are embedded in brittle fault zones of medium depth that connect with the deep conductor, associated with the Caxambu Shear Zone (ZCC).

Conclusions

This work aimed to deepen the hydrogeophysical knowledge of the Caxambu Water Circuit. The results obtained were consistent with previous geological, hydrogeological and hydrochemical studies developed by UFMG and UERJ and published on Pedrosa-Soares (2018).

Two different approaches inside and outside of Caxambu's Water Park. The first, within the park, was carried out a set of measurements with Electrical Resistivity Tomography (ERT) and Audiomagnetotelluric (AMT). These surveys were surveyed close to the main sources of water and to understand the behavior of shallow subsurface geological structures and the dynamics of circulation in the conduction of mineral waters. The second set of measures was acquired outside the Park, also applying the Audiomagnetotelluric and Magnetotelluric techniques. The main objective was to understand the role of deep structures that could be associated with the supply of the region's hydromineral fissural aquifer and the interaction between these deep conductors and shallow sources.

In summary, the occurrence of paleowaters in Caxambu's Water Park is explained by the thermal anomaly associated with the deep root of the ZCC locally influenced by the alkaline rocks of Caxambu Hill, resulting in the coexistence of geothermal gradients. The origin of the shear zone, composed essentially of fractures, allows paleo-waters of regional circulation, originating from deep crustal levels, to ascend to the surface. These conductors saturated with this hypothermal water can be deeply connected and supply the city. The Water Park of Caxambu coincides with the upward flow of a convective cell for the circulation of these regional paleo-waters. Thus, the waters of group II (more salinized) would be those directly related to this deeper circulation, while these paleo waters of group I (less saline) would be associated with a compartmentalization of fracture discontinuity systems in a less deep circulation aquifer (Pedrosa-Soares 2018).

The geophysical results obtained were corroborated with all previous information on hydrochemistry, geology and hydrology. The structures and rocks are mostly spatially arranged in a northeastern direction, with moderate to high dives. The local lithotectonic arrangement with paragnaisses, shale and quartzites from Andrelândia Mega Sequence controls the features of the relief, the surface drainage and the underground aquifers of the locality. The Park is located above a regional shear zone: the Caxambu Shear Zone, structured in gneiss rock, close to the contact with the alkaline intrusion that appears on the slopes and at the top of Morro do Caxambu (Pedrosa-Soares 2018).

Aiming at greater control of the recharge zones protection to allow the conscious exploration of these hydromineral waters in a sustainable way, it is necessary to plan and organize procedures that meet the water demands of Caxambu. In general, specific water consumption grows with a better quality of life and with the development of the urban core. Therefore, a policy for the management of hydromineral resources must contain guidelines, objectives and goals to be achieved including the right to use, control and conscientiously inspect water sources. Thus, within the local demand and availability of water resources, it will be possible to address issues related to quality and scarcity, as well as the appropriate use aimed at optimizing the good for the benefit of society.

Acknowledgments

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Figure 1. Common electroresistivity setup and the equipotential lines produced by current injection on the ground (Adapted from Milson 2003).

Figure 2. Location of the twelve founts there are within the Water Park.

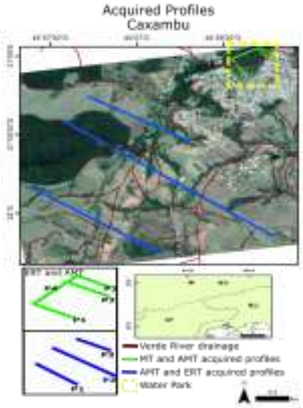

Figure 3. All acquired profiles inside and outside of the Park

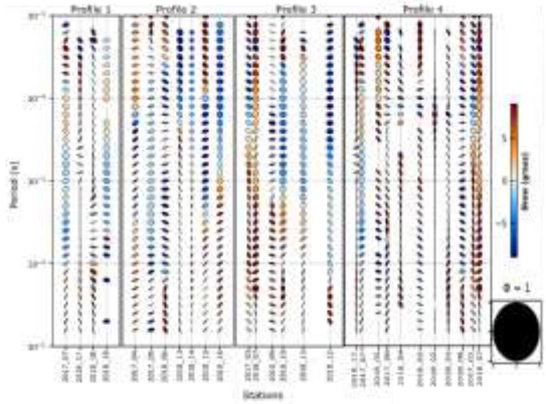

Figure 4. Dimensionality Analysis using Phase Tensor Method at inside park AMT data.

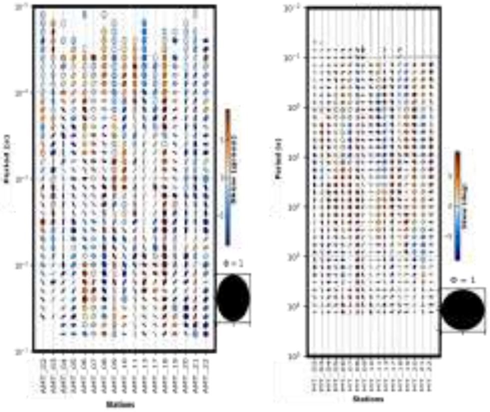

Figure 5. Dimensionality Analysis using Phase Tensor Method at oustide park stations AMT and MT data.

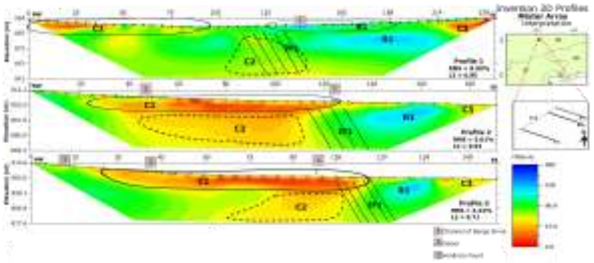

Figure 6. Profiles interpretation surveyed within the Water Park using the Mixed Array.

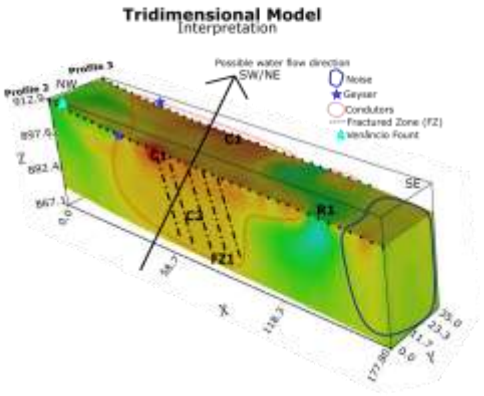

Figure 7. Tridimensional Model interpreted of ERT pseudo-inversion.

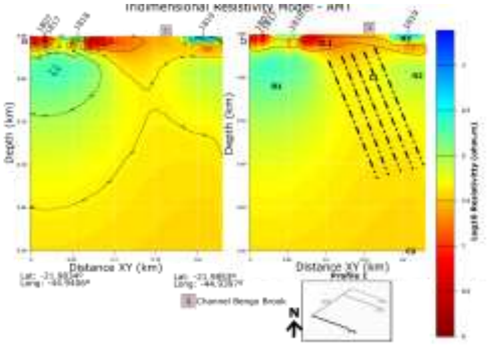

Figure 8. Profile 1 AMT acquired within the Water Park. a) It shows resistivity values identified and b) It presents the model interpretation.

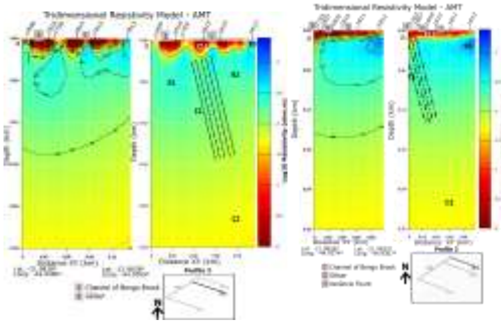

Figure 9. AMT Profiles 2 and 3 acquired within the Water Park. a) It shows resistivity values identified and b) It presents the model interpretation.

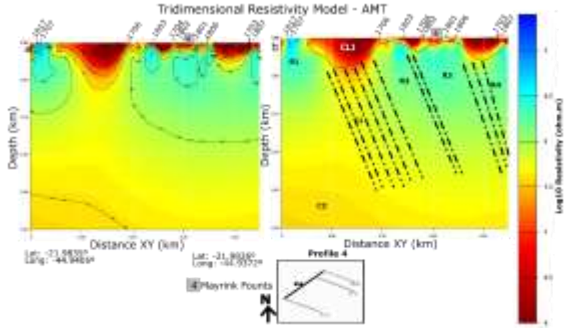

Figure 10. Profile 4 AMT acquired within the Water Park. a) It shows resistivity values identified and b) It presents the model interpretation.

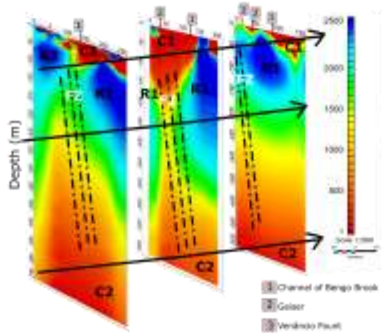

Figure 11. Sections of the Resistivity Cube on perspective.

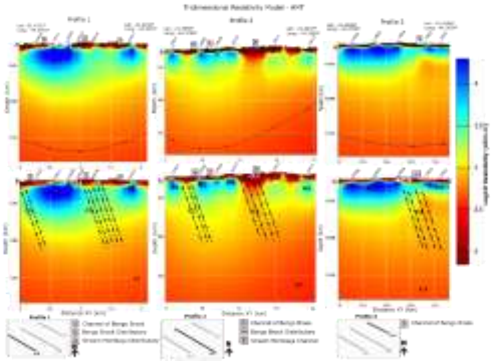

Figure 12. AMT Profiles 1, 2 and 3 acquired outside the Water Park. a) It shows resistivity values identified and b) It presents the model interpretation.

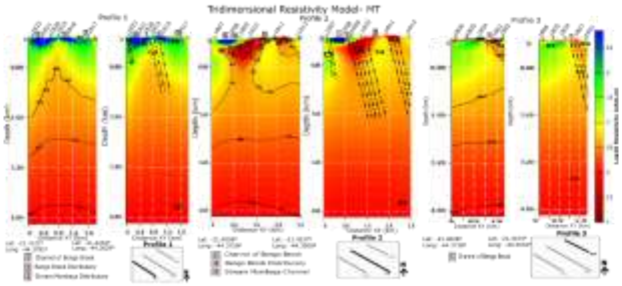

Figure 13. MT Profiles acquired outside the Water Park. a) It shows resistivity values identified and b) It presents the model interpretation.