Gravimetry Applied to Water Resources and Risk Management in Karst Areas: A Case Study in Paraná State, Brazil

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Key words: gravimetry, resistivity, karst aquifer system, gravity inversion.

SUMMARY

Paraná State is located in Brazilian southern part and has an important aquifer which is the source for drinking water to a great part of the people living in Curitiba, its main city. This aquifer is a consequence of karstification phenomena and presents elements that characterize a complete karst aquifer system, like caves, underground water flow and superficial features like dolines and sinkholes. The gravity method was applied on the basis that caves and voids present a strong density contrast when compared with the surrounding rocks. The microgravity technique was employed in the surveys carried through a certain part of the referred aquifer, using in general, 5-meter spacing between observation stations. As result of the surveys, the gravity anomaly maps clearly show areas that present a considerable mass deficiency. Through the gravity inversion process, a certain body is modeled using the observed gravity data and then, the gravity effect caused by this model is calculated. Finally, the resultant model is represented graphically by a three-dimensional surface. Thus, the model allows visualizing the mass distribution in the subsurface, characterizing underground structures that may constitute the fragility of the system, identifying areas that present some geotechnical risk.

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1. INTRODUCTION

In the present work it was developed a study based on the application of geophysical methods in an area placed at Almirante Tamandaré County, such territory occupies almost 80 % of karst terrains. These methods comprises the application of gravimetry together with resistivity surveys and induced polarization (IP), in order to investigate the geotechnical conditions of the terrain through the qualitative and quantitative characterization of geological structures, which were revealed by the geophysical maps.

Given the importance of a good management of the water sources, to guarantee the public provisioning, the detailed investigation of the Karst Aquifer System (KAS) has been object of study as much for civil services as for research institutes, which look for providing elements for a correct evaluation and use of this kind of system.

With the support of gravimetry and resistivity/IP methods, one intends to identify the main existing features in the area of study as well as to quantify their shapes and dimensions based on gravity inversion processes, apparent resistivity and apparent global chargeability. For this it was selected a target-area placed at the middle of the county (Figure 1). This area is indicated in the Figure 2.

2. TARGET-AREA AND GEOPHYSICAL TESTS LOCATION

Figure 1 shows the localization of the Paraná State pointing out Almirante Tamandaré County. The area of the county is integrally over carbonate rocks and recent deposits of the Tertiary/Quaternary.

2.1 Target-area description

Figure 2 shows a geological map of the region under study pointing out the target-area described in this paper. This area is found around the Ambrosio Bini School, which structure suffered a collapse, probably because it was constructed over a risk area, and where are two water exploitation wells.
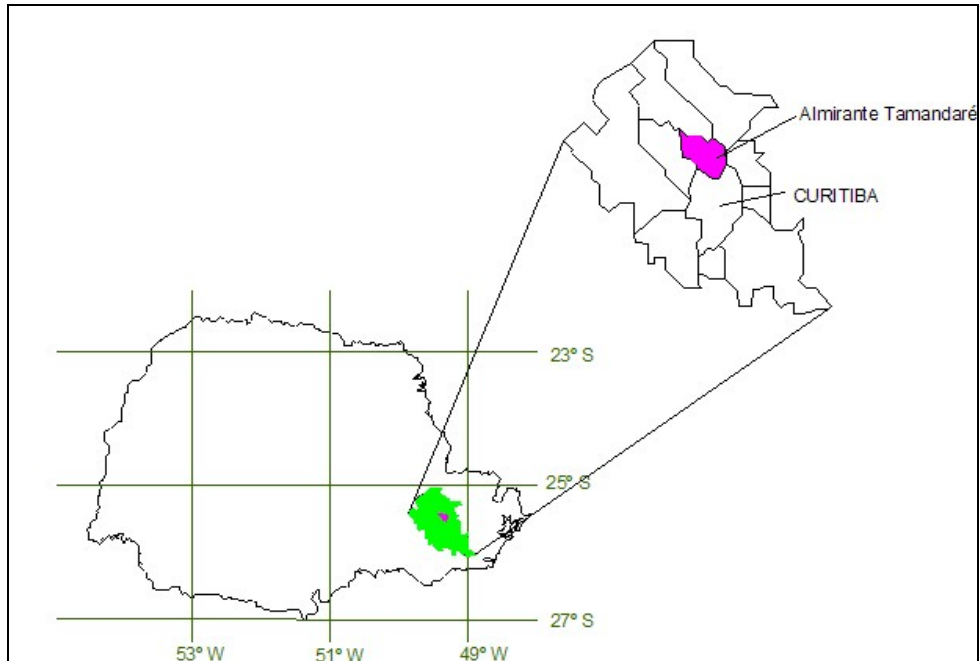
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Figure 1. Localization of Paraná State and Almirante Tamandaré County
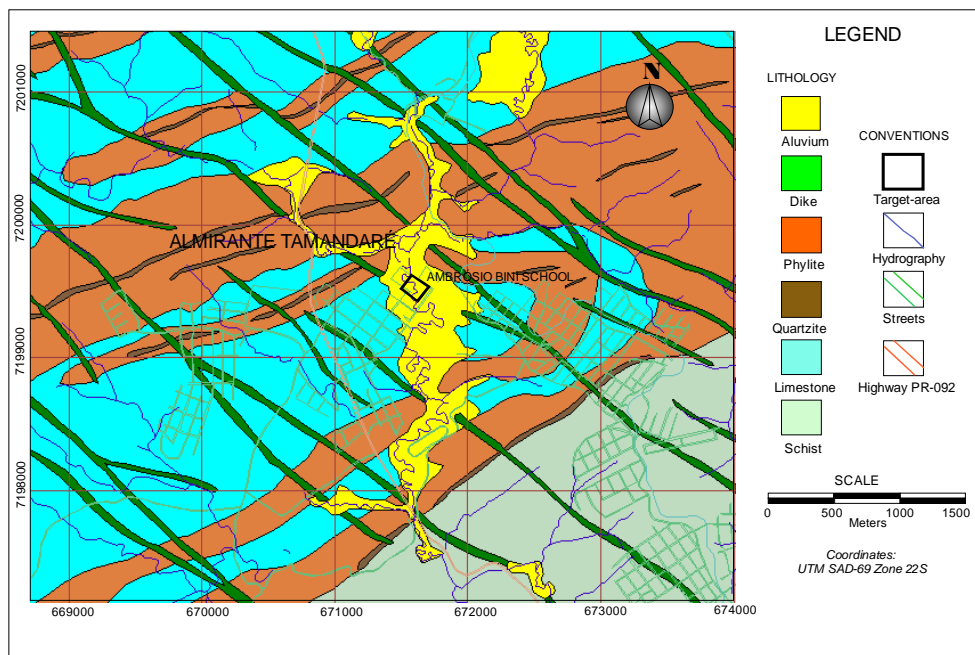

Figure 2. Lithology of the middle county and the target-areas

The surveyed area around the school is approximately 11200 square meters in which were located 417 gravity points, arranged as a square grid of 5 per 5 meters. It was also performed 10 vertical electric soundings spaced by 5 meters (following the Schlumberger array) and 550 meters of 2D electrical imaging (following the dipole-dipole array). The latter involved 5 lines separated by 10 meters. These configurations are shown in Figure 3.
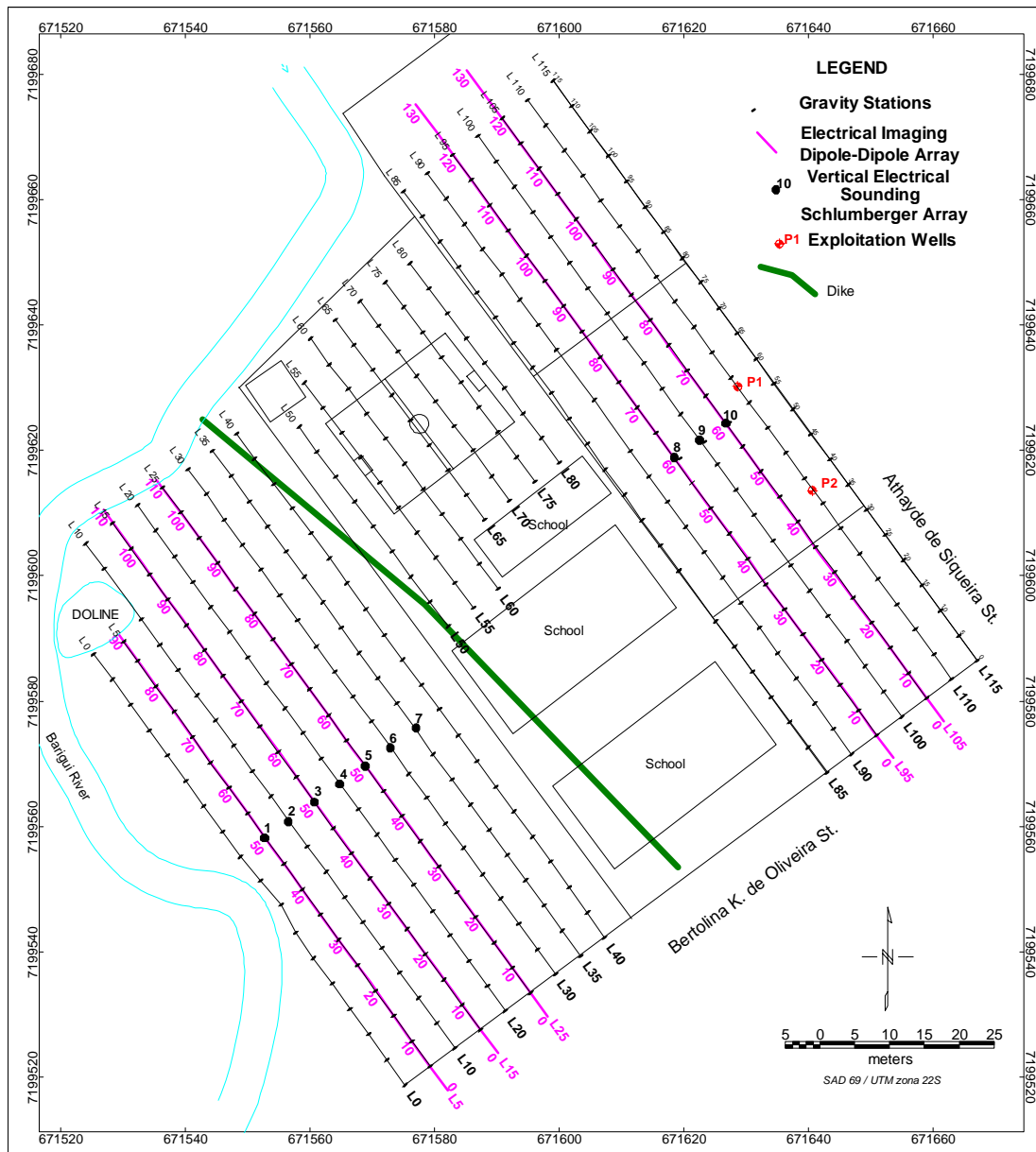
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Figure 3. Geophysical tests around the Ambrosio Bini School

3. GEOPHYSICAL METHODS APPLIED IN IDENTIFYING KARST FEATURES

Surface geophysical methods can be employed to detect and map fractures, cavities and other karst features. According the physical, electrical or chemical properties of the environment, geophysical methods can detect direct or indirectly karst features in a certain region. One of the methods used to identify those features is the gravity method. Using the microgravity technique, small variations of the earth's gravity field can be measured. These measurements are associated to short sample intervals aiming the interpretation of subsurface voids and cavities.

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Microgravity studies performed by CRAWFORD (2000) in United States of America showed good results in detection of voids and in the investigation of collapses under highways. Other studies can be cited as they describe the usage of gravimetry to identify karst features (COLLEY, 1963; ARZI, 1975). FAJKLEWICZ (1976) described the application of vertical gravity gradient measurements to detect tunnels and caves under cities in Poland. BUTLER (1984) applied microgravity to outline a shallow cavity and another filled by water in Florida. AL-RIFAIY (1990) also described the usage of microgravity to detect the presence of cavities on a karst region near Kuwait City.

3.1 Gravity method

Gravity prospecting involves measurements of variations in the earth's gravity field. It is desired to identify local masses of greater or lesser density than the surrounding formations and then, extract some information about them from irregularities on the earth's field. Such irregularities are called anomalies and they are interpreted as a result of density lateral variations of the masses in subsurface, caused by geological structures or bedrocks with different densities (TELFORD *et al*, 1990).

With the help of topographic, geologic and geophysical information, the influence of the known masses can be removed through reductions. In particular, filtering procedures are used to separate the long wavelengths (regional field) and the short wavelengths (residual field) of the anomalies (GUPTA & RAMANI, 1980 *apud* TORGE, 1989). After the separation of the regional and residual fields, arises the problem of determining the parameters that will define the shape and the dimensions of the investigated structure. Such problem is known as the *inverse problem* of gravity prospecting. It does not have a unique solution, i.e., the same gravity field can be caused by masses of different shapes and at different depths.

3.1.1 Gravity inversion

The problem of gravity inversion consists in determining the parameters that describe the shape and position of certain body through the observed anomalies. Despite its ambiguity, the gravity inversion contributes strongly, as it gives important information about the internal structure of the Earth through the determination of the depths and density contrasts. In many cases, the geological interpretation of gravity data consists in exhibiting a structural model that produces a synthetic anomaly more or less identical to the observed one.

The inversion method used in this work was developed by CORDELL & HENDERSON (1968) which considers that the gravity anomalies are disposed in a regular square grid. The method also consider that the structure which causes such anomalies can be approximated by a set of vertical elemental prisms, each one having its cross section area equal to a cell of the regular grid. This method is iterative, i.e., the model is modified several times until the effect caused by the model is in accordance to the observed effect (anomalies).

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Figure 4 shows a 3D structural model computed automatically by successive approximations. The quantities *h* and *t* correspond to the depth of the derived surface and the thickness of the prisms that represent the desired structure.
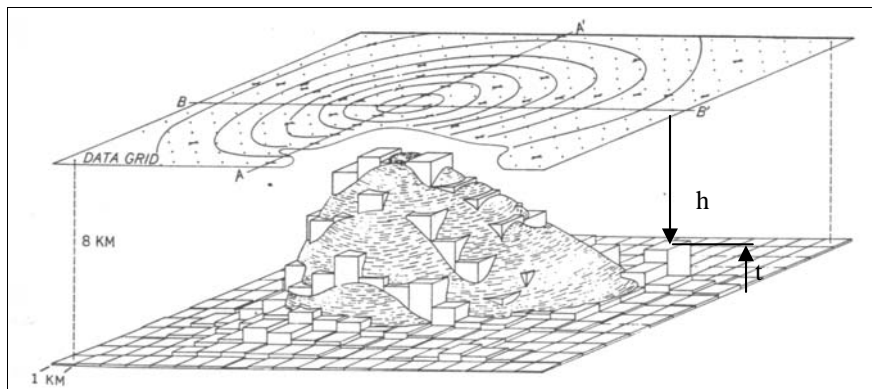

Figure 4. Structural model described by elemental prisms (CORDELL & HENDERSON, 1968)

3.2 Electric methods

Electrical measurements are performed on the terrestrial surface in order to investigate the subsurface conditions in a certain region. The basic principle of the electric methods consists in applying an electric current to the ground and then, the potential differences are measured on the surface (SHARMA, 1997).

The goal of this kind of survey is to determine the resistivity distribution in subsurface through measurements on the surface. From these measurements the apparent resistivity can be estimated. The resistivity of the ground is related to several geological parameters, such as fluid and mineral content, porosity and the degree of saturation in water.

The electric methods are commonly used together with gravimetry, as these different methods can confirm each other for a better interpretation of their results. The information given by the electric profiles can help the gravity inversion as they provide some parameters of the investigated structure, which contributes to its three-dimensional modeling.

3.2.1   Survey techniques

In this work it was used basically two survey techniques, vertical electric sounding and 2D electrical imaging. In the vertical electric sounding technique, following the Schlumberger array, the spacing between the potential electrodes remain fixed while the separation between the current electrodes is expanded in order to obtain deeper information about the electric section. Another classic survey technique is the 2D electrical imaging, following the dipole-dipole array. In this technique the spacing between the electrodes remain fixed while the whole array is displaced following a straight line. Such technique provides information about lateral variations in resistivity. Figure 5 shows this array as it was used in this work.
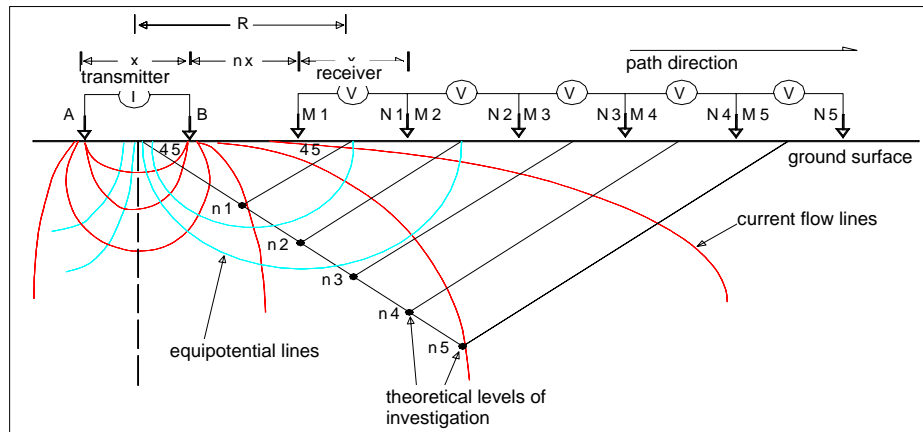
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Figure 5. Dipole-dipole array used in the 2D electrical imaging technique

4. RESULTS

4.1 Gravimetry

The gravity data were collected using a SCINTREX CG-3 digital gravity meter. There were taken 30-second readings for each surveyed point. The data were automatically corrected for the earth tides effect and instrumental drift.

For the interpretation of a gravity survey, it is common to represent the gravity data in the form of anomaly maps. This is made through the processing of field data and computing the Bouguer anomalies. The Bouguer anomalies were computed using the following formula:

$$\Delta g_b = g + 0,3086*h - 0,1119*h - B + C - \gamma$$

Where *g* corresponds to the observed gravity value; the second term is the free-air correction; the third is the Bouguer correction, followed by the term B, that is used to transform the Bouguer plate into a shell. The term C corresponds to the terrain correction and the latter (γ) is the normal gravity value at the latitude of the observed point. Then, these data are represented in a map of isovalues of Bouguer anomalies.

In order to achieve satisfatory results, it is necessary to have very accurate heights on the station points. As shown in the above formula, the Bouguer anomalies are dependent of this value.

Afterwards, it is necessary to remove the regional trend of the Bouguer anomalies, which results in another map called residual anomalies map. The residuals indicate the main sources of anomalies in the observed gravity field. This is done by applying some kind of filtering into the data depending on their trend. Figures 6 and 7 show the Bouguer and residual

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anomalies maps, respectively. In Figure 7, the black rectangle indicates the area used for testing the inversion method.

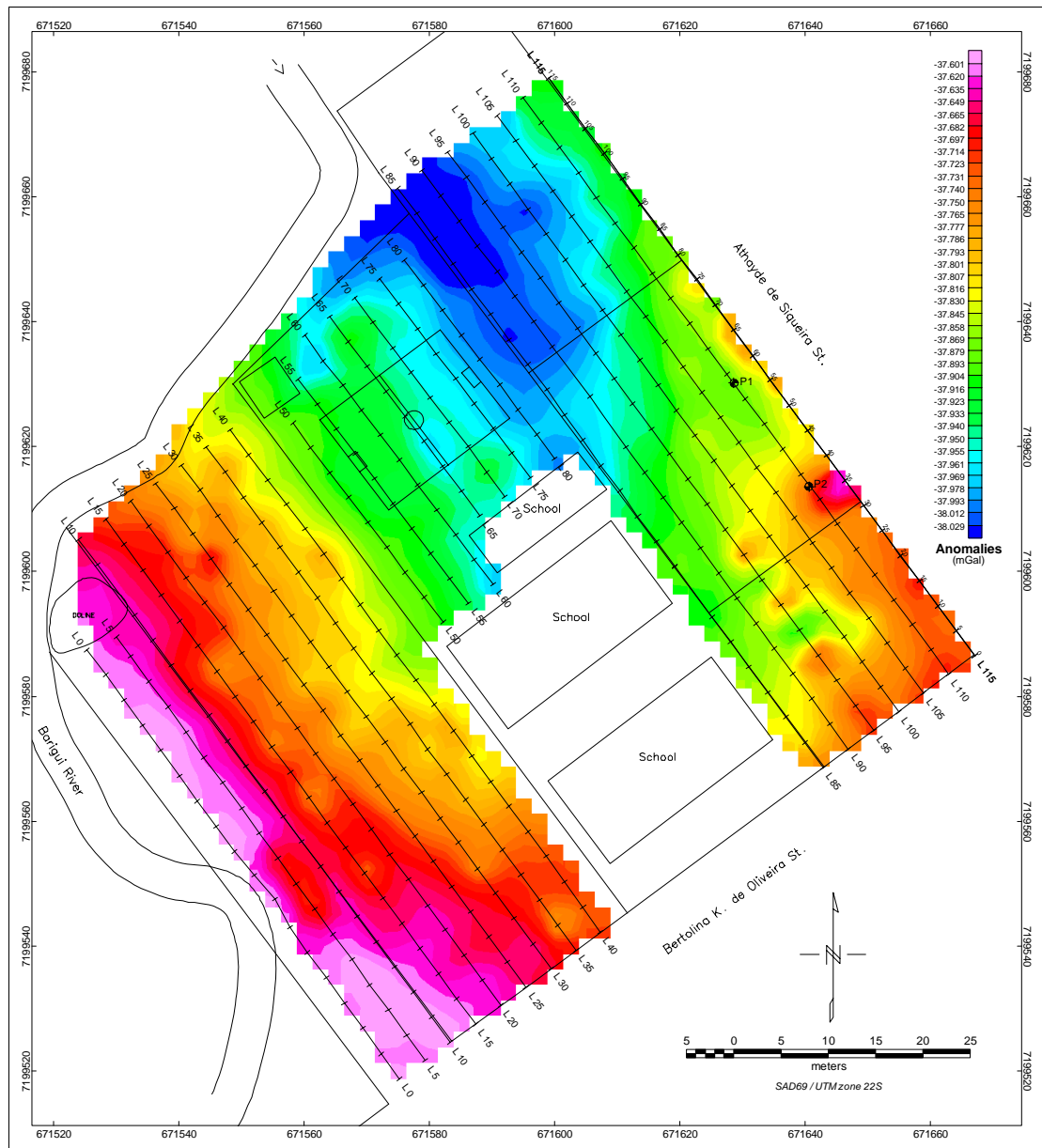**Figure 6.** Bouguer anomalies map

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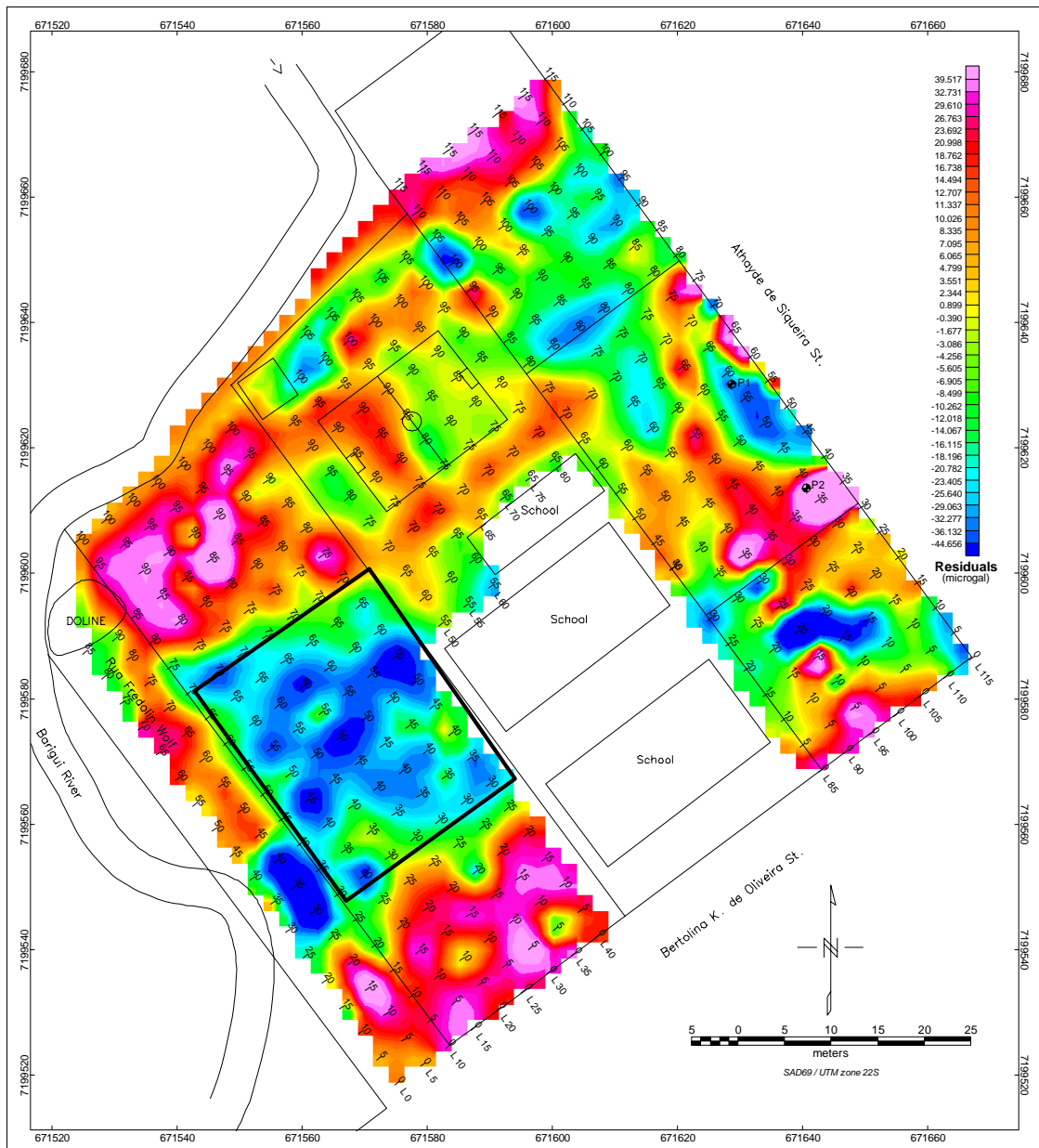Munich, Germany, October 8-13, 2006

Figure 7. Residual anomalies map

4.2 Resistivity

For the data acquisition, it was used a high power transmitter (VIP 3000W) and a multichannel spectral receiver (ELREC 10). Figures 8 to 10 show the pseudosections of apparent resistivity and global chargeability and their respective inversion models of depth. These figures corresponds the Lines 5, 15 and 25 respectively and they are located at the southern part of the surveyed area. These pseudosections were designed on the basis of the field data given by the electrical imaging survey using an adequate software.

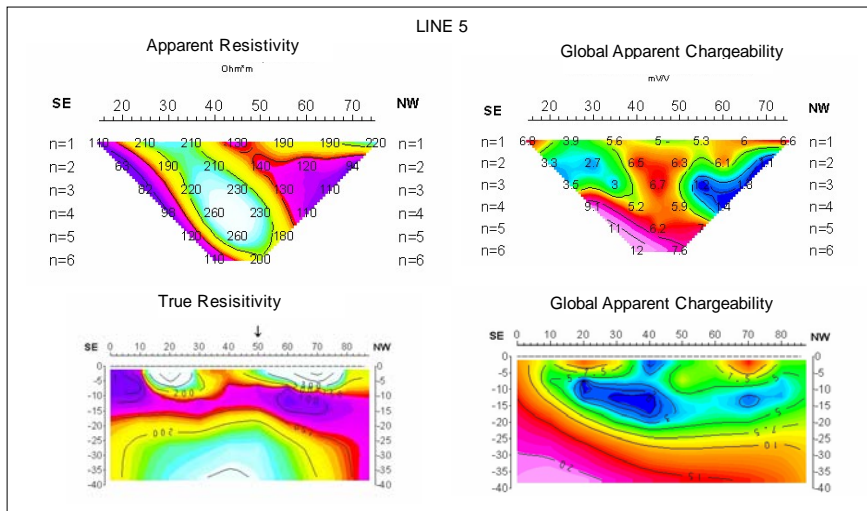Jair Silveira da Silva Junior and Francisco José Fonseca Ferreira
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Figure 8. Pseudosections and depth models of resistivity (left-hand side) and chargeability (right)
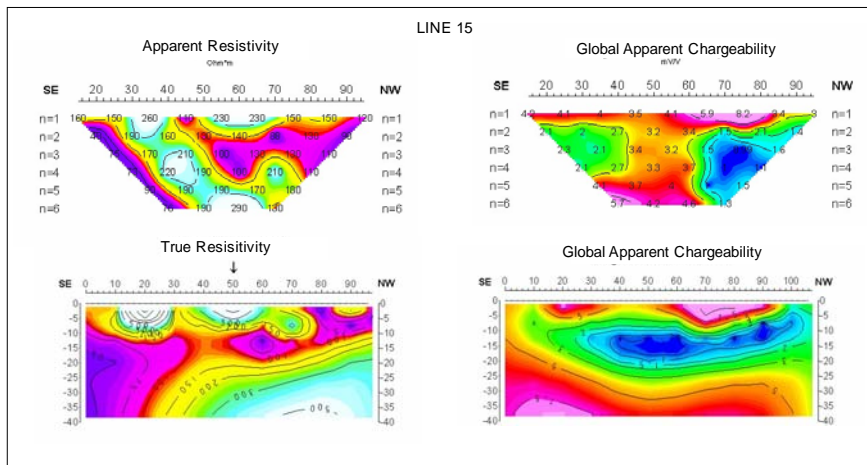

Figure 9. Pseudosections and depth models of resistivity (left-hand side) and chargeability (right)

Figure 10. Pseudosections and depth models of resistivity (left-hand side) and chargeability (right)

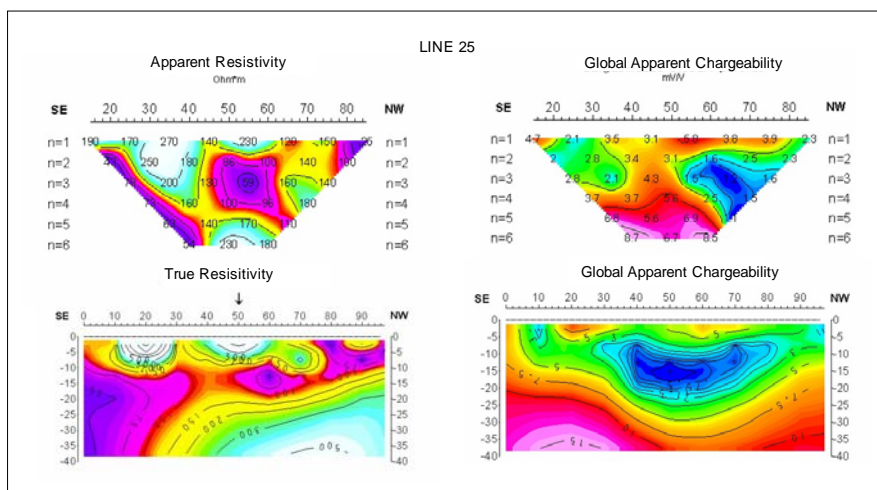Jair Silveira da Silva Junior and Francisco José Fonseca Ferreira
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4.3 Gravity inversion

The gravity inversion was performed using the method described on section 3.1.1. For this, there is an application, developed by USGS (*United States Geological Survey*) in FORTRAN programming language. Its output refers to those referred quantities h and t as indicated on Figure 4. The application also gives the computed effect of the resultant model and its residuals in comparison to the observed effect i.e., the anomalies, used as input to the application. Figure 11 shows the resultant surface of the model, in comparison to the relief (topography) and the observed anomalies. This model corresponds only to the area inside the rectangle showed on Figure 7.

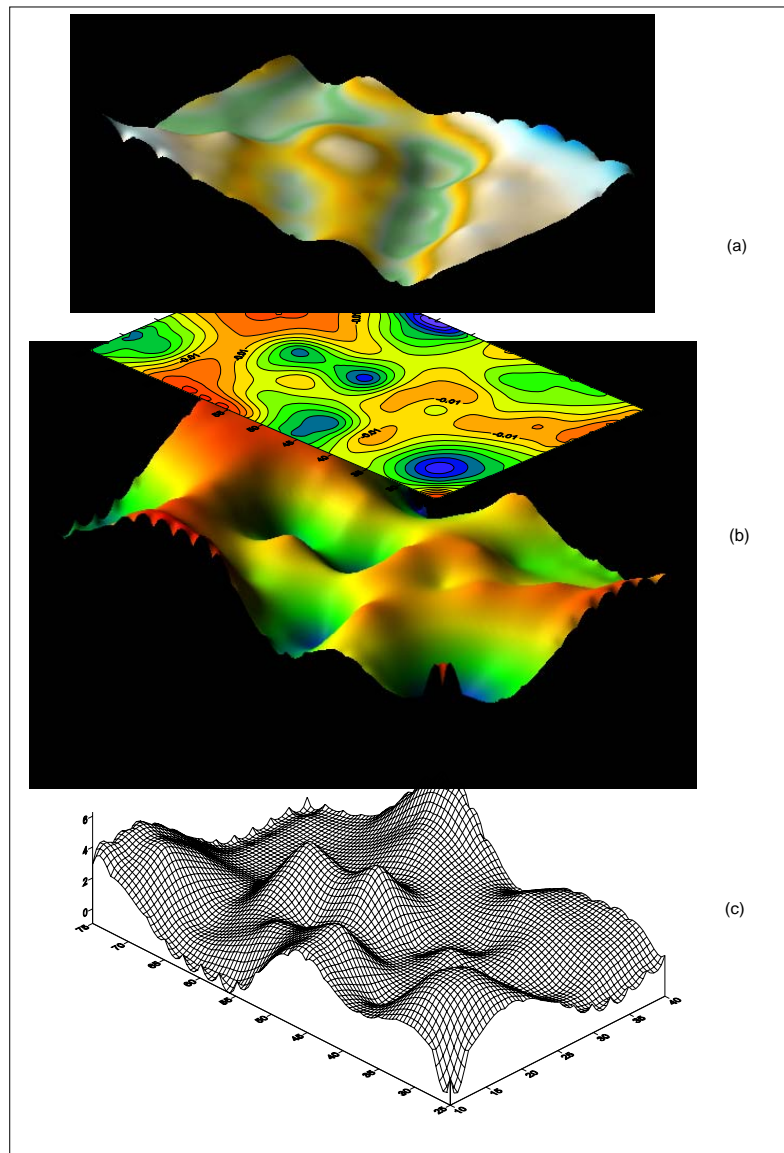**Figure 11.** Gravity inversion model; (a) relief; (b) residual anomalies in plane and 3D presentation; (c) model surface (local coordinate system)

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5. DISCUSSION

Looking at Figures 8 to 10, the resistivity inversion models (left-hand side) indicates zones that are very saturated in water. This is shown by the hot colors which indicate conductive zones characterizing the presence of water since the superficial levels (more or less 5 meters deep) till depths near to 20 meters.

The residual anomalies map shows shallow sources in the southwestern part of the survey area. The shallow sources are usually indicated by short wavelengths, associated to high spatial frequencies. Then, the results of the electric and gravity methods are in accordance, and both indicate an area that presents some geotechnical risk.

The gravity inversion was intended to dimension how large are the zones mentioned above. The inversion model shows that such structures are not larger than 6 meters in its vertical dimension. This is plausible, if we look at the conductive zones in the resistivity models.

6. CONCLUSION AND REMARKS

The use of gravimetry allows to model structures that present some density contrast with relation to its surroundings. But it is sometimes difficult, principally in karst terrains, to assure what kind of filling such structures do have. That is why electrical surveys are also employed, as they can improve the assumption about the content of the investigated structure.

Another question to take into account is that karst terrains do not have the same behavior from each area to another neither their structures have regular shapes. This fact makes always difficult its modeling and interpretation. However, satisfactory results can be achieved if one selects a smaller area to study instead processing the whole survey area. Thus, localized structures can be more precisely modeled than those which are processed together in a larger area.

For helping the planning of a geophysical survey it is recommended an *a priori* knowledge about the local geology. This knowledge may also contribute in interpreting the results of a survey. Information about the density contrast is also a necessary element, as it is one of the required parameters for the gravity inversion.

The gravity data acquisition is another important question, as we are looking for only small variations on the gravity field. The spacing between stations has to be adequate to the dimensions of the studied area as well for the investigated structure in order to avoid losing some important information.

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