Revista Brasileira de Geofísica
RBGf
Brazilian Journal of Geophysics

Revista Brasileira de Geofísica (2012) 30(3): 361-372

ISSN 0102-261X
www.scielo.br/rbg

GROUNDWATER PROSPECTION IN THE MUNICIPALITY OF PIÇARRA-PA USING VERY LOW FREQUENCY AND RESISTIVITY

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Recebido em 23 setembro, 2011 / Aceito em 7 maio, 2012
Received on September 23, 2011 / Accepted on May 7, 2012

ABSTRACT. This study was conducted in the municipality of Piçarra, located in the southeastern part of the state of Pará. The aim of the study was to use geophysical methods to map the lineaments associated with bedrock fractures and the nature of the subsoil using the Very Low Frequency (VLF) electromagnetic method and the electrical resistivity in vertical electrical sounding (VES) technique. The integrated analysis of the geophysical data delineated two hydrogeological domains, namely, fracture zones and sediment layers on the bedrock, that could be potential locations of wells for groundwater extraction. The study was designed to identify the most promising units for groundwater extraction and the best locations for the construction of wells to supply groundwater to the city.

Keywords: fractures, groundwater prospecting, VLF, electrical resistivity.

RESUMO. Esta pesquisa foi realizada no município de Piçarra, localizado no sudeste do estado do Pará. O estudo teve como foco o mapeamento de lineamentos associados a fraturas do embasamento e da natureza do subsolo através de geofísica, usando o método eletromagnético Very Low Frequency (VLF) e eletrorresistividade em sondagens elétricas verticais (SEV). A análise integrada dos dados geofísicos permitiu reconhecer na área dois domínios hidrogeológicos: zonas fraturadas e espessura de sedimentos sobre rochas do embasamento, visando orientar a locação de poços de captação de água subterrânea. O estudo forneceu indicações das áreas mais promissoras à captação de água subterrânea e os melhores locais para a construção de poços para abastecimento da cidade.

Palavras-chave: fraturas, prospecção de água subterrânea, VLF, resistividade elétrica.

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INTRODUCTION

Geophysical methods are widely used for hydrogeological studies in Brazil. For example, the Ceará Foundation of Meteorology and Water Resources ('Fundação Cearense de Meteorologia e Recursos Hídricos') (Funceme, 2011) applied groundwater exploration techniques such as VLF and electrical resistivity integrated with geoprocessing to assess the geology of the crystalline semi-arid region of Brazil.

Souza (2007) discussed an environmental problem facing the Lixão de Serrana region of Ribeirão Preto in São Paulo state. This study focused on the application of geophysical methods, such as electrical resistivity, induced polarization in the time domain and electromagnetic induction, to evaluate the hazards associated with the contamination of tropical soils and groundwater reserves by the accumulation of urban solid waste.

Campos (1996) evaluated the quality and potential of the sedimentary aquifers in the Cabuçu River basin, in the western part of the municipality of Rio de Janeiro, using the electrical resistivity method coupled with the vertical electrical sounding technique.

In the municipality of Novo Repartimento, situated in the state of Pará, Freitas Filho (2006) conducted a survey that used geophysical methods to characterize the water problem of the municipality. The geology of this area consists of metamorphic and igneous rocks. The methods employed by this study involved electrical resistivity and electromagnetic induction.

Bahia (2003) conducted a study to characterize the hydrogeological condition of the area located between the Belém Metropolitan Waste Disposal Site (Depósito de Lixo Metropolitano de Belém, called Aurá) and Lake Água Preta. The primary aim of this study was to determine the influence of the contaminants from the waste disposal site on groundwater resources and to evaluate the possibility of contamination of the source area of Belém's water supply. The study involved electromagnetic geophysical measurements, which indicated the presence of clay layers and groundwater levels relatively close to the ground surface.

Monteiro (1998) applied the electrical resistivity method to explore possible groundwater sites in the southeastern region of the state of Pará or, more precisely, in the city of Palestina on the left bank of the Araguaia River.

Bezerra (1979) performed a study on the groundwater resources of Salvaterra, on the Marajó Island, which also aimed to define and delineate aquifers with electrical resistivity techniques.

In the urban community of Piçarra, in southeast Pará, the water used in domestic supply comes from excavated wells with large diameters and depths of generally less than 10 m (Amazonas-type wells). With the growth of this community and the increase in its population, the current water supply does not meet the increased demand, especially during critical periods of low rainfall. Therefore, complementary sources of water supply are required and deep aquifers could be a viable option. This study describes the application of geophysical methods to identify the most appropriate locations to drill wells for the exploitation of these aquifers.

LOCAL GEOLOGY AND HYDROGEOLOGY

According to Corrêa (1998), metamorphic rocks of the Pequiseiro Formation consisting of micaschist are the predominant rock type in the city of Piçarra. The micaschists display a foliation with an azimuth of 350° that dips between 15° and 25°. These rocks exhibit an altered mantle thickness that range from 1.5 to 12 m, consisting of a thin lateritic layer of approximately 15 cm, followed by a clay horizon 10 to 20 cm in thickness in the central parts of the city that can reach up to 50 cm in thickness in the topographic highs. Following the clay horizon, there is saprolite consisting principally of fragments of partially altered rocks wrapped in a clay matrix. The least altered rocks exhibit closely spaced micro-fractures (approximately five 0.5 cm spaced fractures in 2 cm of the rock body).

The water used for domestic supply in the city comes from the Amazonas wells, which are 6-14 m deep and are excavated by the inhabitants themselves in their backyards. It is common for these wells to be located near cesspools that are approximately 2 m deep.

According to the city inhabitants, most of the Amazonas wells have a clayey material base with low permeability, whereas some have a sandy material base with high permeability. A tube well (unfinished and abandoned) that was drilled in the public laundry, located in Raimunda Mota Street next to the Tiradentes School, had reached the sandy material.

The aforementioned geology of the city area of Piçarra offers two possibilities for groundwater exploitation. The first option involves pumping water from the sandy material found in the Amazonas wells and the tube well at the public laundry. The second option involves pumping water that is contained in the fractures of the micaschists. The first possibility necessitates a large layer of sandy material to obtain a large amount of water. Nonetheless, in both the aforementioned options, it is recommended that the material serving as the source of the groundwater be isolated from the ground by an impermeable layer of clay to avoid contamination with materials and agents that might be harmful to health.

DESCRIPTION OF THE STUDY AREA

The study area is located in the municipality of Piçarra, which was established in 1995 and is located in the southeast of the state of Pará (06°26′17″S and 48°52′18″W) at an elevation of 215 m.

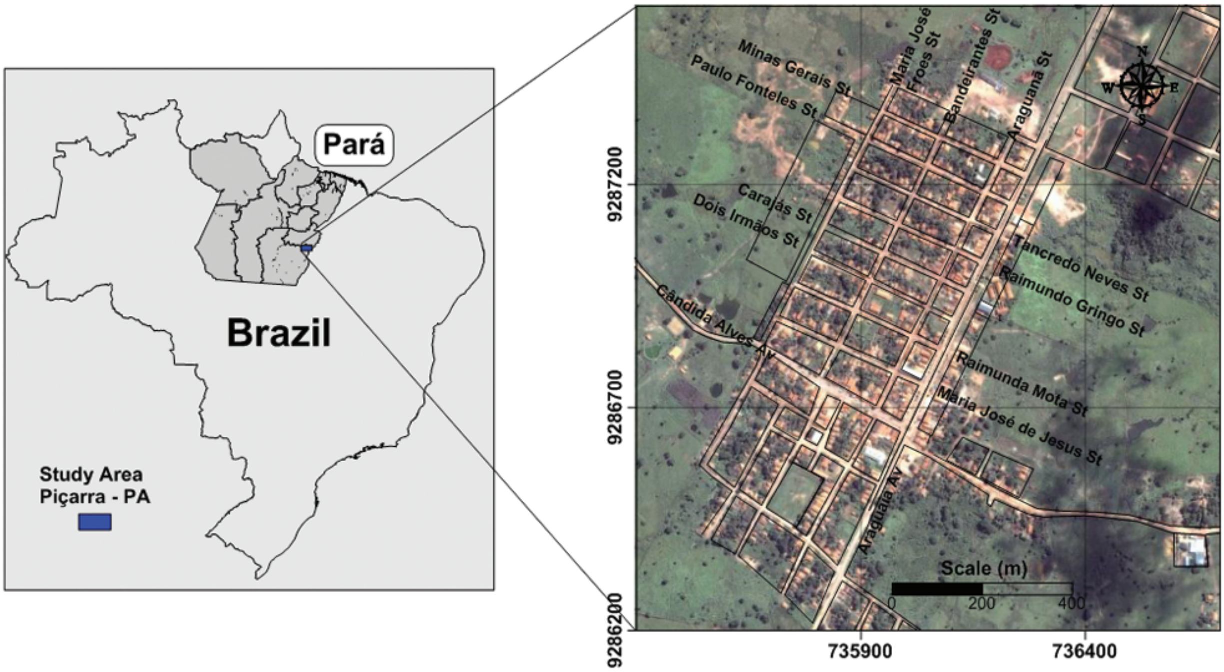

Figure 1 – Location map of the study area.

The area of the municipality is 3326.769 km^2. The municipality is approximately 980 km from the city of Belém and is accessible via highway PA-150 (Fig. 1).

METHODOLOGY

Two geophysical methods, electrical resistivity and VLF, were applied in this study.

Electrical Resistivity Method

The electrical resistivity method measures the resistance of an electric current by applying a direct current (or low frequency current) at two points on the ground (A and B) and the resultant potential difference between two other points (M and N).

Because the subsurface possesses a resistivity distribution, which varies both vertically and laterally due to the heterogeneity of the subsurface geology, the resistivity values thus obtained do not represent the true resistivities of the layers, although the two values are related. The obtained values are known as the apparent resistivities of the layers (Orellana, 1982).

Two procedures are commonly employed in the measurement of the apparent resistivity: a) the current electrodes are moved symmetrically relative to a central point and b) all the electrodes are displaced laterally with the distance remaining constant between them. The first technique is known as vertical electrical sounding (VES) (Orellana, 1982). This procedure determines the distribution of resistivity according to depth. The second procedure is known as the horizontal profiling technique (Orellana, 1982). This technique determines the lateral variation in resistivity at a particular depth, which partly depends on the distance between the current electrodes (AB) (Orellana, 1982).

In electrical prospecting, various types of electrode arrangements (based on the relative position of points A, B, M and N) may be used. The arrangements most commonly used in electrical resistivity surveys are the Wenner, Schlumberger and Dipole-Dipole arrangements.

In this study, the Schlumberger arrangement was used. In this arrangement, the four electrodes are arranged in a line, and the distance between the current electrodes are much greater than the distance between the potential electrodes ($MN < AB/5$, according to Orellana, 1982).

VLF Method

The VLF method is an electromagnetic method that uses signals that are typically generated by fixed radio transmitters used in military communications, which are distributed around the globe. The VLF method operates at the frequency band 15-25 kHz. The signals can also be transmitted from a portable generator that is used in areas in which the primary signal generated by the station is either too weak or is improperly oriented for efficient use in the survey.

The transmitter consists of a vertical antenna through which an alternating current (electric dipole) is passed; therefore, the magnetic field lines are distributed concentrically in the horizontal plane around the antenna. The resulting primary field can be considered uniform (plane waves) at large distances from the transmitter, remaining as so if the geoelectric conditions remain stable in the environment in which the field is propagated.

The current emitted by the antenna generates a primary horizontal magnetic field, which, after penetrating the conducting bodies in the ground, generates secondary magnetic fields. The receiver can measure the tilt angle of the resultant from the interaction between the primary and secondary fields with respect to the primary field (dip angle); the following two parameters are typically recorded: the dip angle and the azimuth of the resultant field. The azimuth has values that are approximately perpendicular to conductive zones. Further details about the VLF method are provided by McNeill & Labson (1991) and Telford et al. (1990).

In a set of measurements obtained transversal to a conducting body, the projection of the conductor on the ground surface is represented by the change of the dip angle values from positive to negative. The point at which this transition occurs is called the crossover. The characteristic of the crossover points, however, is not always clear. In such cases, the values may be filtered according to the procedures outlined in Fraser (1969) and Karous & Hjelt (1983). These procedures involve the conversion of the crossover of the VLF anomaly (which indicates the conductor's position) into a positive peak. This filtering process allows better visualization of the geological structures that produce the anomalous signals.

Resistivity Measurements and Processing

The resistivity measurements were taken using the VES technique. Seventeen VES experiments were conducted at various locations along the streets of the municipality (Fig. 2). The electrodes were placed according to the Schlumberger arrangement, with the minimum distance between the current electrodes equal to 2 m ($AB = 2$ m) and the maximum distance equal to 600 m ($AB = 600$ m). The maximum distance between the electrodes was constrained by the nature of the equipment that was used for the measurements, as the instrument provides unreliable AB measurements for distances greater than 600 m. With the AB spacings that were used in the experiments, it is possible to obtain responses for depths of at least 60 m (10% of the maximum separation between the AB electrodes), which is sufficient to investigate the subsurface in Piçarra. The VES experiments were conducted in areas in which the terrain had the gentlest topographic slopes and conditions permitting good access, and in locations to ensure good mapping of the subsurface. The equipment used in the measurements was the resistivity meter model R100A manufactured by GEOTEST.

The apparent resistivity values measured in the VES experiments were plotted on a bi-logarithmic chart and smoothed to eliminate any geological noise in the measurements, which are typically due to lateral variations in the geological strata. In some cases, the outlier values (values much different from the adjacent values) were replaced by interpolated or extrapolated values. Additionally, the VES data were interpreted by the auxiliary point method, which allowed approximate geoelectrical models to be constructed for the subsurface in which the VES experiments were performed. Finally, an inversion method was applied to the above models using the Interpex 1-D sounding inversion program to realize more accurate models for the subsurface.

VLF Measurements

The measurements for the VLF experiments were taken at intervals of 10 m along the profiles in nine streets inside the town of Piçarra. To avoid interference, the measurements were recorded during a period in which the electrical grid was off, which is common in the city, as it has a poor electrical system. The measurements were acquired along the streets of Minas Gerais, Paulo Fonteles, Tancredo Neves, Raimundo Gringo, Carajás, Dois Irmãos, Raimunda Mota, Maria José de Jesus, and Cândida Alves (Fig. 2). The equipment used was a SCOPAS VLF receiver, Model SE-81, manufactured by Scintrex. The field dip angle resulting from the interaction of the primary and secondary fields was the recorded parameter. The Jim Creek Naval Radio Station was used for the measurements. This station is located in the United States and broadcasts at a frequency of 18.6 kHz.

RESULTS

Vertical Electrical Sounding

Based on the geoelectrical models obtained for the VES measurements, two geoelectrical sections aligned with the lines AB and CD shown in Figure 3 were constructed.

The VES 1, 2, 3, 4, 5, 7, 8, 16, and 17 (Fig. 4) had their geoelectrical models cross-correlated laterally to construct the geoelectric section along line AB (Fig. 5). The depth scale was established from the geoelectrical models. The necessary topographic corrections were performed with the aid of SRTM (Shuttle Radar Topography Mission) imagery.

The geoelectrical models for the VES 15, 6, 4, 3 and 10 (Fig. 6) were also cross-correlated laterally to construct the other geoelectrical section along the line CD (Fig. 7).

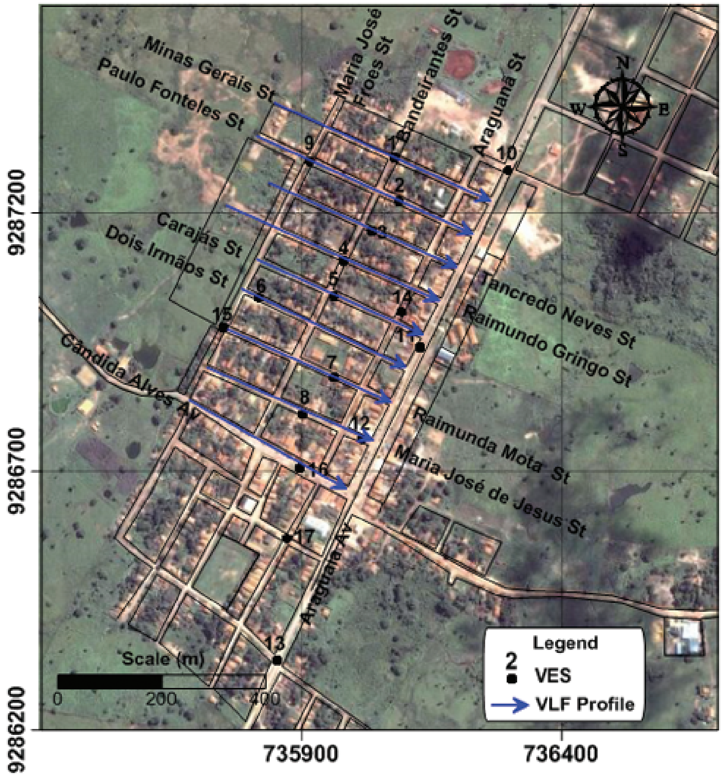

Figure 2 – Locations of the geophysical experiments.

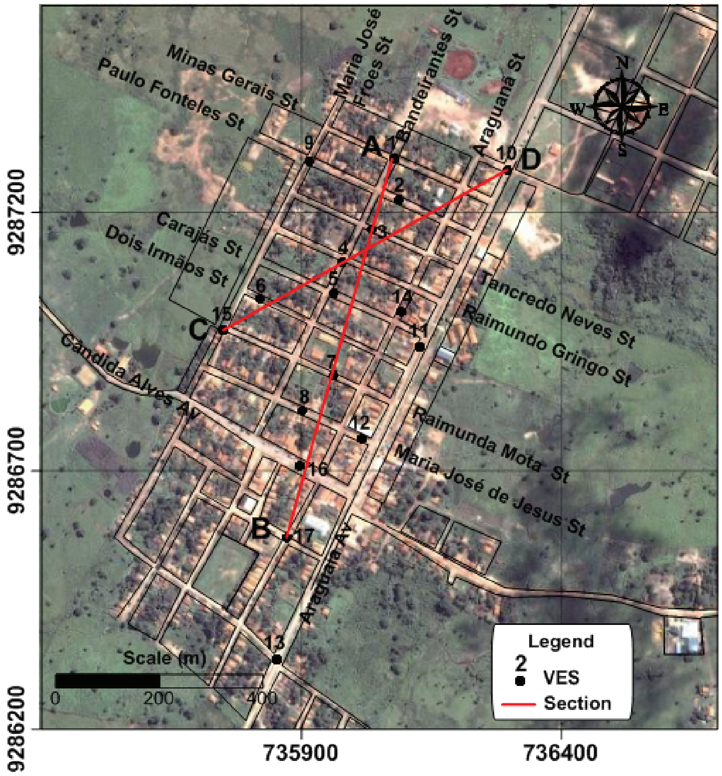

Figure 3 – Location of AB and CD lines used in the correlation of the resistivity models.

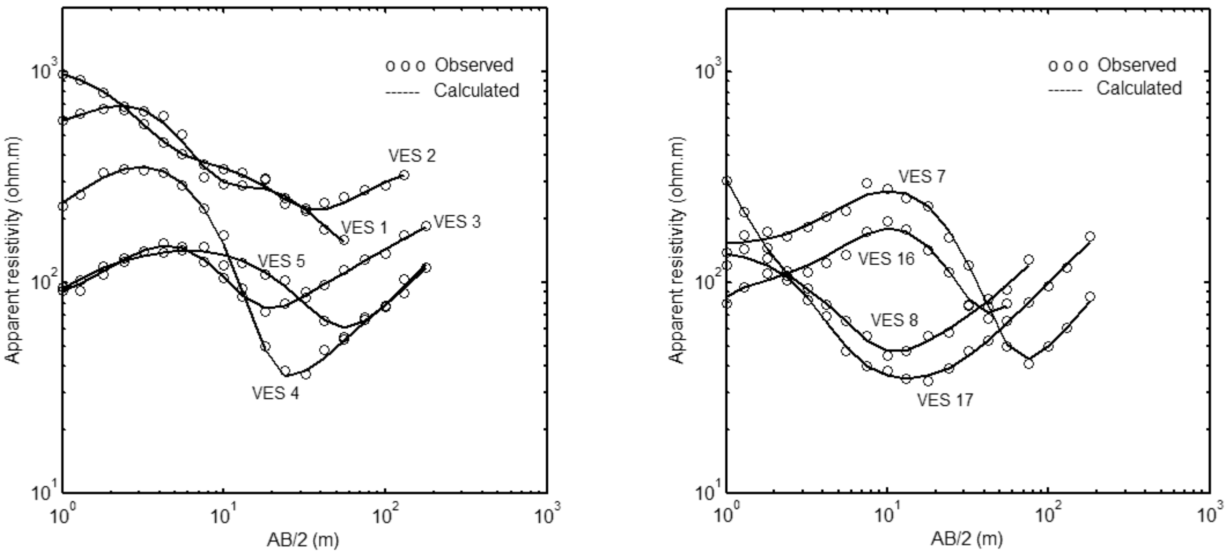

Figure 4 – VES experiments that were used to construct the geoelectrical section along AB in Figure 3.

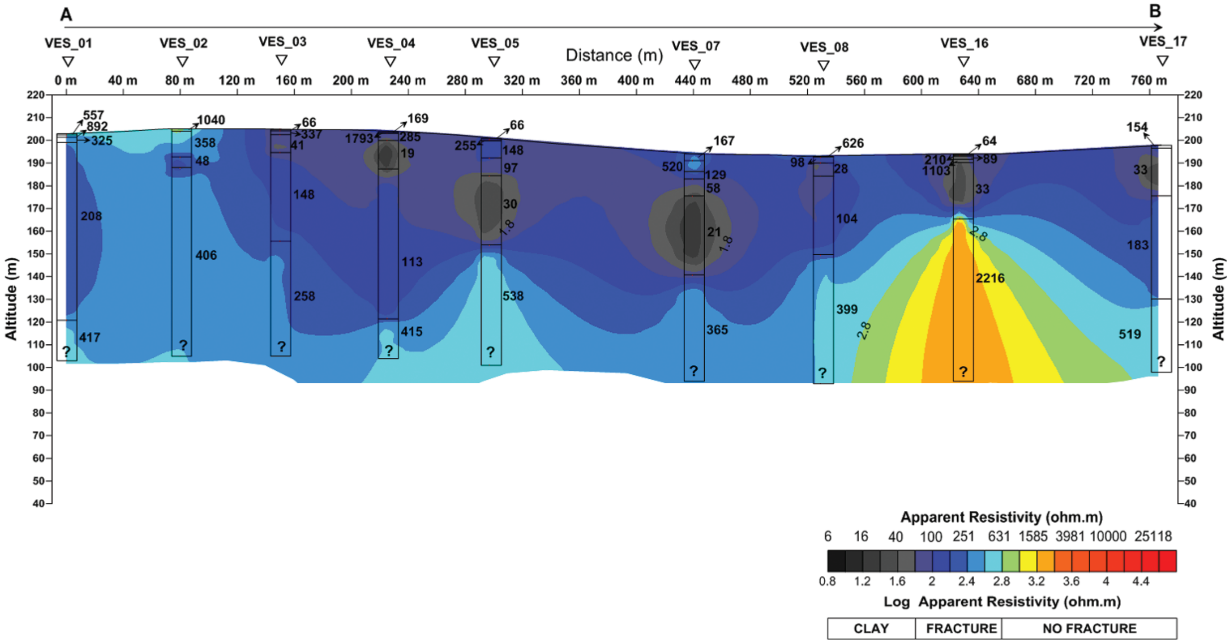

Figure 5 – Geoelectrical section along AB of Figure 3, drawn from the lateral correlation of the geoelectrical models of VES experiments 1, 2, 3, 4, 5, 7, 8, 16, and 17.

The geological information provided by Corrêa (1998), along with the information obtained in this study from the geophysical survey of Piçarra, suggest that values of resistivity less than 100 ohm.m are related to the clay material, whereas values between 100 and 450 ohm.m are related to the fractured bedrock that contains water. The values above 450 ohm.m are associated with the metamorphic bedrock layer containing no fractures. These values made it possible to build the geological sections shown in Figures 8 and 9.

VLF

Before the analysis, the dip angles were pre-processed with filters developed by Fraser (1969) and Karous & Hjelt (1983); such a treatment converts the crossover (indicative of the presence of conductors) into positive “peaks”.

Figure 10 shows the comparison between the raw data and those that were filtered with the Fraser and Karous/Hjelt filters for the Rua Minas Gerais area of study. Evidently, between stations 13 and 15, a crossover in the data indicates possible anoma-

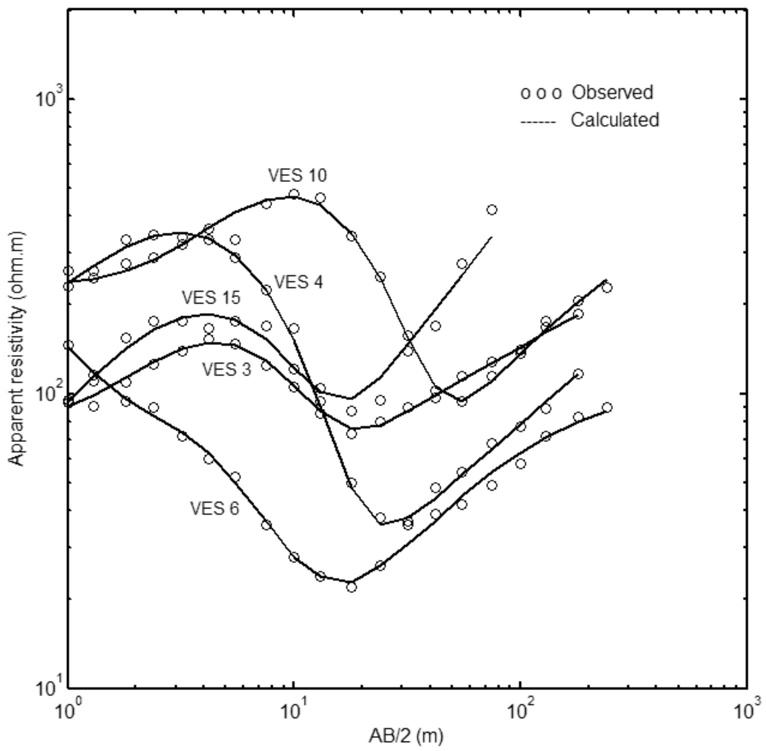

Figure 6 – VES experiments used to construct the geoelectrical section along CD in Figure 3.

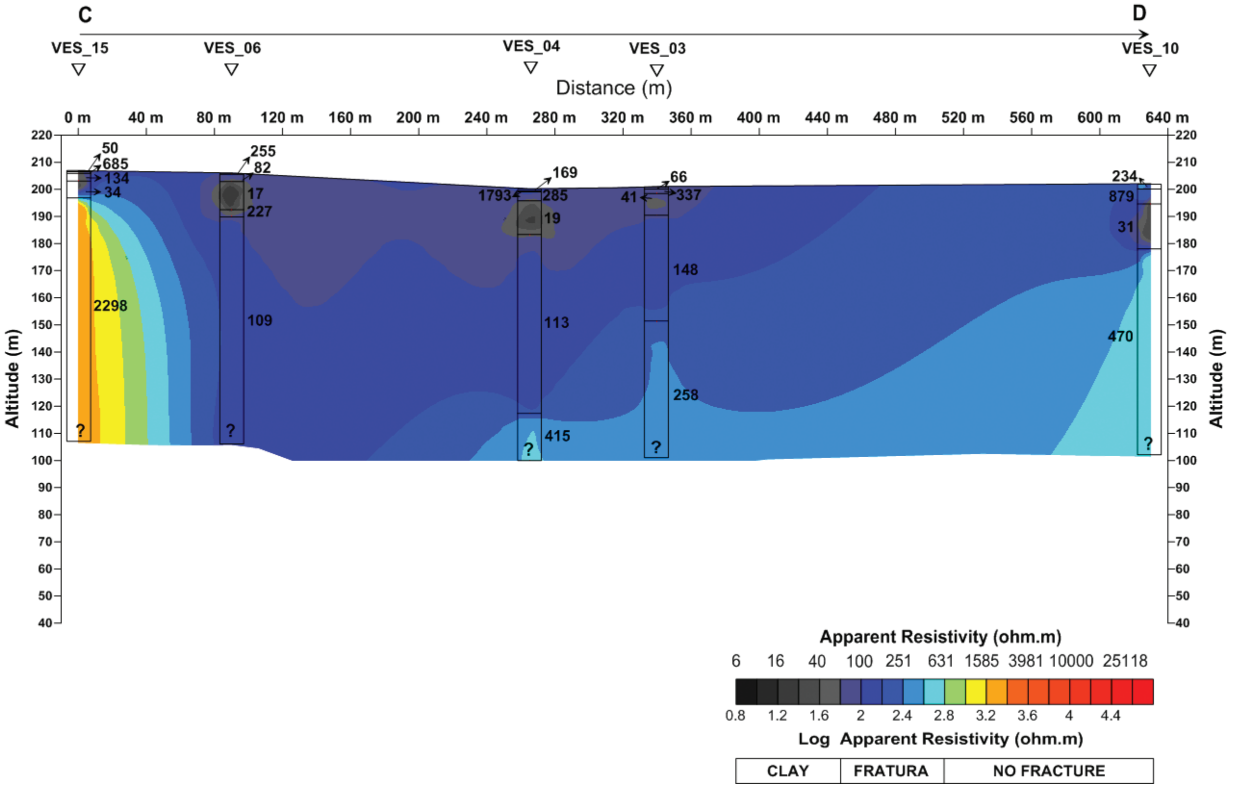

Figure 7 – Geoelectrical section along CD of Figure 3, drawn from the lateral correlation of the geoelectrical models of ves experiments 15, 6, 4, 3, and 10.

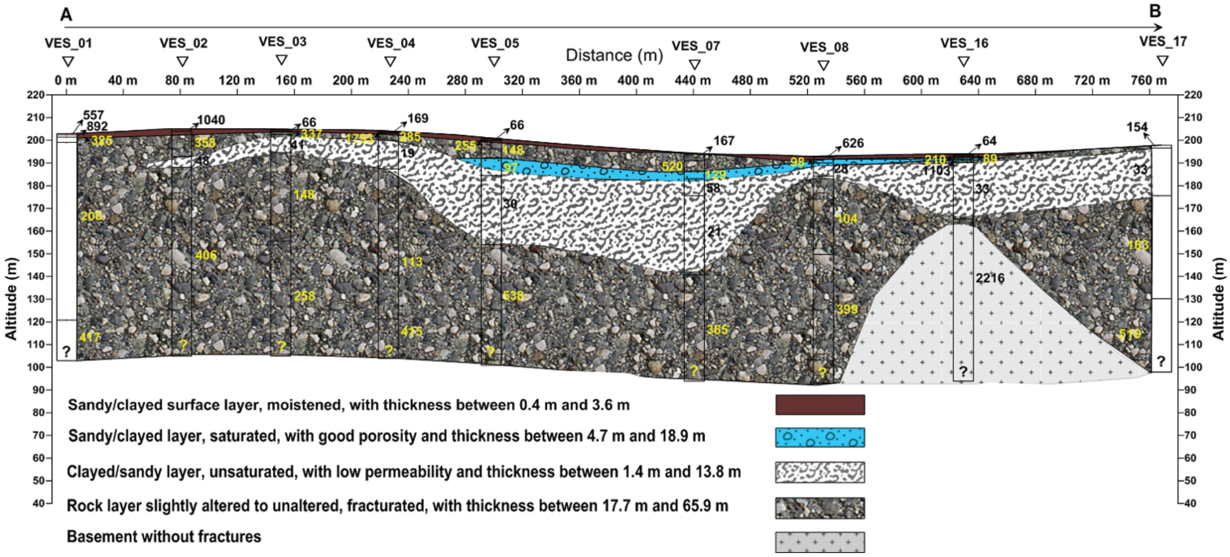

Figure 8 – Geological section drawn from the interpretation of the geoelectrical section along ab.

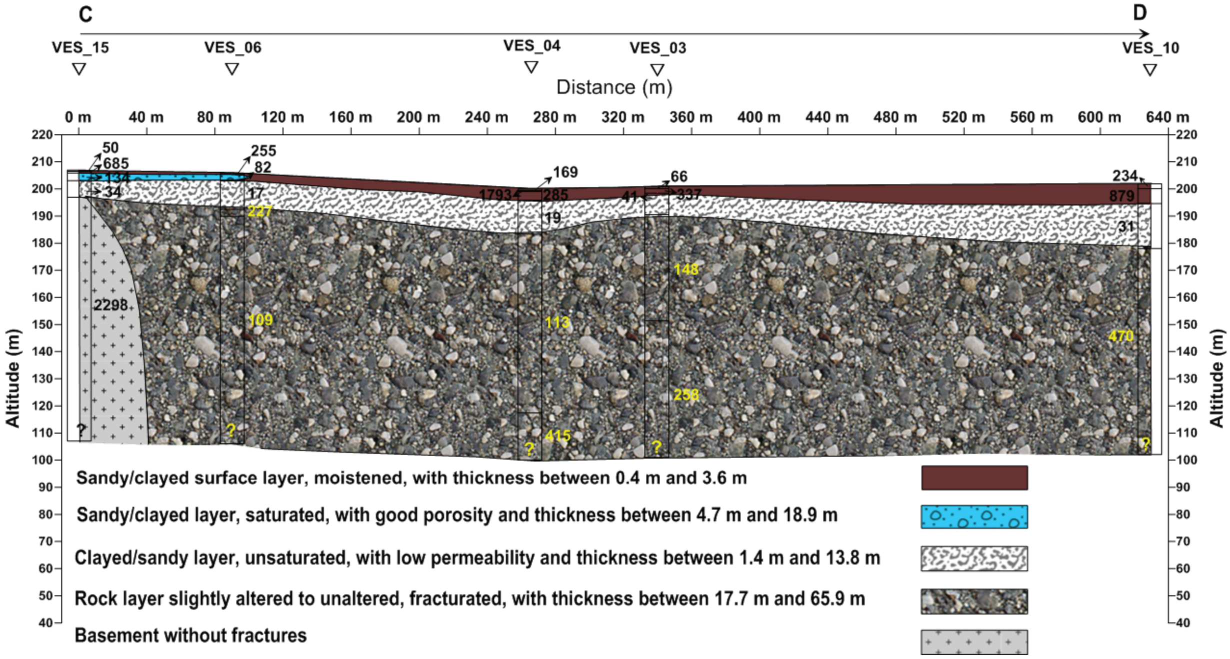

Figure 9 – Geological section drawn from the interpretation of the geoelectrical section along CD.

lous behavior in the subsurface. This anomaly is converted into a positive peak in both the Fraser-filtered data (blue line) and the Karous/Hjelt-filtered data (brown line). Moreover, the peak amplitude from the Fraser filter is more prominent than that from the Karous/Hjelt filter, thereby making the anomaly more easily recognizable in the Fraser-filtered data. Therefore, the data were processed with the Fraser filter.

Figure 11 shows the contoured (equivalued lines) distribution of dip angle values that were obtained from the survey after the application of the Fraser filter. For clarity, Figure 11 only

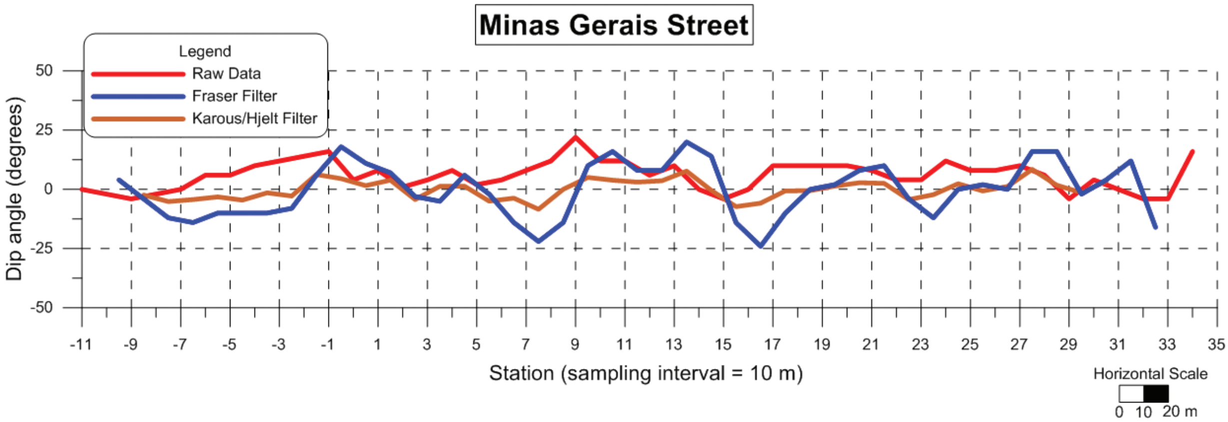

Figure 10 – Comparison between the VLF values filtered with the Fraser and Karous/Hjelt filters. Measured values (red line), filtered with Fraser (blue line) and filtered with Karous/Hjelt (brown line) for Minas Gerais street.

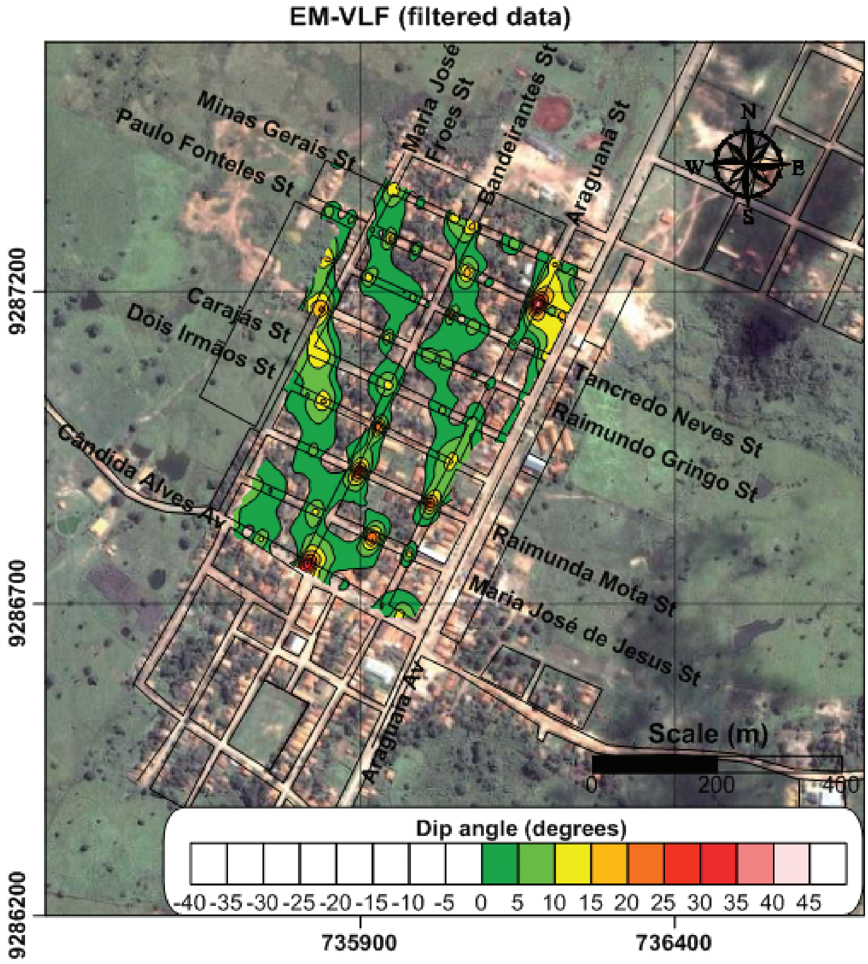

Figure 11 – Contours of the Fraser-filtered VLF values.

illustrates the positive valued contours, thus making the conductor axes easier to identify. The projections of the conductor axes on the surface are shown in Figure 12 according to the filtered value contours. As is evident from the figure, the conductor axes have a preferred NS direction. These conductors are most likely associated with bedrock fractures that are filled with water.

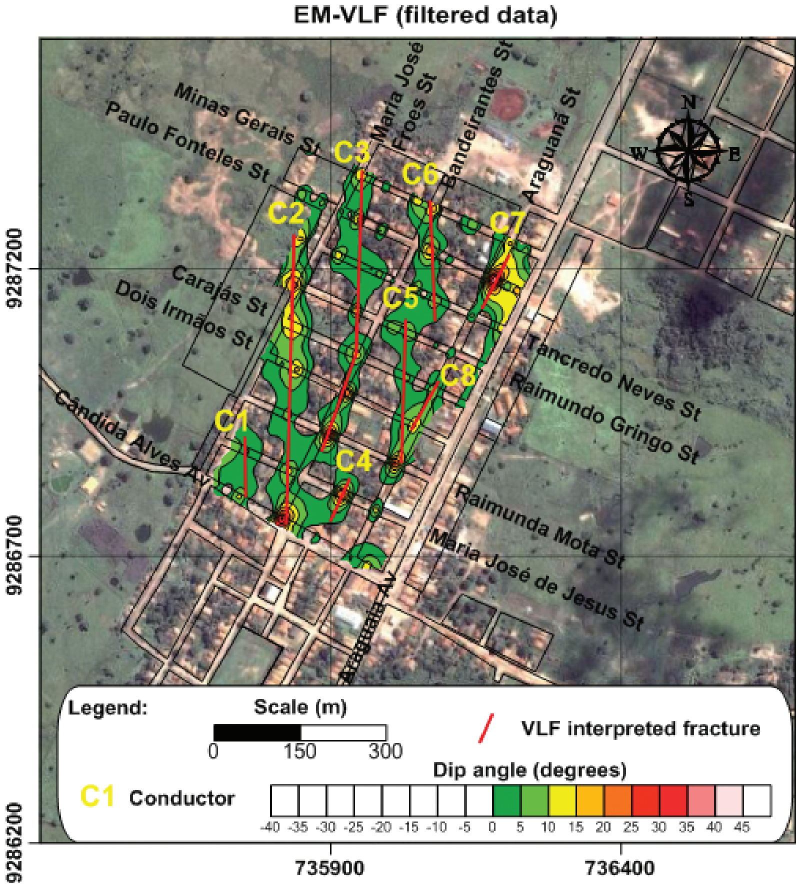

Figure 12 – Projection of the conductor axes on the surface (red lines) as indicated by the positive values of the VLF data filtered with the Fraser filter. The conductor axes were interpreted as fractures in the bedrock.

Correlation between VES and VLF

Based on the geoelectrical models supplied by the VES experiments and its with the geology and the possibility of the existence of fractures as indicated by the VLF method, the following model was established for the subsurface of Piçarra (top-to-bottom order):

1) A superficial layer consisting of landfill, sandy and clayey material, which is sometimes quite humid. The layer can display resistivity values less than 100 ohm.m and thickness ranging between 0.4 and 3.6 m;
2) A sandy to clayey layer with good porosity and saturated containing water, which displays resistivity values ranging between 10 ohm.m and 100 ohm.m and thickness between 4.7 m and 18.9 m. This layer is well characterized in VES experiments 2, 3, 6, 8, 10, 13, 14, and 16;
3) A clayey to sandy unsaturated layer, with low permeability and thickness ranging from 1.4 m to 13.8 m;
4) A zone of slightly altered to unaltered rocks containing fractures, which display resistivity values ranging between 100 ohm.m and 450 ohm.m. These layers have thicknesses ranging from 17.7 m to 65.9 m. The layers appear in VES experiments 1, 4, 5, 7, 9, 11, 12, 15, and 17; and
5) Zones of unfractured rocks that display resistivity values greater than 450 ohm.m.

The geophysical survey established a subsurface model of the area, in which two promising units were identified as potential sources of water for the town of Piçarra. These units are the saturated sandy-clayey layer and the zone of fractured metamorphic rocks. The greatest thicknesses of these units were estimated at the positions of VES experiments 7 and 4, respectively.

The correlation between the VLF and electrical resistivity results indicates that the most promising area for the construction of water capitation wells in the region is in the location of the VLF conductors for VES experiments 1, 2, 3, 4, 5, 6, 8, and 9. This region is marked with blue in Figure 13.

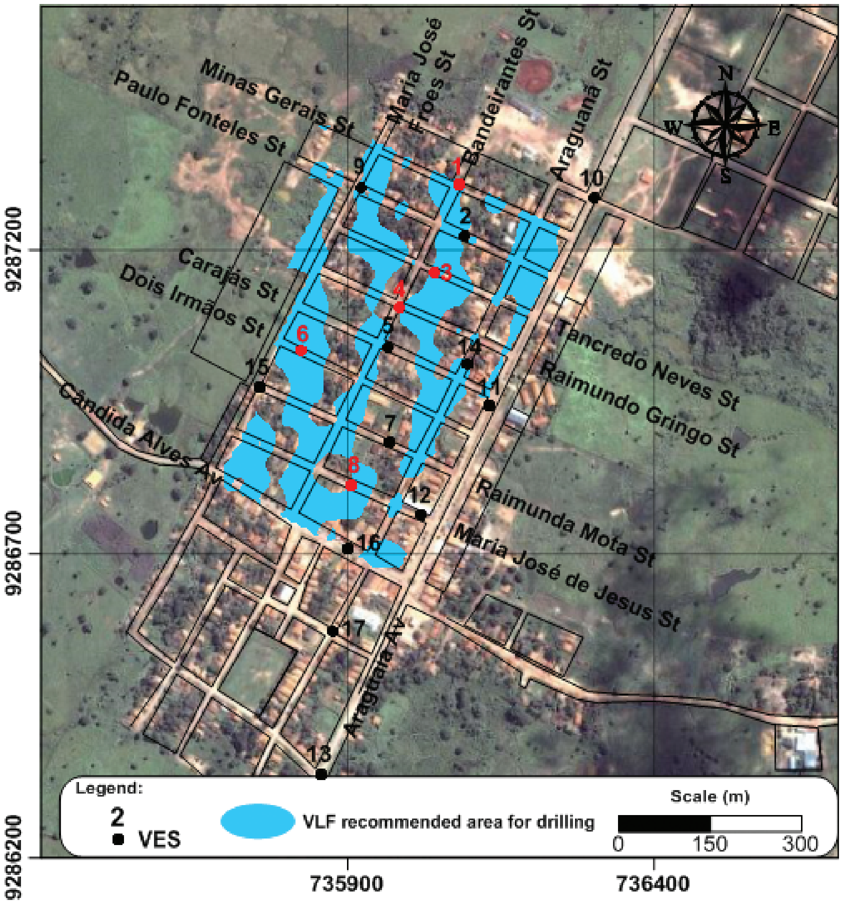

Figure 13 – Recommended locations for wells for groundwater extraction. The areas in blue were those indicated by the VLF experiments. The numbers in red indicate the location of the VES experiments that produced the best indications.

The locations of VES experiments 1, 3, 4, 6, and 8, identified by red numerals in Figure 13, are recommended as top priority for the construction of capitation wells because these locations are most likely to have fractured metamorphic rocks that contain water and a substantial thickness of saturated sandy material that is also isolated from the ground surface by an impermeable layer of clay, thus preventing contamination of the underground water. The locations of VES experiments 2, 5, and 9 should be considered as a secondary priority for drilling wells.

CONCLUSIONS

This study shows that part of the study area consists of metamorphic rocks with potential for exploitation for groundwater.

The preferred direction of the fractures that contain water as identified by the VLF is NS, which is consistent with the geology of the area.

Based on the agreement between the VES models, VLF data, and geological information, it was possible to identify the positions of the conductors that were associated with the fractures containing water and to estimate the thickness of the fractured rock.

According to the analysis of the geoelectrical models, the greatest thickness of fractured rocks was approximately 65.9 m in the Raimundo Gringo street, near the C5 conductor, as indicated by the VLF.

The best locations for a drilling area, as indicated by the VLF and VES experiments, are in the vicinity of the VES experiments 1, 3, 4, 6, and 8 because the fractured metamorphic rocks in these areas contain water and a large thickness of sandy material occur at these sites that are isolated from the ground surface by an impermeable clay layer, which protects the aquifers from contamination by harmful materials and surface agents.

ACKNOWLEDGMENTS

This study was financed by Science, Tecnology, and Environment State Secretary (SECTAM) of state of Pará government and executed with support of the Geophysical Prospecting Laboratory, Faculty of Geophysics of Federal University of Pará.

The authors also thank the technicians Afonso Quaresma de Lima e Álvaro Silva Prestes for their help during the field work.

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