Hydrogeophysical Evaluation of Serra dos Martins Formation at Serra do Bombocadinho, NE Brazil

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This paper was prepared for presentation during the 18th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 October 2023.

Abstract

The use of groundwater in regions with hydrological deficits is a good alternative as it possesses more permanent and environmentally conscious characteristics. This article evaluates the potential of the Serra dos Martins sedimentary formation for the production of good-quality groundwater in the Serra do Bombocadinho region, north/central part of Paraíba state, Brazil. The method applied is based mainly on hydrogeophysical investigation through electrical resistivity method (electrical tomography, ERT), on the mode of vertical electrical sounding (VES) with multilevel gradient electrode array. Seven ERT lines were recorded. Mathematical inversion of the data resulted in two-dimensional geo-electrical images of the subsurface. A pseudo-3D resistivity model was produced through geo-electrical data image interpolation. Rock samples were picked up for petrophysical analysis and the electrical conductivity of local groundwater samples was measured. The Archie-Winsauer model was applied to estimate the volume of water contained in the subsurface. An estimated in situ reserve of 25 million cubic meters of water was observed in the investigated area (760 hectares). Making the proportional calculation for the whole sedimentary area (3145 hectares) an approximate volume of 100 million cubic meters of groundwater was estimated. Based on electrical resistivity and porosity data it was possible to estimate the volume of water contained in the saturated rock. These findings are fundamental for sustainable planning and management of water resources.

Introduction

The geology of the State of Paraíba is dominated in three quarters of its extension by the occurrence of rocks of the crystalline basement, however, there are in the micro region of Curimataú important sedimentary occurrences of the Serra dos Martins Formation (SMF). One of these sedimentary bodies was mapped (CPRM, 2021) in the municipalities of Cuité and Barra de Santa Rosa. This micro region, due to the semi-arid climate and climate changes, suffers from the deficit and poor distribution of water resources. In addition to the fact that surface waters are increasingly contaminated by human activity, there is a deficiency in precipitation and an excess of evaporation of these resources. Groundwater use is an alternative way to attenuate this reality, as it has a more permanent nature, practically does not suffer from evaporation during dry periods, and is more environmentally conscious regarding the effects of human action. Therefore, investigating the potential of the SMF for the supply of good quality groundwater, is a scientific activity of great social and economic importance for the region.

In general, sedimentary rocks have much higher water storage and transmissibility properties than igneous or metamorphic rocks, constituting granular reservoirs with much greater potential for the production of groundwater. Currently, there is sparse information about the hydrogeological potential of SMF occurrence at Serra do Bombocadinho site and this study contributes to fill this gap.

The Serra dos Martins Formation is dated by Morais Neto *et al.* (2009) as Cenozoic covers (Eocene/Paleocene). It is composed at its base of homogeneous and friable sandstones, whitish in color, poorly selected, locally conglomeratic and kaolinitic, with silicified layers. In its intermediate portion, banks of homogeneous clayey sandstones are described with a yellowish-red color, with subangular to rounded quartz grains and on the surface of the formation there is a lateritic crust of reddish to purple color, with poorly selected angular quartz pebbles (GUIMARÃES *et al.*, 2008).

This paper is an experimental study, combining field and laboratory activities, to investigate the hydrogeophysical characteristics and quantify groundwater reserves using geophysical subsurface imaging and petrophysical tests on rock samples of the Serra dos Martins Formation, collected at the Serra do Bombocadinho region of the Paraiba state, northeast Brazil.

Method

A bibliographical survey about the Serra dos Martins Formation (SMF) was carried out, with information on the sedimentology, stratigraphy and petrography of the lithotypes in the study area. The SMF sedimentary occurrence under study is totally located in the western Curimataú micro region of the Paraíba State (Figure 1).

Rock samples were collected at seven outcrops. As a sampling criterion, the stratigraphy of the SMF in the region was followed, from the base to the top, as well the proximity to the surveyed geoelectric sections. The samples were used to create plugs for carrying out petrophysical tests. Water samples were collected from wells in the region and their electrical conductivity was measured. The Archie-Winsauer model was applied in order to evaluate the groundwater reserves at the investigated site.

Geophysical survey

To carry out the hydrogeophysical surveys, the eletroresistivity method was applied in the form of electrical tomography (ERT). It was adopted the vertical electrical sounding (VES) with a multilevel gradient array. Electrical methods are non-invasive in nature, not altering the physical environment, in addition to being easy to apply and quick to assess large areas at a relatively low cost (BRAGA, 2006). The use of ERT method has shown successful applications to investigate rock discontinuities, depth of the rocky top and thickness of sediments, recognition of hydrogeological characteristics and groundwater flow factors, determination of different geoelectric strata, presence of clayey layers and tectonic structures (SARAIVA, 2010).

The multilevel gradient electrode array was used due to its better data acquisition logistics and higher resolution in comparison to Wenner and Schlumberger arrays, as discussed by Aizebeokhai & Oyeyemi (2014) and Martorana *et al.* (2017).

Geophysical lines were drawn seeking a representative areal distribution of the sedimentary occurrence. In the studied area, seven geophysical lines were executed, as can be seen in Figure 1.

For recording data in the field, parameters were adopted according to the depth of investigation and the resolution required in each line, as well the time necessary to data recording using a mono-channel equipment. In lines 1 to 6, the intended depth of investigation was close to 100 meters, so we used a maximum spacing between the current electrodes equal to 500 meters and we adopted a minimum separation between potential measurement electrodes equal to 20 meters.

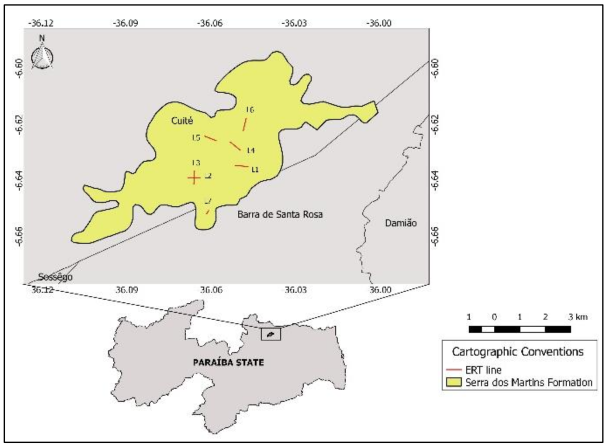

Figure 1 - *Location map of SMF at Serra do Bombocadinho with indication of geophysical lines carried out in the area of study.*

The investigation on Line 7 aimed to compare the geological description of an active well, as described by the landowner, with the respective geoelectric section. The maximum depth of the well is 35 meters, so there was no need to investigate up to 100 meters deep. Particularly in this line, a maximum distance between the current electrodes equal to 150 meters was adopted with a minimum separation between the potential measurement electrodes of 5 meters, increasing the resolution of the geoelectric image.

For the hydrogeophysical surveys of this work, we used a mono-channel Bodenseewerk GGA 30 resistivemeter. After data recording in the field, they were inverted by the RES2DINV software (GEOTOMO, 2003). Data inversion consists of minimizing the difference between the calculated values of apparent resistivity and those measured in the field, adjusting the resistivity of each block, generating geoelectric sections (LOKE & BARKER, 1996).

The data from the geoelectric sections were interpolated in order to generate a pseudo three-dimensional model for the sedimentary occurrence. The applied interpolation technique used the inverse square of the distance approach.

Petrophysical Analysis

The rock samples required prior preparation, so that they are cylindrical in shape and with dimensions of 3.8 cm in diameter and with an ideal height of around 5 cm, suitable for the conditions of the equipment available at the UFCG Petrophysics Laboratory.

Rock samples collected in the field may be of two types: 1) rock blocks of decimeter dimensions extracted from outcrops; or 2) rock cylinders extracted directly from the outcrops using a portable gasoline-powered plugger. To obtain Type 1 specimens it is necessary to saw the rock sample, extract plugs in a benchtop plugger and to ensure flat and parallel faces in a plug rectifier. In case 2, there is no need to extract plugs in a bench plugging machine. Both rock samples were used in this work, but mainly of Type 2.

After the preparation step, the plugs were placed in a drying oven at a temperature of 90 degrees Celsius for 24 hours. Then, the dimensions of the plugs were measured using a digital caliper and then weighed on a semi-analytical precision scale.

For laboratory petrophysical tests, a gas permoporosimeter was used. The total density of the plug was measured by the ratio between the mass measured in the sample after drying and the volume calculated from the measured dimensions. The gas permoporosimeter is based on the Boyle-Mariotte law to analyze the porosity and the density of grains. This law indicates that, in closed systems and without temperature variation, the product between the volume of gas and its pressure remain constant before and after the interconnection of two subsystems.

Eight samples were analyzed in the petrophysics tests. Due to the scarce rocky outcrops in the investigated area, three of them were collected near existing wells, and the rest along the access slope to the sedimentary plateau of the occurrence, close to geophysical line L1 (Figure 1). The indication of the places where the rock samples were extracted can be seen in Figure 2.

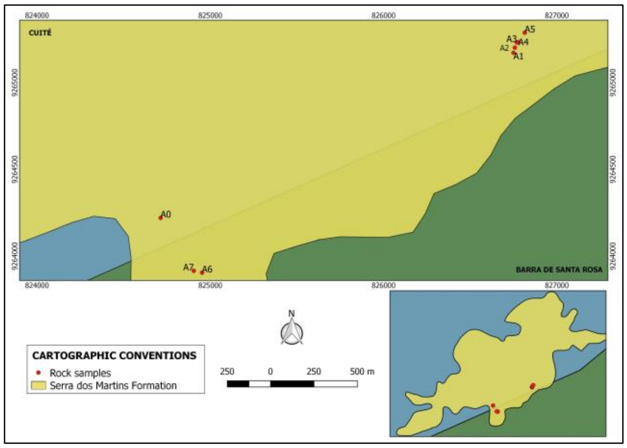

Figure 2 *- Location of extraction sites for rock samples from the sedimentary occurrence.*

The calculation of groundwater reserves is based on expressions that relate the electrical resistivity of the saturated rock with the electrical resistivity of the water that saturates the rock, the porosity of the rock, the tortuosity of its permeable channels and a cementation exponent, which depends on the rock type.

Archie (1942) proposed the so-called formation factor (F), which corresponds to the ratio between the electrical resistivity of the rock saturated with water (Ro) and the resistivity of the water that saturates the rock (Rw).

$$\mathrm{F} = \frac{\mathrm{R_0}}{\mathrm{R_w}} \tag{1}$$

Later, Winsauer *et al*. (1952) proposed that the formation factor would be a function of the porosity (ϕ), the tortuosity coefficient (*a*) and the cementation exponent (***m***).

$$\mathrm{F} = \frac{\mathrm{a}}{\phi^{\mathrm{m}}} \tag{2}$$

Combining the two equations and applying the logarithmic function, we arrive at

$$\log(\phi) = \frac{[\log(a) - \log(F)]}{m} \tag{3}$$

Therefore, knowing the resistivities of the saturated rock and the saturating fluid, in addition to the range of porosity variation, it is possible to estimate the values of the parameters ***a*** and ***m***. With this, it is possible to calculate the porosity value by knowing the electrical resistivity value of the rock.

The electrical resistivity values of the rock saturated with water are extracted from the geoelectric sections, while the resistivity of the water that saturates the rock is obtained through laboratory measurement of the electrical conductivity of water samples collected in wells. With three-dimensional models generated for the subsoil of the investigated area (from the geoelectric sections) it is possible to estimate the volume of water contained in the subsoil.

Results

Hydrogeophysical Investigation

Due to limitation on the number of pages, only three of the seven geoelectrical sections are shown (figures 3 to 5). They are representative of the general geophysical response on the whole sedimentary occurrence, whose behavior can be seen in the geoelectric sections for lines 1, 2, 3, 4, and 6. This general model contains three different layers. The layer 1 is a resistive unit that extends from the ground surface to about 20 to 30 meters depth. The layer 2, which is located below layer 1, is conductive (in blue) and is found up to 80 meters depth. This suggests a water-saturated unit. Alternatively, its low resistivity may results of a combined effect of water and clay. Finally, the layer 3 (warm colors), found below layer 2 exhibits high electrical resistivity, inferring that it is composed of rocks from the crystalline basement or dry and cemented sandstones.

Geoelectric sections for lines 5 and 7 exhibit deviations from the dominant model. In line 5, the subsurface configuration diverges from the dominant pattern for the sedimentary occurrence, indicating a subvertical discontinuity, suggesting the action of different local sedimentation and/or structural evolution processes.

The line 7 is located in an area where a lagoon forms during the rainy season. There is a well that produces water in the center of this line. In its geoelectrical section can be observed a conductive surface layer that extends to a depth of approximately 12 meters, which are saturated sediments. Below it, there is an interval of electrical resistivity that increases continuously from the base of the conductive layer to a depth of about 20 meters. This layer with variable resistivity was interpreted as composed of altered crystalline rock. Below 20 meters of depth, there is a homogeneous layer of high electrical resistivity, which was interpreted as sound crystalline rock.

The Figure 6 shows the pseudo-3D model generated for a volume containing all the geoelectric sections studied in the sedimentary occurrence. The water-saturated layer is seen in this model in blue and purple colors. Considering that sandy-clayey sediments and sandstones, such as those occurring in the investigated area, present electrical resistivities between 40 ohm.m and 300 ohm.m when saturated with water, the volumes of water contained in the rock volume of the pseudo-3D model can be estimated after petrophysical analyses.

The software used for data interpolation allows calculating the volume of rock contained in the layer with electrical resistivity values between these limits. This calculation indicates that for the investigated area (760 hectares), the volume of rock saturated with water is 410 million cubic meters. To calculate the volume of water contained in this rock volume, it is necessary to estimate the porosity effectively saturated with water, which is done by applying the Archie and Winsauer equations.

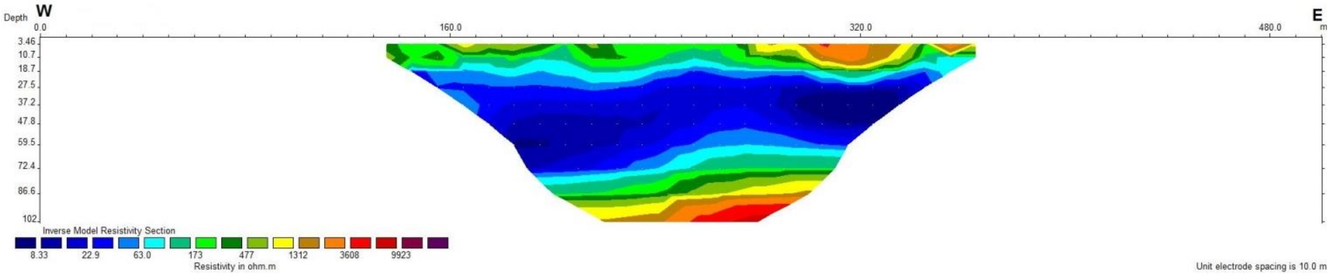

Figure 3 - *Geoelectric section for line 1.*

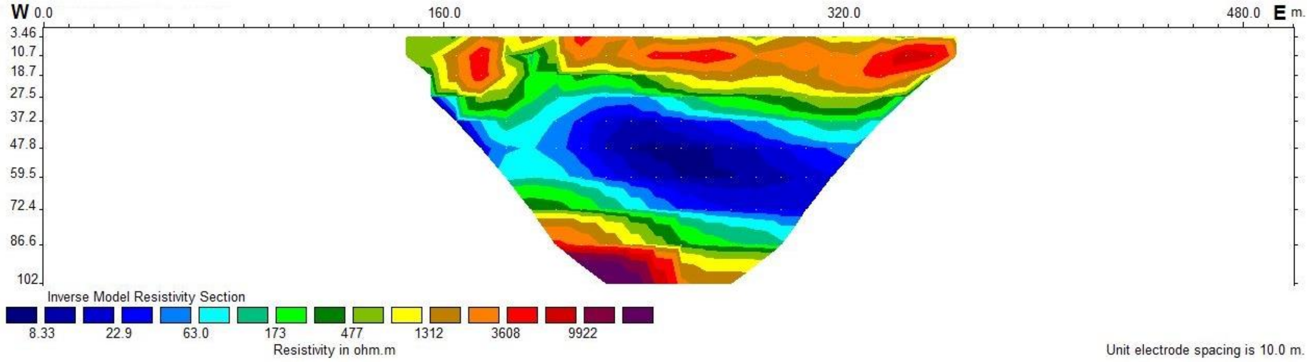

Figure 4 - *Geoelectric section for line 2.*

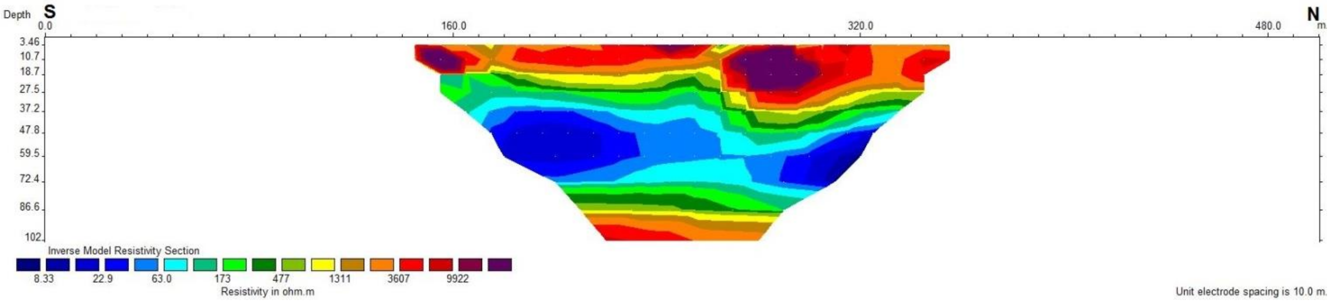

Figure 5 - *Geoelectric section for line 6.*

Petrophysical Analysis

The measured values of porosity and grain density in rock samples collected from outcrops are shown in Table 1. It can be observed that the porosity values vary from about 5% to 36%. The Figure 7 shows the values of porosity, grain density, and bulk density of the samples with respect to the sampling point altitude. It can be seen that the samples collected near wells have a higher average porosity value (30.2%) than the average porosity value (14.4%) of the samples collected on the slope near line L1. The average porosity of all samples is 20.3%.

The Figure 8 shows a high inverse correlation between porosity and bulk density, indicating that an increase in porosity results in a reduction in rock density. However, the Figure 9 shows a reasonable direct correlation between porosity and grain density, indicating that rock samples rich in minerals lighter than quartz (density = 2.65 g/cc) have lower porosity values. One possible reason for this is the partial obliteration of the initial pore space of the rock by hydrated clay minerals.

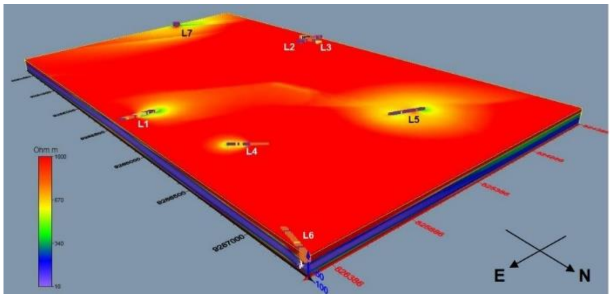

Figure 6 - *Pseudo-3D model for electrical resistivity of the studied area.*

Reserve Calculation

Knowing the resistivity values of the saturated rock and saturating fluid, as well as the porosity values, the parameters ***a*** and ***m*** can be estimated. This allowed for the calculation of the value of porosity saturated with water.

Table 1 *- Petrophysical properties measured in extracted rock samples of the sedimentary occurrence.*

Sample	Latitude UTM (24S)	Longitude UTM (24S)	Altitude (m)	Sample density (g/cm^3)	Grain density (g/cm^3)	Porosity (%)
A0	9264221	824713	638	1.711	2.678	36.1
A1	9265172	826750	590	1.837	2.591	29.1
A2	9265202	826758	592	2.171	2.465	11.9
A3	9265232	826770	595	2.229	2.340	4.7
A4	9265234	826778	595	2.237	2.365	5.4
A5	9265288	826815	601	1.881	2.375	20.8
A6	9263905	824952	634	1.927	2.422	20.4
A7	9253916	824904	633	1.706	2.584	34.0

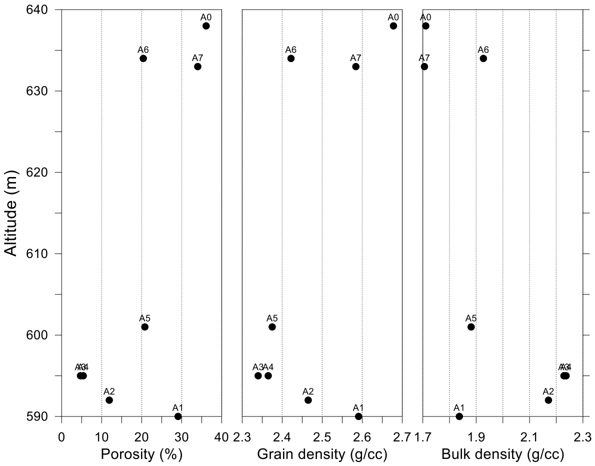

Figure 7 *- Relationship between the petrophysical properties and the altitude of the point of collection, for rock samples from the sedimentary occurrence.*

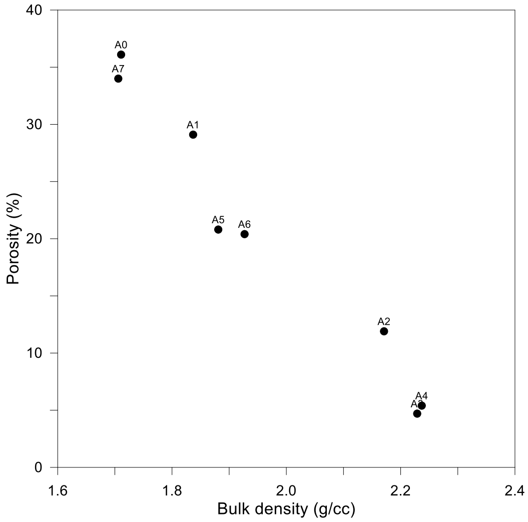

Figure 8 *- Relationship between porosity and bulk density.*

The resistivity values of the water-saturated rock (Ro) are extracted from the pseudo3D model (Figure 6), while the resistivity of water (Rw) saturating the rock is obtained through the measurement of its electrical conductivity. The average conductivity of the water produced in the investigated wells is 3793 S/cm, which corresponds to an electrical resistivity of 2.64e-06 ohm.m. Considering that the rock saturated with water presents electrical resistivity between 40 ohm.m and 300 ohm.m, equation (3) can be applied to the electrical resistivity data to estimate the saturated porosity at each voxel of the pseudo3D model. Thus the volume of water contained in the conductive unit of the rock model is calculated.

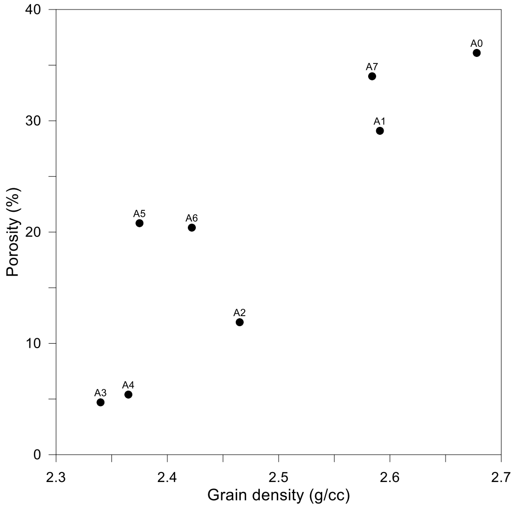

Figure 9 *- Relationship between porosity and grain density for rock samples.*

The Figure 10 presents the saturated rock porosity as a function of the rock electrical resistivity at the depth points where this latter property was measured along the geophysical lines. This relationship was obtained considering that ***a*** = 2 and ***m*** = 6, which provide porosity values compatible with those measured in petrophysical tests.

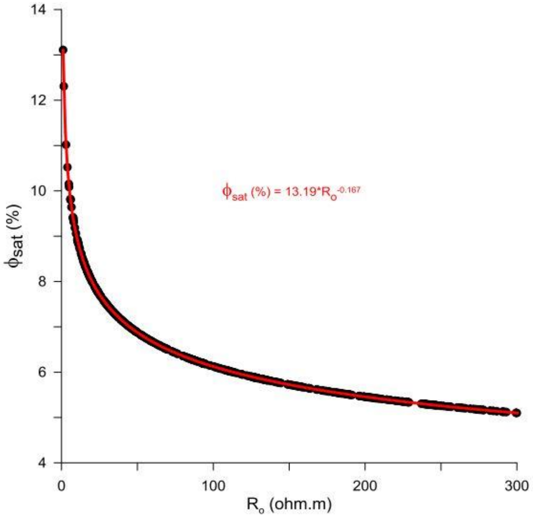

Figure 10 *- Relationship between saturated rock resistivity and porosity saturated in water (**a** = 2; **m** = 6; Rw = 2.64e-6 ohm.m).*

Applying the regression function from figure 10 to the pseudo3D model data, an estimate of 25 million cubic meters of in situ reserves of water was obtained within the investigated area (760 hectares). Proportional calculation for the entire sedimentary occurrence area (3145 hectares) yields an approximate volume of 100 million cubic meters of groundwater contained in that sedimentary occurrence.

However, given this significant volume of water, it is clear that the volume that can be effectively produced is much smaller. Under normal conditions, the annual volume that can be produced from an aquifer without causing damage to the formation is equivalent to the annual recharge received by that aquifer. In turn, the annual recharge volume is directly related to the annual precipitation and the nature of the terrain, which controls the rate of water infiltration into the subsurface.

The average annual precipitation for that region is about 550mm, and assuming that 20% of the precipitation volume infiltrates into the soil in that area, the annual recharge volume is only 3.5 million cubic meters. However, during prolonged dry periods, the produced volume may temporarily exceed the recharge, provided that this water deficit is compensated during a period of higher rainfall.

Conclusions

The geological analysis of the studied sedimentary occurrence revealed the presence of sandstones, conglomeratic sandstones and conglomerates, with different degrees of silicification. The hydrogeophysical investigation allowed the identification of distinct layers in the subsurface, including a resistive layer close to the surface, a conductive layer saturated with water and a deep layer of high resistivity, which may be correspondent to rocks of the crystalline basement or silicified sandstones.

Based on the electrical resistivity values of the rock saturated with water and the porosity, it was possible to estimate the parameters ***a*** and ***m*** and calculate the porosity saturated with water. This information was applied to the pseudo-3D model, allowing estimation of the volume of water contained in the saturated rock.

The results indicate an estimated volume of 25 million cubic meters of water in situ in the investigated area, corresponding to approximately 100 million cubic meters of groundwater in the entire sedimentary occurrence. However, it is important to consider that the sustainable production of groundwater is related to annual recharge, which depends on precipitation and infiltration rate in the soil.

In conclusion, the results obtained in this study provide important information about the geological and hydrogeophysical characterization of the sedimentary occurrence, as well as estimates of the volume of groundwater present. These data are fundamental for the planning and sustainable management of water resources, considering the natural limitations of the aquifer and the region's demands in terms of water availability.

Acknowledgments

We would like to express our sincere thanks to all the people that contributed to carry out this work, especially to land owners and our institutions (UFCG and IFPB). This work is part of a research project funded by FAPESQ, the Paraíba state R&D agency.

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