Groundwater volume estimation of an area with metamorphic rocks by ERT

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Abstract

The electrical resistivity tomography (ERT) method was applied in an area with a predominance of metamorphic rocks of Archean age in order to estimate the in situ volume of groundwater, which is already produced, processed and bottled for human consumption. Five 2D lines were recorded and data were two-dimensionally processed and then interpolated, alternatively, by the methods of Inverse Square of Distance and by Kriging, to generate pseudo-3D models of the subsurface. In the area investigated, groundwater is already produced through a network of wells, so that the productivity of the wells could be compared with the depth range of the wells within the conductive region of the three-dimensional model. Rock samples were collected in the field and, after preparation, submitted to porosity tests. The adoption of a petrophysical analysis procedure, based on the application of Archie's equation, allowed the calculation of reserves in place. Taking the average of the volumes obtained by the two alternative methods of interpolation, the measured reserve for the investigated area is 4.5 million 20-liter bottles, which served as support for the decision to increase investments and, consequently, production.

Introduction

The area investigated is composed of rocks of Archean age (2.5 to 4.6 billion years) with quaternary cover over the thalwegs of the drainage lines. The rocks of the site make up the Cabaceiras Complex, formed by tonalitic-granodioritic orthogneiss with metamafic intercalations (CPRM, 2005). Figure 1 shows the geological map of the municipality of Queimadas, where the investigated area is located, identified as Fazenda Nova, to the south of the municipality.

The analysis of the structures present in the rocks of the investigated area allowed to identify foliation with WSW-ENE direction and open fractures in the NNW-SSE direction, being one of the objectives of the study to evaluate the relative contribution of each of these types of geological structures to the flow and storage of groundwater in the area.

Fazenda Nova is located in a sub-watershed that, for the context of the municipality of Queimadas, has the highest capacity for meteoric water collection and drainage formation. The hydrogeological favorability in the region of Fazenda Nova is caused by the existence of a drainage channel of second fluvial order, which crosses the farm, passing through the area of the weir. This is the main mechanism of recharge of fractures and porosity resulting from weathering of subsurface rocks. This percolation of water was responsible for feeding the local fissure aquifer over the years, allowing the capture of groundwater with good flows. In addition, the local topographic conditions condition the existence of a region of greater favorability in places where the potentiometric surface presents lower elevations. In this site groundwater is already produced through a network of six wells (Figure 2).

Method

The method employed in this work consists of the application of electroresistivity tomography (ERT) for the identification of regions of conductive rock which may indicate volumes of rock saturated with water. ERT was applied as 2D lines whose geoelectric images were interpolated in order to generate three-dimensional models of electrical resistivity for the region investigated. Five 2D lines were recorded, all with a length of 500m, minimum spacing between electrodes of 20m and a multilevel gradient arrangement (Dahlin & Zhou, 2006). Four lines were recorded perpendicular to direction of open fractures, and a central line in the direction perpendicular to the anterior ones and parallel to the rock foliation. The location of the ERT lines is shown in Figure 2. Pick up of rock samples allowed laboratory tests to be carried out to measure petrophysical properties. A sample of water collected from a well in the area allowed the measurement of the groundwater electrical conductivity. Calibration of Archie's equation to experimental data allowed the calculation of saturated porous volume for the whole three-dimensional model, thus obtaining an estimate of *in place* groundwater volume.

Data interpolation was performed in order to generate a 3D model for the investigated area. This model allows to spatially visualize the arrangement of zones of low electrical resistivity and quantify their volumes, which may correspond to zones carrying groundwater. For the generation of the three-dimensional model, two alternative methods were used: 1) Interpolation by the inverse square method of distance; and 2) Interpolation by the geostatistical method of kriging.

The generation of the 3D model by the inverse square method of the distance is faster, because it considers only a purely mathematical criterion for the interpolation of the data. This criterion says that two points of the model present values of the investigated variable (in this case, the electrical resistivity) that depend only on the inverse of the square of the distance between these points.

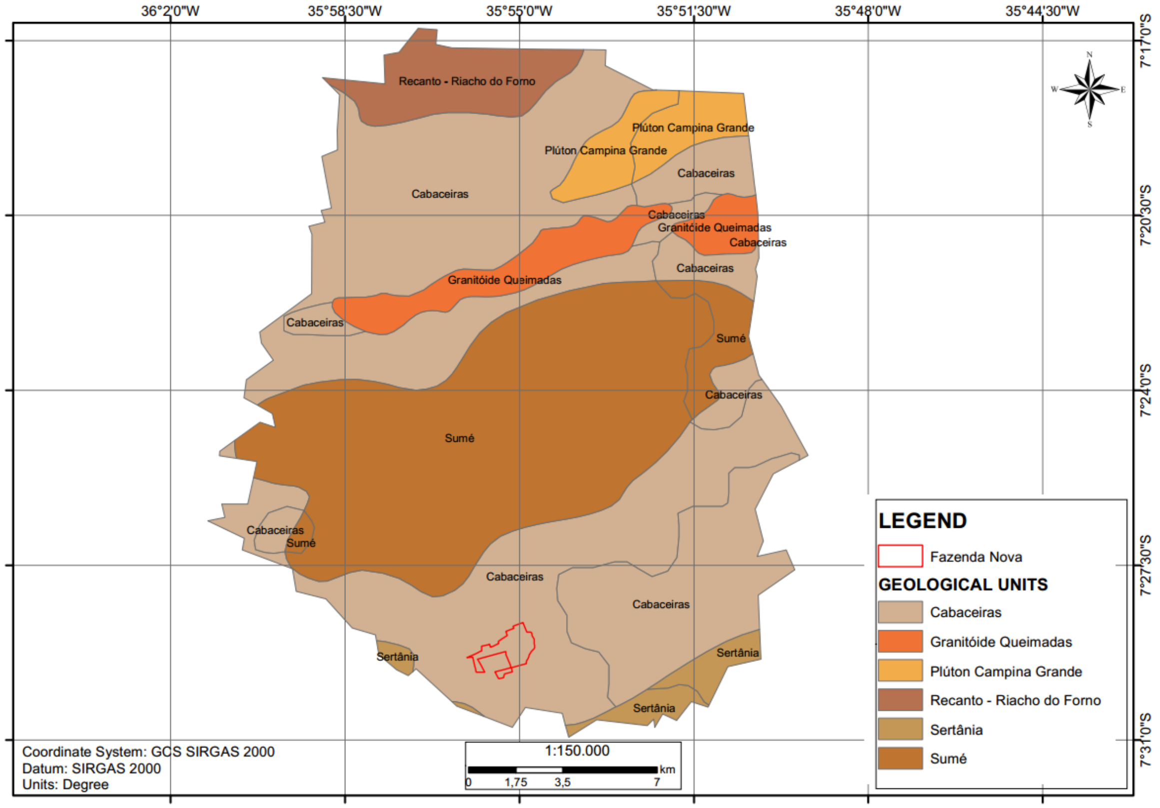

Figure 1 – Geological map of Queimadas municipality with indication of the Fazenda Nova site.

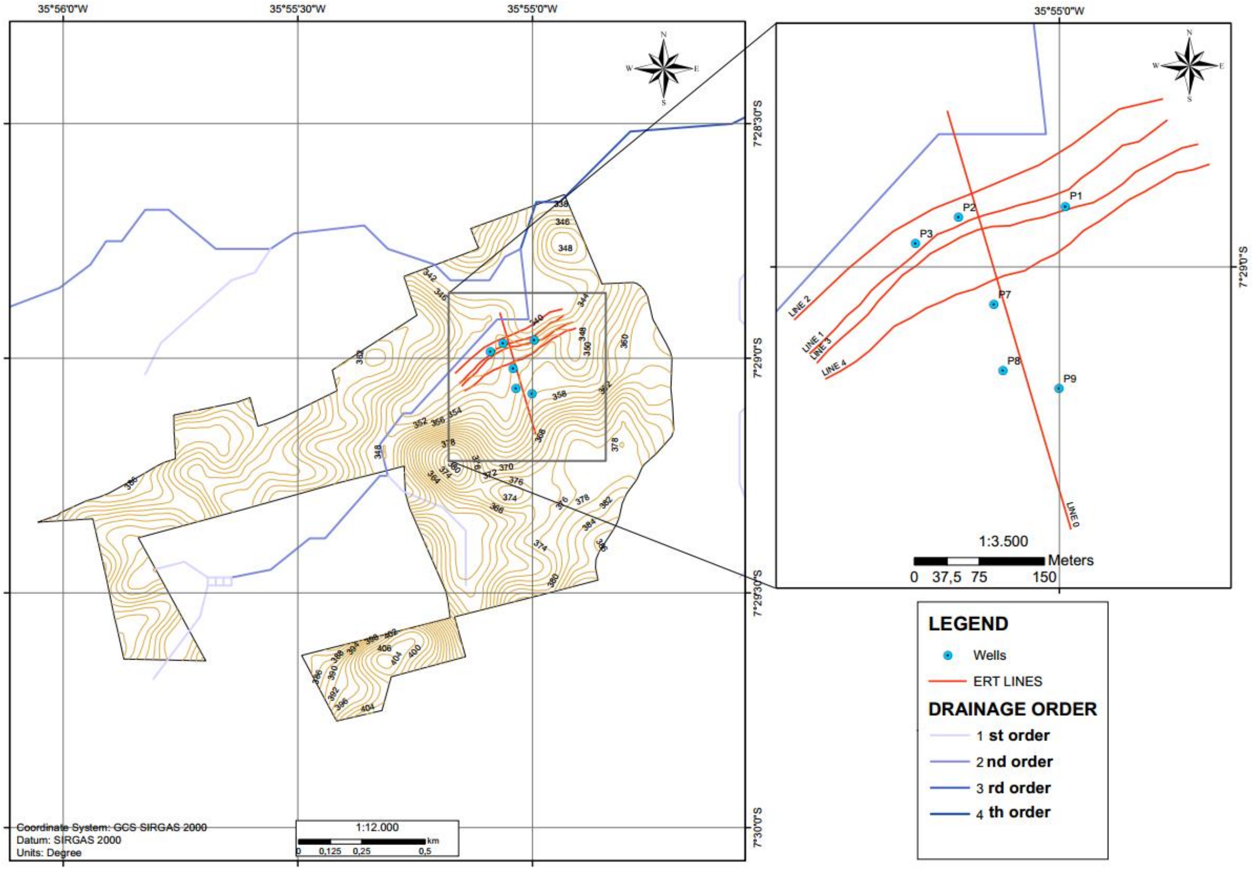

Figure 2 – Topography of Fazenda Nova site with fluvial order of drainages and location of ERT lines and wells.

Kriging is a widely accepted geostatistical technique and regarded as the best technique for spatial interpolation of geological data (Kitanidis, 1997). It is based on the measurement of the spatial continuity of the phenomenon analyzed, which in this case is the spatial distribution of electrical resistivity values in the subsurface. Kriging is a theoretically more accurate technique, but one that requires greater analytical effort.

The 3D models obtained allow to calculate the volume of rock and sediments that contain water, that is, the volume of material whose electrical resistivity is less than or equal to 400 ohm.m. However, water occupies only the porous spaces of these materials, so it is necessary to measure the rock porosity in the investigated area.

In order to measure this porosity I laboratory, three rock samples were extracted in the vicinity of well P1. Figure 3 shows the photograph of the three samples in which porosity was measured using the gas expansion method (Tiab & Donaldson, 2004).

Figure 3 - Rock samples (SV_1, SV_2 and SV_3) used in petrophysical tests.

There are two types of porosity: the primary porosity, formed by the empty spaces between the mineral grains, which in metamorphic rocks such as those occurring in the investigated area is always very small (around 1%); and secondary porosity, which in this type of rock corresponds to the empty spaces caused by fractures, fissures and also by physical and chemical changes of the rocks that occur over geological time. For the type of rock that occurs in the area investigated, secondary porosity is dominant. Samples SV_1 and SV_2 are hard rocks with a low degree of cracking, while sample SV_3 is friable rock with a high degree of alteration.

Calculation of groundwater reserves is based on two expressions relating the electrical resistivity of the saturated rock with the electrical resistivity of the water that saturates the rock, the rock porosity, a tortuosity coefficient 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 water-saturated rock (Ro) and the resistivity of the water that saturates the rock (Rw).

$$F = \frac{R_o}{R_w} \qquad (1)$$

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

$$F = \frac{a}{\emptyset^m} \qquad (2)$$

Joining the two equations and applying the logarithmic function yields

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

Therefore, knowing the resistivities of saturated rock and of saturating fluid, in addition to the range of variation of the porosity (Table 1), it is possible to estimate the values of the parameters *a* and *m*. With this it is possible to calculate the water-filled porous volume knowing the rock electrical resistivity values.

The electrical resistivity values of water-saturated rock are extracted from the 3D model of electrical resistivity, while the resistivity of the water that saturates the rock is obtained through laboratory measurement of its electrical conductivity. The conductivity measured in the ground water sample was 3710 μmho/cm, which corresponds to an electrical resistivity equal to 2.7 omh.m. Considering that the rock saturated with water has an electrical resistivity of at most 400 ohm.m, equation 3 can be applied to the electrical resistivity data in order to estimate the saturated porous volume at each point of the 3D model. Thus, it is possible to calculate the volume of water contained in the whole rock model.

Results

After data processing (Loke & Barker, 1996), the geoelectric sections obtained are presented in figures 4 to 8. The 3D model obtained by the inverse square method of the distance can be visualized in Figure 9A, along with the location of the wells already existing within the volume of the model. The colors indicate the electrical resistivity values, as indicated in the legend. Values equal to or greater than 500 ohm.m appear in red, while values equal to or less than 10 ohm.m appear in purple. Figure 9B shows the corresponding 3D model obtained by the geostatistical kriging method.

Figures 10A and 10B show the models cut below the 300 m topographic level. In this figure all points of the surface in dark blue color have electrical resistivity equal to 400 ohm.m. This value was considered as the maximum value of electrical resistivity expected for a fractured and/or altered metamorphic rock containing water, as proposed by Gallas & Giardin (2016). Both models show that the wells with the highest producing potential are wells P1, P2 and P7, while the one with the lowest potential is well P9. This result is consistent with flow rate values presented by these wells, as can be seen in Figure 11.

Figure 12 shows the porosity variation as a function of electrical resistivity at the points at which electrical resistivity was measured along geophysical data lines. This relationship was obtained considering *a* = 1 and *m* = 1.3, which provide porosity values compatible with those measured in laboratory.

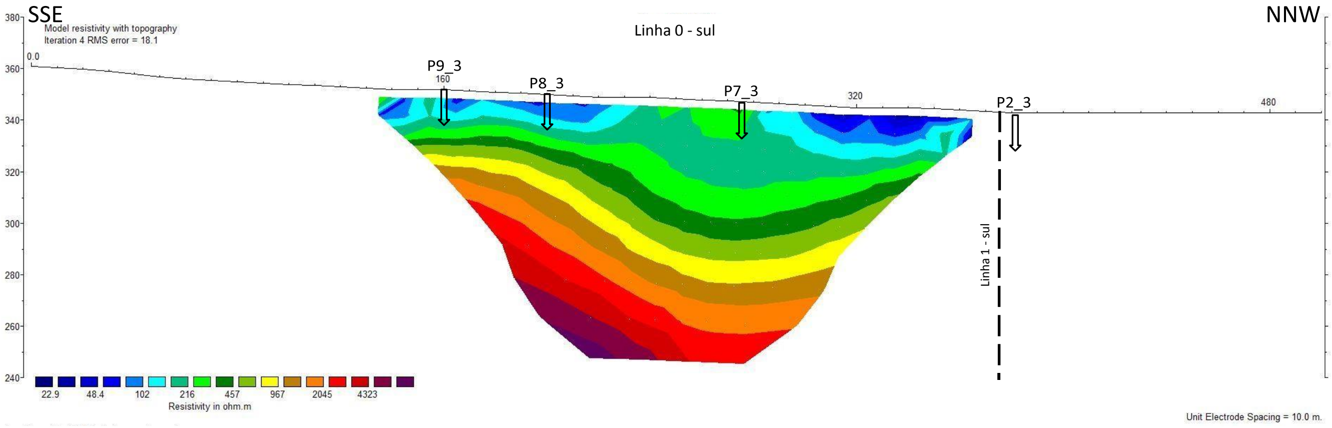

Figure 4 - Geoelectric section resulting from the two-dimensional inversion of the Line 0.

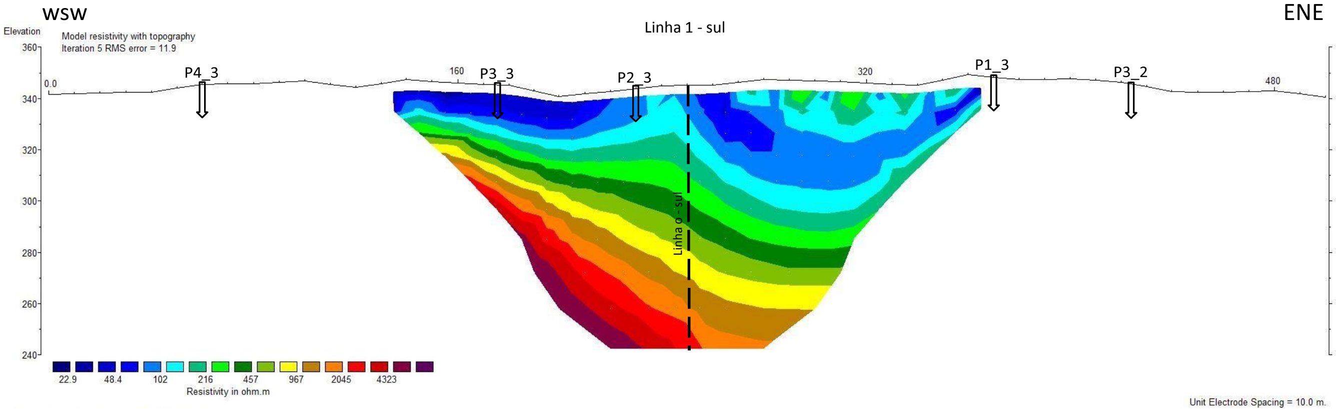

Figure 5 - Geoelectric section resulting from the two-dimensional inversion of Line 1.

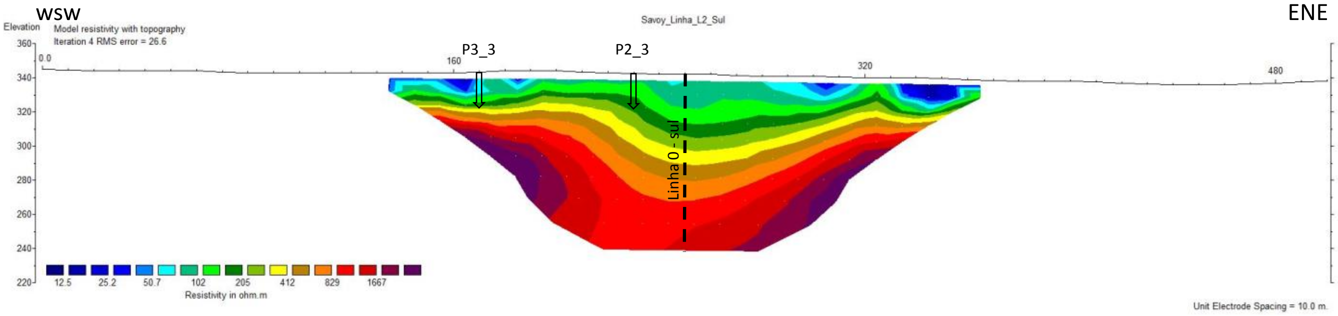

Figure 6 - Geoelectric section resulting from the two-dimensional inversion of Line 2.

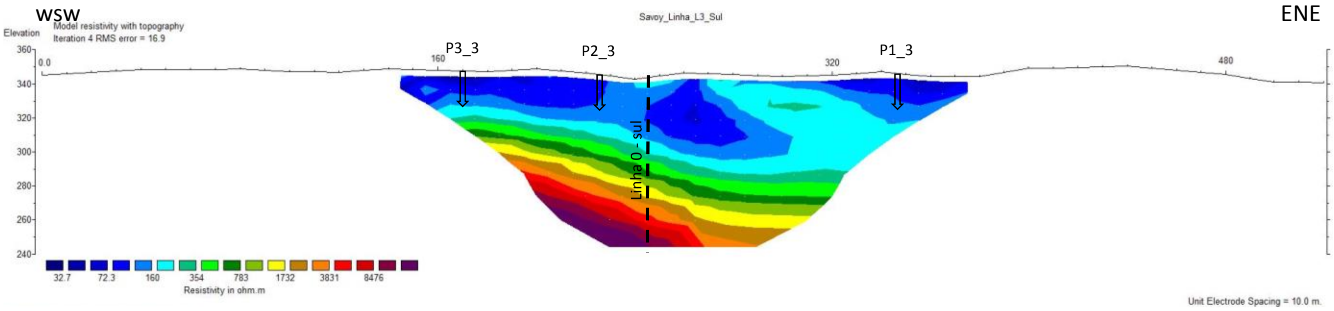

Figure 7 - Geoelectric section resulting from the two-dimensional inversion of Line 3.

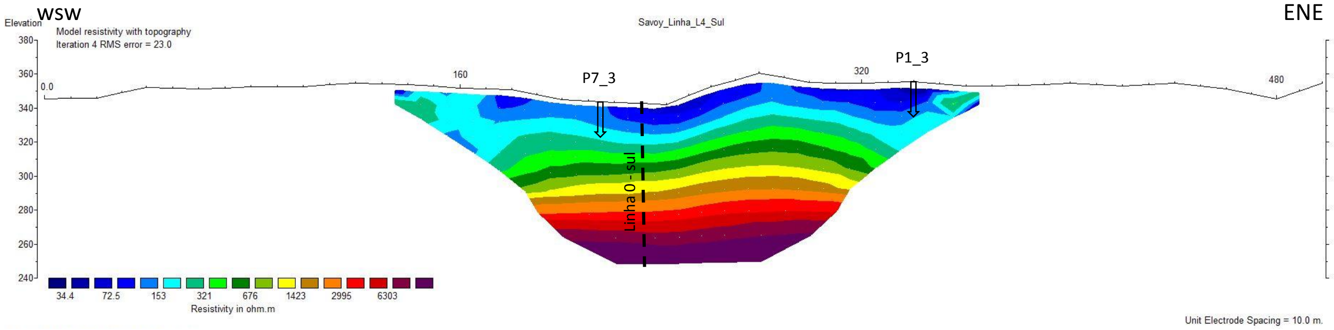

Figure 8 - Geoelectric section resulting from the two-dimensional inversion of Line 4.

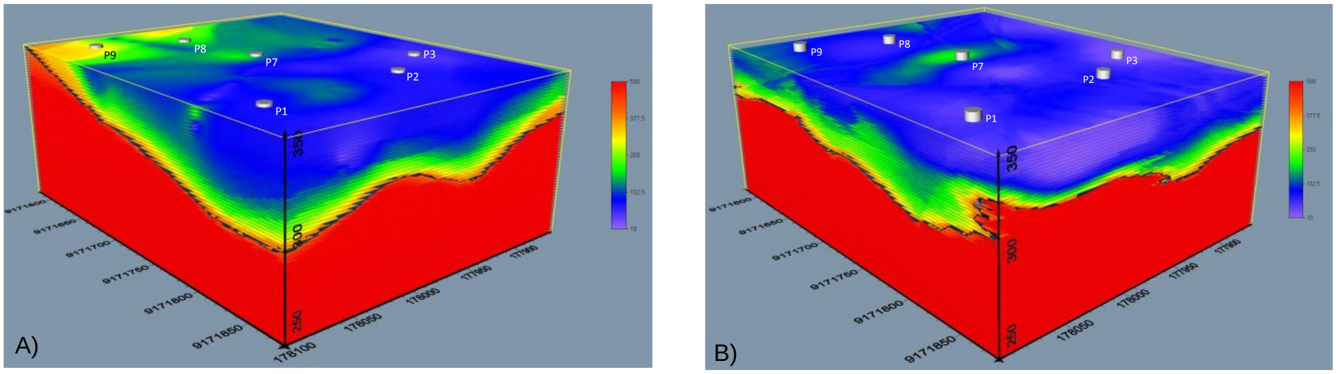

Figure 9 – 3D model obtained by the inverse square method of distance (A) and by the Kriging method (B).

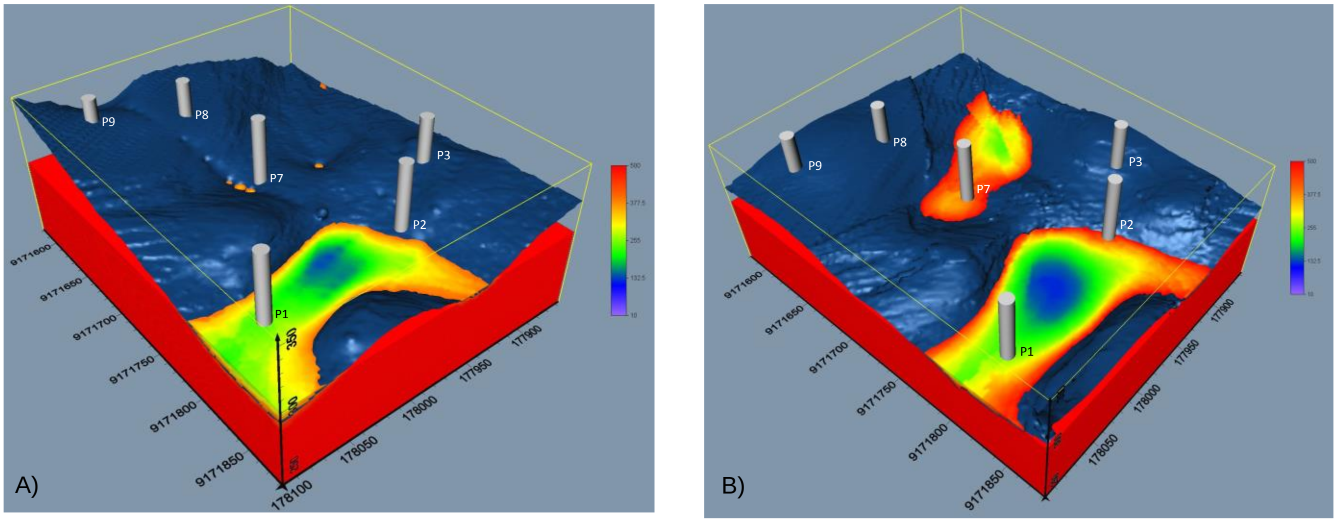

Figure 10 - Models of Figure 9 cut below the 300m quota with the addition of a surface corresponding to 400 ohm.m.

Table 1 – Petrophysical properties measured in the rock samples collected in the investigated area.

Sample ID	Dry Weight (gm)	Grain Volume (cc)	Grain Density (gm/cc)	Pore Volume (cc)	Porosity (%)	Length (cm)	Diam. (cm)	Caliper BulkVol (cc)	Temp (C)
SV_1	146.2	53.38	2.738	0.877	1.6	4.868	3.767	54.3	23
SV_2	232.8	73.92	3.149	0.543	0.7	6.811	3.731	74.5	23
SV_3	128.2	48.50	2.643	7.581	13.5	5.154	3.722	56.1	23

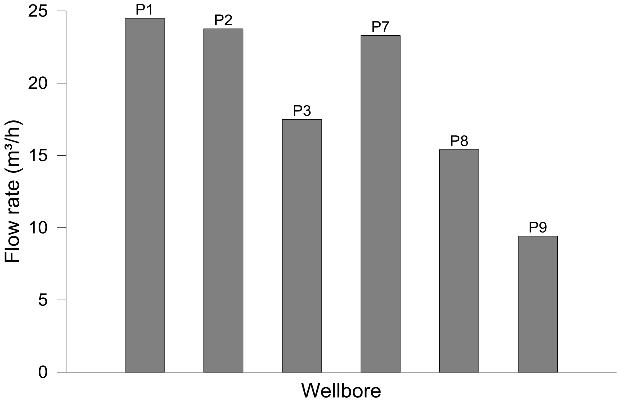

Figure 11 – Flow rates presented by the wells of the investigated area.

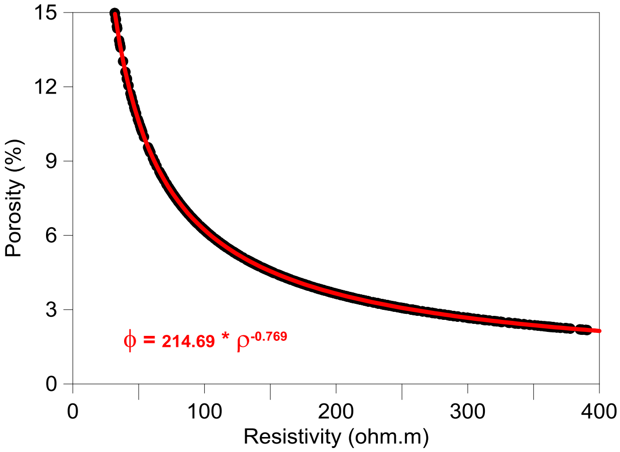

Figure 12 - Relationship between porosity and electrical resistivity determined for the investigated area.

$$\emptyset = 214.69\rho^{-0.769} \quad (4)$$

By applying equation 4 to all elements of the 3D model and integrating them, the total saturated porous volume is calculated. Only those elements of the volume whose resistivity is less than or equal to 400 ohm.m are taken into account. In addition, all elements of the model whose elevation is above 340 meters were excluded in order to discount the topographic variations of the terrain above the water level.

Thus, the groundwater reserves estimated for the area by the inverse square method of the distance were 4.3 million of bottles (20 liters each), while by the kriging method they were 4.7 million bottles. Taking the average for both alternative methods, the measured *in place* reserve for the investigated area is 4.5 million bottles.

It should be taken into account that the area investigated is 7.4 hectares, which corresponds to only 3.7% of the area of Fazenda Nova, although this is the most promising area of the farm for this purpose. If we consider that the reserves of the rest of the farm are proportional to 1/5 of the reserves for the investigated area, this adds reserves of the order of 23.5 million bottles, resulting in total inferred reserves of 28 million bottles.

Finally, attention should be drawn to the fact that these measured and inferred reserves concern the volume of water contained in the subsoil. Certainly the volume capable of being extracted is much smaller. On the other hand, groundwater reserves are dynamic. The volume contained reflects the reality of the moment when the geophysical survey was carried out. Aquifer recharge seasons will contribute to the increase of reserves, while prolonged periods of drought will cause their reduction.

Conclusions

The ERT method was successfully applied for the evaluation of *in place* groundwater reserves in an area composed of Archean metamorphic rocks. The approach efficiency was proven by the good correspondence between the thickness of the intervals of the wells that cross conductive regions of the electrical resistivity model and the flow rates presented by these wells.

Petrophysical analysis showed the groundwater is stored mainly in intervals of metamorphic rock with a high degree of alteration and, consequently, with high porosity. Fracture porosity plays a secondary role in the investigated area.

Finally, the *in place* groundwater reserves estimated for the investigated area provided technical support for decision-making on the expansion of investments in order to increasing production, which was really achieved.

References

ARCHIE, G.E. (1942). The electrical resistivity log as an aid in determining some reservoirs characteristics. Petroleum Technology, v. 5, p. 54-62.

CPRM (2005). Projeto cadastro de fontes de abastecimento por água subterrânea: Diagnóstico do município de Queimadas.

DAHLIN, T.; ZHOU, B. (2006). Multiple gradient array measurements for multi-channel 2D resistivity imaging. Near Surface Geophysics 4 (2):113-123.

GALLAS, J.D.F.; GIARDIN, A. (2016). Eletrorresistividade na prospecção de aquíferos fraturados. Revista Águas Subterrâneas, 30(1):119-13.

KITANIDIS, P.K. (1997). Introduction to Geostatistics: Applications in Hydrogeology. Cambridge University Press, 249 p.

LOKE, M.H.; BARKER, R.D. (1996). Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophysical Prospecting, v. 44, p.131- 152.

TIAB, D.; DONALDSON, E.C. (2004). Petrophysics: Theory and practice of measuring reservoir rock and fluid transport properties. Elsevier, 889 p.

WINSAUER, W.O; SHEARIN JR., H.M.; MASSON, P.H.; WILLIAMS, M. (1952). Resistivity of brine-saturated sands in relation to pore geometry. Bulletin of AAPG, vol. 36, nº 2, p. 253-277.