Geoelectric data input in the preliminary characterization of thickness and calculation of permanent reserves of Barreiras Aquifer - the lower course area of Maxaranguape River-RN

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Abstract

The target of this research is the lower course area of the Maxaranguape River, located on the east coast of Rio Grande do Norte, and particularly in the hydrogeological domain of Barreiras Aquifer. This study aimed to characterize the thickness of the Barreiras Aquifer in the study area, in order to make an estimate of the permanent hydrogeological reserves in mentioned area. For this purpose, we used the geophysical method of resistivity running the vertical electrical sounding (VES) with Schlumberger electrode array, combined with lithological profile information available from wells in the area. Thus, the data integration from the interpretation of VES 11 and hydrostratigraphic / lithologic data obtained from 20 wells profiles, as well as bibliographic data about the area available was performed.

Inverse models from the interpretation of the field curves of apparent resistivity (obtained using the IPI2WIN software), additionally to the data mentioned herein, enabled the elaboration of the saturated thickness map, using a geostatistical treatment (interpolation and gridding) and the preliminary calculation of the permanent hydrogeological reserve of Barreiras Aquifer. In general, the saturated thickness values range between 19m and 60m, predominantly thickness of 45 m.

The preliminary calculation of the permanent hydrogeological reserve was performed through the product between the area of the aquifer occurrence in the region (200 km^2), the average thickness of saturated values determined (45m) and the average effective porosity (7.60%), obtaining a saturated volume for permanent reservation of $6{,}84 \times 10^8$ m^3.

Introduction

The eastern coastline of the entire northeast region of Brazil has always lived with a conception that water was a nearly inexhaustible resource, either by the high rainfall and its perennial rivers or by the occurrence of aquifers with high potential. However, this assumption, combined with the agro-industrial and urban development, has led to a "culture of waste", and therefore an increase in the demand for water, especially in large urban centers. For this reason, some care must be taken in order to preserve these aquifers, always looking for a better planning for the use of groundwater.

The Barreiras Aquifer, which covers much of the east coast of Rio Grande do Norte State, is the largest spring of groundwater of Eastern State coast and the main source of water supply in the metropolitan region of Natal (SERHID, 1998). The aim of this research is the region of the low course of the Maxaranguape River (Figure 1), in hydrogeological domain of the Barreiras Aquifer. The site rainfall index relatively high, combined with the natural discharge of that aquifer makes Maxaranguape River perennial in its middle and lower course. The region now reported encompasses about 200km2 and includes counties of Maxaranguape and Ceará-Mirim/RN.

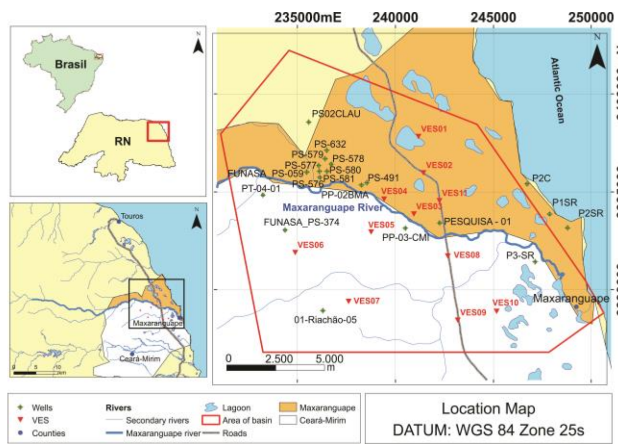

Figure 1 - Map of location of the study area, in addition to SEV's and wells in Maxaranguape-RN region.

The lithostratigraphy of the area is characterized by two sequences (Bezerra, 1998; Lucena, 2005): a non-outcropping, formed by crystalline basement (composed of granite, gneiss, migmatites and granodiorites) and the mesozoic carbonate sequence (one sandstone unit at the base and other calcareous at the top, with interbedded sandstone); and the other outcropping, consisting of terciary-quaternary cenozoic sediments, represented by the Barreiras and Potengi Formations, and quaternary covers (beachrocks, dune fields, sandy covers, beach sands, alluvial deposits and mangroves). The Barreiras Formation consists lithologically by clastic rocks, ranging from shales to conglomerates with predominantly clayey sandstones.

In hydrogeological context, the study area, particularly, is of great importance, since it is a strategic surface and underground water reserves, including to Natal. According to Lucena (2005), approximately 80% of the water supply of the counties of the east coast of the state is realized from the aquifer in question, which is intended both for human consumption as for industrial use and irrigated agriculture. The hydrogeological basement of this aquifer is composed by the top of the mesozoic carbonate sequence non-outcropping, composed basically by shale-sandstone to claystone of calciferous composition, this with reduced hydraulic conductivity (Lucena, 2005; Silva et al, 2014). Overlapping the aquifer's basement are found predominantly sandy sequences with the presence of clay lenses, typical of the Barreiras Aquifer, being the general hydraulic character of the aquifer regarded as unconfined, although with local semi-confinements (IPT, 1982; Lucena, 1999). Recent studies in the Brazilian northeast highlight the influence of the local structural partitioning of the aquifer in the increasing thickness of the saturated zone (Lucena et al, 2006; Lucena et al, 2013). The aquifer exploitation flows are proportional to the saturated thickness, reaching values greater than 100 m^3/h in the areas of greater thickness (Lucena, 2005). Pumping tests conducted in the area, by Melo et al. (2013), allowed us to evaluate parameters such as hydraulic conductivity and transmissivity, which were obtained average values of $1{,}0 \times 10^{-4}$ m/s and $3{,}0 \times 10^{-3}$ m^2/s, respectively, considering the unconfined conditioning of the aquifer. In addition, the same study found that the thickness of the aquifer ranges between 19m and 50m. A descriptive petrographic study of thin sections of Barreiras Aquifer carried out by Silva et al (2014) allowed to obtain an average value of the parameter effective porosity (7.60%), which was used for calculating the permanent reserve of the aquifer in this work.

Methodology

The methodology used in this research included the integration of data from the interpretation of 11 vertical electrical sounding (VES) performed in the area, hydrostratigraphic / lithological data of 20 wells profiles - provided by CAERN, FUNASA and SEMARH-RN (inserted in the hydrogeological database from the Department of Geophysics of UFRN) and bibliographic data available on the area. Inverse models obtained from the interpretation of the apparent resistivity field curves, using of IPI2WIN software, together with the data of wells mentioned herein, provided the elaboration of the saturated thickness map and subsequently the preliminary calculation of the permanent hydrogeological reserve of the Barreiras Aquifer in the study area.

The geophysical method of resistivity, given its recognized applicability in groundwater research, was adopted in this work by using the vertical electrical sounding (SEV) technique with Schlumberger type electrode array. The method of the resistivity is based on determining the apparent resistivity of the substrate from the response to the flow of an electric current (Ward, 1990). The basic principle of the method consists of applying an artificial direct current to the soil using a electrode located at surface, with the aim of measuring the electrical potential generated in the vicinity of the current flow. Using a pair of current electrodes (AB) and a pair of potential electrodes (MN), represented in figure 2, may obtain the potential difference generated, being possible to associate it with the electrical resistivity of subsurface rocks and later relate to lithological variations, fracturing, saturation, salinization and/or contamination in the subsurface, among other aspects.

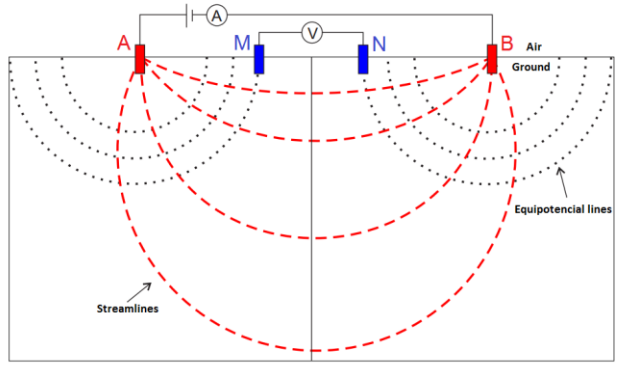

Figure 2 – Illustration of the behavior of the streamlines and equipotential during an investigation of vertical resistivity, using two current electrodes (red) and two potential electrodes (blue).

Starting from the principle of Ohm's Law and knowing the intensity of electric current (i) used, the potential difference (Δv) measured and the geometry of the electrodes distribution (k), it's possible figure out the resistivity of the semi-space in the subsurface by means of equation 1:

$$\rho = k \cdot \left(\frac{\Delta v}{i}\right) \text{ (Equation 1)}$$

The vertical electrical sounding (VES) consists the research of vertical resistivity variations, considering a central point of the array to determine the thickness and apparent resistivity of the layers in the subsurface. The depth of investigation depends on factors such as electrical resistivity of rocks in the subsurface, the adopted array type, spacing of the electrodes, among others. As it increases the spacing between the current electrodes (AB) is usually reaches greater depths of investigation. As a result of the execution of a SEV, a field curve is obtained involving spacing of the electrodes and their apparent resistivity values.

The Schlumberger array is featured by electrodes aligned symmetrically with respect to a central point and on the same straight line, where the potential electrodes (M and N) are placed between the current electrodes (A and B), with a distance less than AB/2 (MN < AB/5). In this electrode array, progressively increases the spacing between current electrodes A and B, keeping fixed the separation between the potential electrodes M and N, so that electric current flows at greater depths, thus providing higher investigation depths. However, when the potential difference values are lower, there is a tendency that occurs an inaccuracy of measurements. Thereby, the correction of this effect is required, using an operation named *embreagem*. The operation is to increase the accuracy of ΔV values from the spacing of the electrodes MN (keeping fixed the electrodes AB), accomplishing two potential difference readings: one keeping the initial MN spacing and one with the highest MN spacing. Then AB reduces the spacing of the electrodes as before, repeating the reading already MN with the new spacing. Thus, some curve segments are plotted on the graph, approximately parallel, each related to *embreagem* performed.

The interpretation of the apparent resistivity curves sought to associate geoelectric layers to geological strata, from the variation of the physical parameter resistivity (ρ) by depth or thickness. Wells data contributed to the interpretation stage, thus can correlate geoelectric horizons to lithological strata, by running adjacent calibration surveys the wells, with known lithological profiles. Furthermore, additional information field were necessary to support the interpretation of some electrical soundings. Wells data, together with the interpretative models of SEV's were subsequently subjected to a geostatistical treatment (interpolation and gridding), enabling the development of the saturated thickness map in the lower course area of the Maxaranguape River.

For the evaluation of permanent reserves of the aquifer, parameters were used such as the effective porosity and local saturated mean thickness, and their respective area of occurrence (Feitosa et al., 2008). To determine the thickness of the layers and elaboration of the map of thickness saturated zone were used information from lithologic well logs and data obtained by applying the geophysical method of resistivity (technique of vertical electrical sounding), as reported.

The preliminary calculation of permanent hydrogeological reserve was performed through the product between area of the aquifer occurrence in the region (200 km^2), the average thickness of saturated values determined (we used a representative value of 45m) and the average effective porosity. The last one was obtained from a descriptive petrographic study of thin sections of Barreiras Formation performed by Silva et al (2014), which allowed obtaining an average value of the parameter effective porosity of 7.60%. In this context, the permanent reserve is expressed by the equation 2:

$V_s = \phi_e \cdot A \cdot b$ (Custodio & Llamas, 1983; Feitosa *et al*., 2008)

Where: V_s = volume of saturation / permanent reserves (m^3); ϕ_e = average effective porosity; A = area of the aquifer occurrence (m^2); b = average saturated thickness in that area (m).

Results

Based on information from 20 wells that sectioned the entire aquifer (Table 1) and data from 11 VES was possible to provide a saturated thickness map of Barreiras Aquifer in the lower course area of Maxaranguape River (Figure 5).

The saturated thickness values in the table were obtained from the difference between the depth values of the hydrogeological basement and static level in wells. The well 01-Riachão-05, which presented the highest saturated thickness value (57,30m), also showed the greatest depth of hydrogeological basement (77m), while the P2C and P1SR wells had the lowest saturated thickness value (22m).

Table 1 - Wells data used in creating the saturated thickness map. (Source: Hidropoços, Aquonsult, FUNASA, SEMARH and CAERN).

Name of well	UTM X	UTM Y	Saturated thickness (m)
FUNASA_PS-059	235500	9396000	41,20
FUNASA_PS-374	234390	9393040	37,06
PESQUISA – 01	242257	9393424	47,10
PP-02BMA	238270	9395352	35,23
PP-03-CMI	240508	9393150	52,33
01-Riachão-05	236300	9388932	57,30
PT-04-01	233262	9394828	54,90
PS-491	238540	9395465	41,67
PS-577	236103	9396329	38,62
PS-578	236742	9396412	50,83
PS-579	236424	9396677	47,82
PS-580	236138	9396041	33,89
PS-581	236513	9396035	44,59
PS-576	236152	9395741	33,61
PS-632	236512	9397122	44,76
P2C	246730	9395410	22,00
P1SR	247874	9393871	22,00
P2SR	248776	9393166	51,00
P3-SR	247128	9391437	26,00
PS02CLAU	235585	9398556	40,70

Regarding geoelectric surveys were performed 11 VES. For interpretation of field curves, it was assumed that all the layers of the medium were homogeneous, isotropic, flat and parallel. It was sought a fit between the field and the interpreted curve by varying the parameters of the initial model, based on observations in the field, information obtained from the well data and prior knowledge of the geology of the region (bibliographic study area). Thus, geoelectric layers were associated with a particular lithology, from the variation of resistivity values versus depth, by geoelectric calibration shown in Figure 3 (SEV-03 adjacent to the well PT-04 BMA). The lithologic profile used in this calibration is shown in Figure 4.

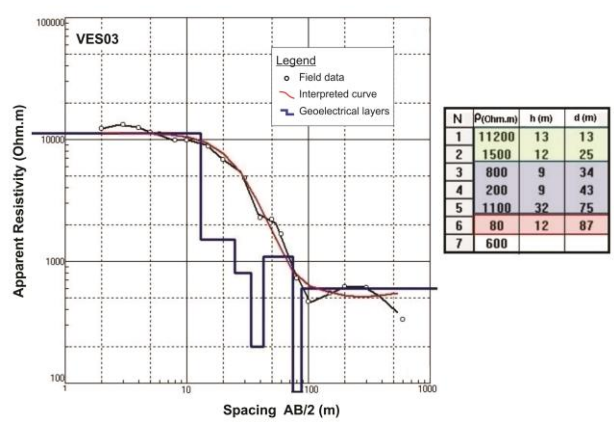

Figure 3 - Curve of resistivity (VES03) used for geoelectric calibration in Maxaranguape-RN area. The geoelectrical model interpreted is shown on the right, where N denotes the number of layers; ρ is the resistivity; h and d, refer to the layer thickness and depth, respectively.

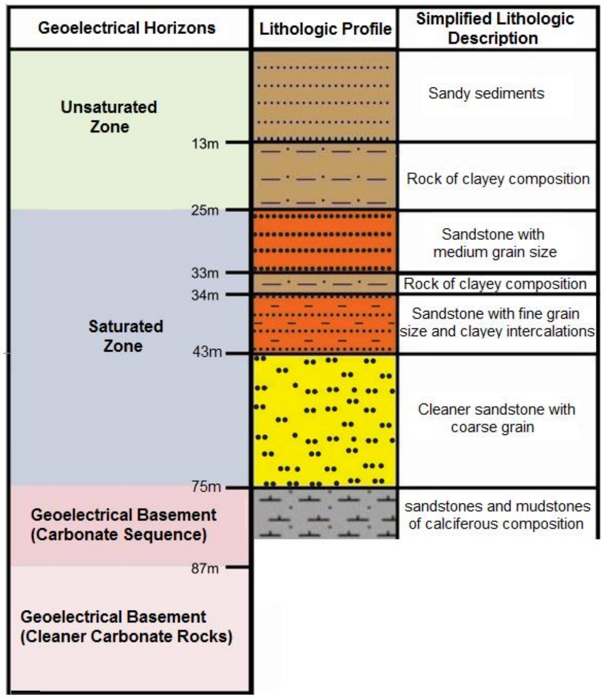

Figure 4 - Geoelectric calibration. Layout of geoelectrical model interpreted in conjunction with the lithological profile of the well PT-04 BMA and its simplified lithological description.

In the calibration was set out the number of layers and fixed the thickness values of each layer of the model. These information were obtained from well logs, requiring only the resistivity values of the model layer. Thus, a geoelectrical model (resistivity x thickness) with lithostratigraphic and hydrogeological embedded constrained was defined. This model shows the number of layers (N), the apparent resistivity values (ρ), saturated thickness (h) and depth (d) of the layers.

Three geoelectrical horizons were defined based on the resistivity and thickness values (Figure 4):

-Unsaturated Zone: the two shallower layers with resistivities of 11200 and 1500 Ohm.m, representing the unsaturated zone (green), with a total thickness of 25m, related to sandy sediments, sandstones and/or rock of clayey composition;

-Saturated zone: the following three layers (3, 4 and 5) correspond to the Barreiras Aquifer (saturated zone - blue), with a thick of 50m and the top and bottom depths of 25 and 75m, respectively. Between the third and fifth layers, there is a clay layer, thin (1 m thick) and very conductive, that under a geoelectrical point of view, may not be detected, being suppressed by the adjacent sandstone layers (phenomenon of suppression of layers). Accordingly, layers 3 and 4 were interpreted as a single layer of sandstone with medium grain size, thickness of 9m and resistivity of 800 Ohm.m. Then, the layer 4 (9m thick) is more conductive (200 ohm m) due clayey intercalations between a fine sandstone. On the basis of the aquifer, is a cleaner and resistive sandstone (1100 Ohm.m) with a thickness of 32m;

-Geoelectrical Basement: with 12m thick and very conductive (80 Ohm.m), represent the top of the carbonate sequence non-outcropping, corresponding to sandstones and mudstones of calciferous composition. Finally, the last layer is related to cleaner carbonate rocks with resistivity of about 600 Ohm.m, although this value should not be taken as representative of the same due of maximum spacing electrodes adopted (AB / 2 = 600 meters).

Thus, the geoelectrical model interpreted above was used as the basis for quantitative interpretation of the other soundings. After reviewing the data of all VES and their respective geoelectrical models (see Table 2), it can be concluded that the aquifer thickness values range nearly between 19 and 60m, and its maximum depth is approximately 25m, and near outcrops (rivers and lakes) the depth of the aquifer is just over 1m.

Table 2 - 11 VES performed in Maxaranguape with their saturated.

VES	UTM X	UTM Y	Saturated Thickness (m)
VES01	241174	9397806	19
VES02	241435	9395974	60
VES03*	240935	9393856	50
VES04	239428	9394614	32
VES05	238760	9392954	50
VES06	234881	9391906	46
VES07	237608	9389406	44
VES08	242664	9391724	52
VES09	243171	9388450	47
VES10	245169	9388896	40
VES11	242236	9394542	50

In order to elaborate the saturated thickness map (Figure 5), interpolation and gridding of well data and the interpretation of the SEV was performed.

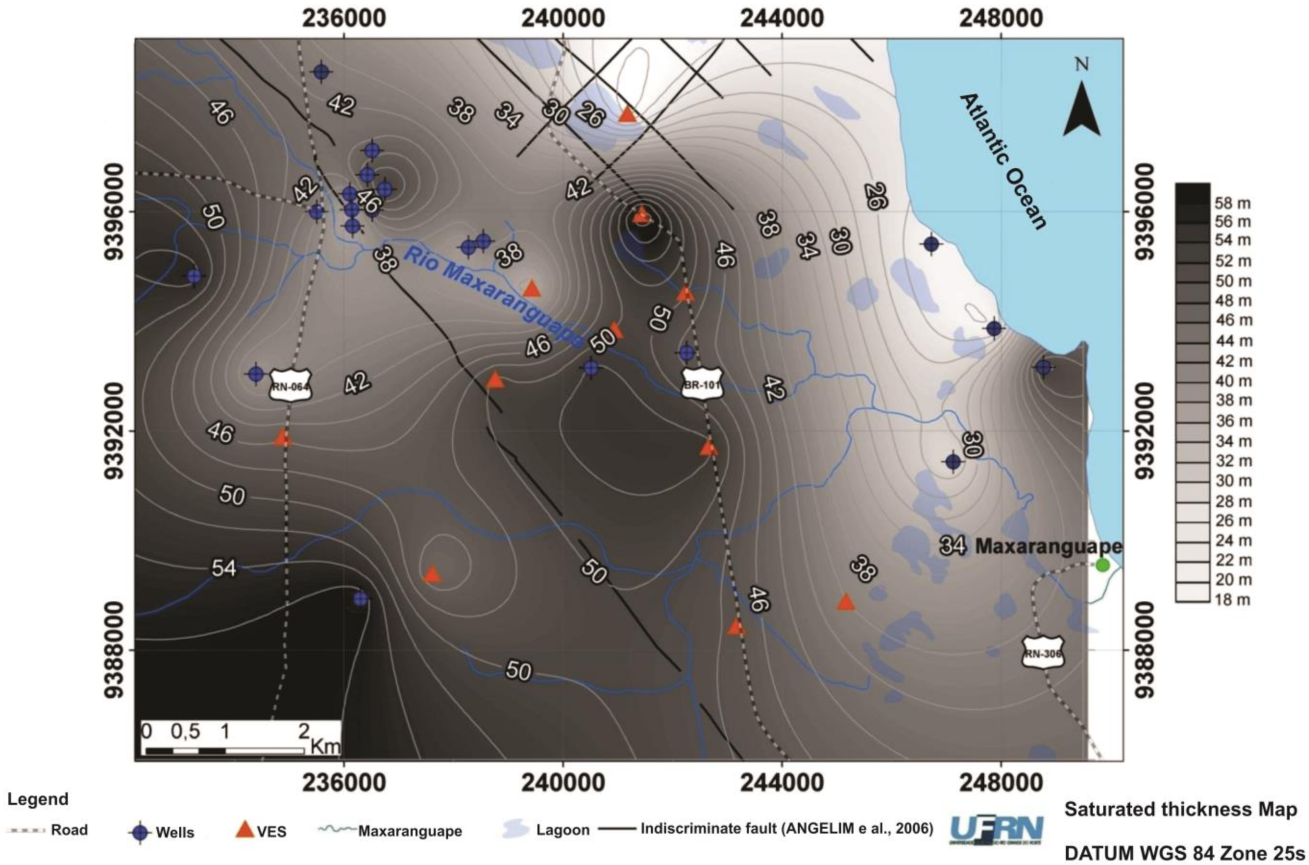

Figura 5 – Preliminary map of saturated thickness in the lower course region of the Maxaranguape River.

Analyzing the map of Figure 5, we observe higher values of thickness in the central, southwest and northwest region of the map, ranging between 46 and 58m. As it approaches the east coast the thickness of the aquifer tends to decrease in the north, reaching almost 20m, while south tends to increase again. In accordance with the variation of thickness values, the northern region shows values of 18 to 34m, while heading to south part such saturated thicknesses are of the order of 36 to 52m approximately, supporting the structural control perspective of the aquifer's geometry.

The preliminary calculation of permanent hydrogeological reserve of the Barreiras Aquifer in the lower course of the River Maxaranguape area was performed after elaboration of the saturated thickness map. However, since this is a preliminary study, this evaluation was carried out using a representative average of saturated thickness, not taking into account structural factors that possibly affect the thickness variations of the aquifer in question. Thus, the equation of permanent reservations was used an average value of effective porosity parameter (ϕ_e = 7.60%) for the entire study aquifer area, a mean thickness value (representative), b = 45m, and area of the aquifer occurrence was calculated using ArcGis software (version 10.1) A = 200x10^6 m^2.

$$V_s = 0.076 \times 200\text{x}10^6\,m^2 \times 45m = 6{,}84 \times 10^8\,m^3$$

In this context, the permanent hydrogeological reserve the aquifer is 6,84 x 10^8 m^3.

Conclusions

The integration of geological and geophysical information (lithological data and thickness data of the layers associated with the geoelectric models from the interpretations of the SEV) allowed the elaboration of the saturated thickness map of the Barreiras Aquifer as well as the calculation of permanent hydrogeological reserve in the study area.

In areas where well data were scarce were performed VES which allowed observation of three well-defined horizon: an unsaturated zone, with resistivities greater than 1100 Ohm.m; the saturated zone (aquifer) with resistivities ranging between 160-1100 Ohm.m, where more conductive values were associated to sediments with presence of some kind of clay material and the more resistive were associated with cleaner sands; and the conductive hydrogeological basement aquifer, with resistivity between 20 and 80 Ohm.m, associated with sedimentary rocks of calciferous composition.

The areas that showed higher saturated thickness, when correlated with more sandy sedimentary rocks, might be considered areas with higher hydraulic potential, more likely to drilling wells.

The procedure of hydrogeological reserves assessment must be accepted with restrictions, since that it is a preliminary methodological approach, considering mean values of the parameters involved, which can lead to considerable differences with the real accumulated volume of water resources. Thus, in large areas as a watershed, the knowledge of structural control is essential for a more consistent and true calculation, taking into account the variations of saturated thickness along the area under investigation due to the regional tectonic and structural evolution.

The permanent reservations may be quantified individually for each structural block and its total value achieved through a sum of the local permanent reserves volume for each sub-area defined. Thereby, considering the growing and permanent need for identification and consequent preservation of the most promising areas in terms of hydrogeological reserves, it should be noted the proposal of a more realistic assessment of permanent hydrogeological reserves in a structurally controlled context, i.e., starting from the assumption of occurrences of saturated thickness variations due to local faulting.

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