ESTIMATION OF TOTAL GROUNDWATER RESERVES AND DELINEATION OF WEATHERED/FAULT ZONES FOR AQUIFER POTENTIAL: A CASE STUDY FROM FEDERAL DISTRICT - BRAZIL

Abstract

Unplanned urban growth exerts significant stresses on the underlying aquifers in terms of increasing the groundwater extraction and reducing the surface area for aquifer recharge. This situation has led to a more difficult process in the search for new locations of productive tubular wells, particularly in the Federal District of Brazil. In this region, the groundwater extraction is challenged by fractured aquifers with difficult identification of hydraulic tarps and significant uncertainty in the estimation of recharge potential. The aim of the present study is to optimize the demarcation of new locations of tubular wells by conducting geophysical investigations. In the first stage, based on the information of the physical environment and data from the existing wells, the total exploitable amount of groundwater was calculated. Then Electrical Resistivity Tomography (ERT) was carried out along specific sites, which were selected based on the surficial characteristics. The resistivity values obtained from the dipole-dipole array were inverted and the resultant conducting zones (weathered rocks and fractures) were delineated, which represent possible hydraulic traps where groundwater may exist. Based on the results, the suitability of the selected sites for deep tubular wells installation was prioritized on a linear scale varying from 1 to 5, where 1 is the highest and 5 is the least suitable. Based on this approach, eight new deep tubular well sites were proposed and classified. The study provides a promising framework for investigating groundwater in fractured aquifers.

Keywords: ERT; fracture; groundwater; environmental factor; tubular wells

ESTIMATIVA DE RESERVA TOTAL DE ÁGUA SUBTERRÂNEA E DELINEAMENTO DE ZONAS DE ALTERAÇÃO/FRATURAMENTO DE AQUIFERO EM POTENCIAL: ESTUDO DE CASO NO DISTRITO FEDERAL – BRASIL

Resume

A expansão urbana descontrolada resulta num uso indiscriminado dos aquíferos diante do aumento da extração de águas subterrâneas, com consequente redução das áreas de recarga. Este panorama implica em dificuldades crescentes de busca por locais para perfuração de novos poços de captação profunda, particularmente no Distrito Federal no Brasil. Nesta região, a extração de águas subterrâneas e particularmente desafiadora pela ocorrências de aquíferos fraturados, sistemas que implicam certa dificuldade na definição de condicionantes hidráulicos e significativas incertezas na estimativa do potencial de recarga. O objetivo do presente estudo é otimizar a definição de pontos para perfuração de poços tubulares baseado em investigações geofísicas. A primeira etapa do estudo foi baseada em informações de fisiográficas e na coleta de dados sobre poços existentes, além de cálculo da quantidade total de água extraída pela rede de poços de atividade. Em seguida foram realizadas linhas de tomografia de resistividade elétrica (ERT) em locais específicos e previamente selecionados. Os valores de resistividade obtidos por meio do arranjo dipolo-dipolo foram processados e permitiram a gerar modelos de inversão 2D, nos quais foi possível identificar zonas de baixos valores, relacionadas com rochas alteradas e fraturas com água, representantes de possíveis zonas fluxo hidrogeológico. Os resultados serviram de base para seleção de locais para locação de poços de captação profunda, com prioridade definida por uma escala linear com variação de 1 a 5, onde o valor mais alta indica os locais mais favoráveis. Baseado neste proposta, foram classificados e indicados oito novos locais para perfuração de poços profundos. Este estudo proporcionou uma rotina de métodos com resultados promissores ao estudo de aquíferos fraturados.

Palavras-chave: ERT; fratura; água subterrânea; ambiental; poço tubular

Introduction

There is a worldwide increase in water demands because of the growing global population that exerts stresses on aquifers (Hussain et al. 2017) and other water resources. The same is the case with the Federal District of Brazil, where the unplanned urban growths in the surrounding regions of Brasilia are on the rise. In order to fulfill the rising water demands, new groundwater prospects are being investigated with consideration of the geology of the region. The Federal District of Brazil is constructed on a complex and heterogeneous groundwater flow system which constitutes of both porous and fractured hydrological regimes having variable hydrogeological characteristics such as hydraulic conductivity and permeability.

The pioneering work on the hydrogeology of the Federal District was carried out by Romano & Roses (1970). Subsequently, the contributions of Barros (1987 and 1994) were important for the assessment of groundwater in the region. After that a succession of works has been developed in the region and the most important among them are: Mendonça (1993); Amore (1994); Campos and Freitas-Silva (1998 and 1999); Zoby (1999); Campos & Tröger (2000); Souza (2001); Carmelo (2002), Cadamuro (2002), Cadamuro et al. (2002), Cadamuro & Campos (2005), Joko (2002); Moraes (2004); Campos (2004); Arraes et al. (2005); ADASA (2007); Lousada (1999 and 2005); Lousada & Campos (2005); Gonçalves (2007 and 2012); Correia (2011); Souza (2013) and Nunes (2016).

Groundwater can be found in weathered and fresh rock interface (Hasan et al. 2018). In the case of hard rock joints, fractures and fault zones (which are created by different chemical or tectonic processes) can store as well as transport groundwater. The fracture aquifers also exist at deeper depths and are pumped by the installation of deep tubular wells (100-200m). In addition to the presence of fractures, another important parameter for groundwater prospecting is the recharge potential of the site. Therefore, groundwater prospecting in such regions is a challenging task where the presence of fractures as well as the intrinsic properties and physical environment of the site can play essential roles.

In addition to the traditional approach used for assessing the physical environment data, geophysical methods offer advantageous opportunity to detect the variation in ground condition and the delineation of the zones that can appear as possible traps for groundwater in karst environment (Hasan et al. 2018). A wide range of geophysical techniques has been applied for mapping the hydrogeological settings for groundwater prospecting. In particular, Electrical Resistivity Tomography (ERT), which has been recognized as an economic and noninvasive geophysical technique with reasonable accuracy in the detection of hydrogeological features (fractures/weathered zones), can provide better structural information of highly heterogeneous karst features (Redhaounia et al. 2016). In ERT, a known amount of current is passed through the earth and a developed potential difference is observed which can be used for the subsurface analysis after inversion. ERT has been applied in many previous studies for the search of new groundwater prospects (Hasan et al. 2018) as well as for the monitoring of existing groundwater reservoirs (Hussain et al. 2017).

This paper presents a case study from the Federal District of Brazil, where ERT, as well as the existing geological and hydrogeological information of the study area, were utilized to optimize the demarcation of new tubular wells locations. The study provided an introduction to the aquifer system of the area and then proposed and applied an integrated approach in which the recharge potential of the study area as well as the presence of fractures and weathered zones (conductive zones detected by ERT) were used as a criterion for the estimation of groundwater potential. The investigation was conducted on 8 sites in the Federal District of Brazil and the results were analyzed and ranked on a linear scale varying from 1 to 5, where 1 is the most suitable site for extracting groundwater and vice versa.

Description of the study area and methods

The study was conducted in *Solar Condominio*, which is located in the middle course of the *Taboca and Taboquinha Ribeirão* sub-basins (Figure 1). The area has already seven deep tubular-wells installed, six of them are in operation. The region constitutes of an aquifer system having moderate potential for production with an average flow of around 7.5 m^3/h (Table 1).

Figure 1 (a) Location of Brasilia on Brazil map, (b) location of the study area on map of Brasilia and (c) soil classes, drainage network and lineation of the study area.

The Taboca and Taboquinha River sub-basins are located in the south and central portions of the Federal District and geologically constitute units of the *Paranoá* and *Canastra* groups (Campos et al. 2013). The Paranoá Group is represented in the sub-basin by its *Ribeirão Contagem* (MNPparc) formation, which is further divided into two sub-units as upper and lower (Figure 2), where the Ribeirão Contagem Formation (MNPparc) and *Córrego of Sansão* (MNPpacs) lie on the top (Campos et al. 2013). The lower sub-unit of Ribeirão Formation consists of thin to medium-sized quartzites, white or light gray in color, well sorted, mineralogically mature, usually very silicified and having well-rounded grains. At the top, massive quartzites of the Ribeirão Contagem Superior Formation, characterized by the alternation of millimeter to centimeter levels of pure quartzites white to creamy color having millimeter to centimeter levels of ferruginous quartzites of medium particle size and gray in color. The *Córrego do Sansão Formation* (MNPpacs) is also divided into two subunits as; upper and lower (Figure 2). The Lower Sansão Stream Formation sub-unit consists of homogeneous metarithmites with regular centimetric intercalations of metassiltites, metalamides and fine quartzites that appear in different colors as gray, yellow, rosy or reddish. The Canastra Group occupies about 70% of the area of the Taboca and Taboquinha Ribeirão sub-basins, which consists of phyllites, predominated by chlorite phyllites and quartz chlorite fengita filitos.

Figure 2 (A) Declivity, (B) hydrogeology and (C) soil maps of the Ribeirão Taboca-Taboquinha sub-basin. Upper insert shows the position of the study area on the map of Brasilia.

Structurally, the area is located on the southeastern flank of the Brazilian Structural Dome (Freitas-Silva & Campos, 1998). The NW-SE fracture-fault system controls the main drainage of the Taboca and Taboquinha streams that flow in the study area. The NE-SW system corresponds to the conjugate pair of the NW-SE system, which is in the predominant direction of the lineaments. The structural analysis of these systems, as well as the asymmetries of drainage slopes are shown on declivity map (Figure 2), were predominantly high angle fractures and faults with recessed blocks which are important features for the groundwater prospecting.

There are four large sets of residual soils in the Taboca and Taboquinha Ribeirões sub-basins (EMBRAPA, 2013). These residual soils are deposited on the saprophytes of the Paranoá and Canastra groups. The soil of the area is divided as quartzarenic neosols, latosols red-yellow, cambisolos and plintossolos (Figure 2). In the geomorphological context, the Taboca-Taboquinha sub-basin is located in the São Bartolomeu Rio Superior Course Unit (Novaes Pinto 1987, 1994). The Taboca-Taboquinha sub-basin are subdivided into six geomorphological units as Plateau Plateau, Elevated Plateau, Smooth Section, Dissection Unit-High Course, Dissection Unit-Low Course, Dissection Unit-Lower Middle Course, Dissection Unit - Middle Higher Course.

Aquifer Domains

The Brazilian hydrogeological system is dominated by aquifers developed in fissures, covered by weathering layer of soils and altered rocks having variable hydrogeological characteristics (permeability and thickness). In Brasilia, two distinct aquifer domains are presented as (i) Porous Domain Aquifers (PDA) and (ii) Fractured Domain Aquifers (FDA) (Table 1).

Porous Domain Aquifers (PDA)

There are no sedimentary rocks with interstitial spaces, so this domain consists of soils and the mantle of rock alteration (Saprolite) in the area. Locally, the importance of aquifers in this domain is linked with several parameters, out of which only two are highlighted here as saturated thickness (b) and hydraulic conductivity (K), both are related to the geology and geomorphology of their substrate. The domain is further subdivided into three systems as areas with latosoils (Paranoá rocks), areas with structural soils (pelitic and carbonate rocks of the Paranoá Group) and areas with cambisoils and neosoils (pelitic rocks of the Paranoá and Canastra groups). These sub-domains are named as P1, P2, P3 and P4, based on the ‘b’ and ‘k’ values (Table 1). The aquifers of the Porous Domain within the study area are of P3 and P4 sub-systems with the argisoils/nitosoils and cambisoil/litolithosoils, respectively. The P3 has larger thicknesses (>5 m) and low hydraulic conductivity, while P4 has smaller thicknesses (usually less than 1 meter, but it can reach 2.5 m) and low hydraulic conductivity. The P4 water flow is very restricted, generally smaller than 300 l/h and shallow wells are installed in this aquifer, not present in the studied area, but are quite common in the surroundings.

Table 1 Summary of the classification of Domains, Aquifer Systems/Subsystems of the Federal District with respective mean flows (Campos and Freitas-Silva, 1999).

Fractured Domain Aquifer (FDA)

The Fractured Domain Aquifer (FDA) is associated with groundwater stored in the discontinuities related to faults, fractures, and joints in the absence of residual primary porosity in the rocks of the Paranoá Group. The primary porosity was completely obliterated by the recrystallization of minerals and cementation originated by the metamorphic processes. The domain is represented by the systems of unconfined or confined aquifers, of restricted lateral extension, with strong heterogeneity and anisotropy responsible for the storage and circulation of deep groundwater. The hydrodynamic characteristics are variable in the domain depending on the type of rock. The density of the discontinuity in the rock body (Campos,

2004) controls the hydraulic conductivity of the aquifers. Generally, the fractured aquifers are pumped by means of deep tubular wells with depth varies from 100 to 200 m in the Federal District. The recharge occurs through descending percolation of rainfall water. Other important factors that control the recharge depends on soil conditions, type of vegetation cover, soil thickness and percentage of urbanized areas. In the study area, the Paranoá PPC subsystem and the Canastra System, F sub-system occur. Figure 9 presents a conceptual groundwater model in the area.

Figure 3 Schematic representation of the conceptual model of the aquifer system in the southern part of Brasilia (Lousada and Campos, 2006).

Electrical resistivity Tomography (ERT)

The visible structural lineaments were extracted from the satellite images and digital terrain model, at scale 1: 10,000. This information was used for the planning of electrical resistivity survey in the area (terrain conditions, environmental restrictions etc.). Eight areas were selected for the electrical resistivity profiles (Figure 4).

The measurements of electrical resistivity using different electrode arrangements have generally been used to identify stratigraphic variations or to locate objects whose dimensions and depths range from meters up to a few kilometers. Recently, automatic data collection systems have emerged that has seeded up both measurement and interpretation of the ERT data. The devices for electrical resistivity measurements typically consist of a four-electrode system, two of which are used to pass electric current (I) to the ground, and the other two are used to measure the potential difference (V) between them. By obtaining the potential difference and the current flowing in the medium, the apparent electrical resistivity of the medium is obtained which depend on the geometric factor (K), a function of the configuration of the electrodes. Depending on the research objective the electrodes configuration can be conducted in several ways as Wenner, pole-polo, pole-dipole, dipole-dipole, Wenner-Schlumberger and gradient. Each arrangement has specific characteristics such as spatial resolution (dipole-dipole and pole-dipole), depth of investigation (pole-pole) and signal-to-noise ratio.

In the present study, the dipole-dipole electrode arrangement was adopted. The result of the acquisition is a set of electrical resistivity data obtained at various depths forming a pseudo-section. This, in turn, reflects the behavior of the subsurface in response to the passage of electric currents. Each geological material shows a very broad range of resistivity, which depends mainly on the mineralogical composition of the rock, degree of weathering, the amount of fluids present in the pores of the rock, and the salinity of the fluid.

Figure 4 Locations and photographs illustrating the acquisition of ERT data on the selected sites in the study area.

The acquisition of the geophysical data was executed along with eight profiles (Figure 4), each one of 360-meters in length and in NW-SE direction, perpendicularity to the structural lineaments used as a criterion of location selection to start the line avoiding the need to open bits. In the field, the electrical resistivity data were collected with the electric walk investigation technique, using the electro-dipole-dipole arrangement, with a spacing of 10 meters between the electrodes. The data acquisition protocol with the multi-electrode cables was elaborated in the software ELECTRE II, version 05.06.00, (IRIS Instruments) for acquisitions with 36 electrodes.

For the adequate deployment of the geophysical prospecting, the field activities were carried out during the dry season, which avoided the presence of moisture in the soil, thus helping to minimize the absorption of electric current in the surface soil. The data were acquired with SYSCAL Pro 72 equipment (manufactured by IRIS Instruments), which consists of an interleaved acquisition module in multi-electrode cables. Thirty-six metal electrodes were used to inject current and measure the electric potential generated by the current flow in the subsurface. The equipment has the best available accuracy equal to 0.2% and with a resolution of 1 microV at a temperature ranging from -20 to + 70ºC.

The filtering and topographical correction on the dataset were performed in the PROSYS II software, version 03.13.06 (IRIS Instruments). In order to determine the effective depth, the pseudo-sections of electrical resistivity were inverted using the computer program RES2DINV, version 3.53 (Geotomo Software). The geological-geophysical sections were also prepared in the same software for the interpretation. The 2D model divides the subsurface into a series of blocks to determine the resistivity; its product is the apparent resistivity pseudo-sections that fit with the field data, using an inversion process based on the variation of the least square method. The results obtained were presented in the form of 2D resistivity sections.

Results

Estimation of Groundwater Reserves

The entire area of the *Condominio Solar* is mainly in the form of Aquifer Subsystem F, of the Canastra Aquifer System. Subsystem F is one of the lowest production aquifers in the Federal District with an average flow rate of around 6500 L/h. The best flow rates are obtained in neotectonic fault/fracture zones, especially in the NW-SE, NE-SW, NS and EW directions of the area. In addition, the small soil thickness (porous sub-system P4) overlying the subsystem F, and low permeability of the phyllites causes great difficulties in the implementation of infiltration induced systems (artificial recharge).

The physical environment and climatic (rainfall) information are used in the determination of the deeper aquifers flow as well as the elements for their sustainable management and exploitation. Taking this into account, the main parameters for the volume calculations and flow rates estimation and the outflows of groundwater extraction of the study area are calculated (Table 2).

The average climatic conditions of the Federal District which are marked by the strong seasonality, with two contrasting seasons are considered for the study area. The period between May and September is evidenced by low precipitation rate, low cloudiness, high evaporation rate and low relative air humidity. The period between October and April presents distinct patterns, and the months from December to March constitute 47% of the annual precipitation. The average annual precipitation of the Federal District is about 1500 mm, however, for the purpose of estimation of water reserves, an average rainfall of 1450 mm was considered in the present study.

Table 2 Parameters used in the estimation of groundwater reserves of Condomínio Solar of Serra.

Twelve percent (12%) of the total precipitation infiltrates the vadose zone and effectively reaches the saturated zone (Carmelo, 2002). This is considered for the areas occupied by subsystem P1, however, for the subsystem P4, a value 8-9% is determined based on the physical environment of the area.

The total area of the *Condominio Solar* is 250.99 ha (2.509.900 m^2), 63.2% of which is destined for residential, commercial lots and institutional areas, and 36.8% is reserved for the green areas. Thus, for the purposes of the calculations of the Total Exploitable Reserve (TER) for the area, the green areas (923,500 m^2) plus 30% of the urbanized area (475,920 m^2) are used.

In order to establish a sustainable exploitation rate, the following parameters for a conservative estimation are considered as: (i) The whole area is covered by the Porous System P4, represented by shallow changes; (ii) The entire area of the C*ondominio* is composed of the aquifer sub-system-F; (iii) For the calculation of the renewable reserve of the sub-system-F, the effective recharge rate of the porous system is 10% of the total annual precipitation.

The reserve that is renewed annually from the infiltration of rainwater through the unsaturated zone to the saturated zone of the porous system to the saturated zone of the rocky fractured environment is calculated by Equation 1.

$$RrF = A \times REF \times AAP \quad \text{(Eq.1)}$$

where:
RrF = Renewable reserve of sub-system -F;
A = System area available for infiltration (green area + non-edificated area);
ERF = Effective recharge percentage from the overlapping porous system;
AAP = Average annual precipitation.
After substituting the above values from Table 2 into Eq (1), a numeric value of ‘RrF = 162,400 m^3/year’ is obtained.

The water reservoir is permanently contained in the rock fracture systems of the Canastra Aquifer Subsystem. It is calculated for different depths as a function of the different Interconnected Fracture Rates (IFr), which tends to decrease with depth due to the increase of the lithostatic pressure. Permanent reserve of system-F (RpF) can be calculated using Equation. 2.

$$RpF = RpFs + RpFi = (A \times bs \times Ifii) + (A \times ps \times Idif) \quad \text{(Eq. 2),}$$

where:
RpFs = Permanent reserve of system F
RpFi = Permanent reserve of system-F inferior interval;
A = Area of fractured domain;
bs = Thickness of upper fracture zone;
Ifii = Index of fractures having larger interconnection interval;
ps = pore spacing of lower zone;
Idif = Index of deeper interconnected fractures.
Substituting the above values gives in equation 2 gives RpF = 1,400,000 m^3.

For the location of the deep tubular wells in the investigated area, all the information regarding the physical environment as described above were obtained from already installed seven wells in the considered area (Figure 12, Table 3). However, the access to the constructive and geological profiles of the wells are not available, the existing information mainly includes the well’s depth and pumping rate as can be seen in Table 3 and Table 5.

Table 3. Data of existing wells in the area.

Site Selection

Based on the inverted resistivity, geological sections of the ground were prepared along with each profile. Low, medium and high resistivity zones are delineated on the inverted resistivity data. These resistivity zone are associated with the dry soil, saprolite and carbonate rocks. Along with these resistivity zones, there also low resistivity zones that represent the fractured or weathered zones within these geological formations. These conductive zones, including any surficial features such as depression where rainfall water can accumulate, are recommend for the installation of deep tubular wells.

On profile SS01 (Figure 5) two anomalous features of low resistivity were found which might be associated with the fractured structures in the subsurface with a possible presence of groundwater. The installation of two medium priority wells are recommend. This profile has three lithologies as dry soil, saprolite and carbonate bedrock.

Figure 5 (a) The inverted resistivity and (b) lithological cross-sections, possible positions of fractures and the selected sites for deep tubular installation.

On profile SS02 (Figure 6) two anomalous features of low resistivity were found which might be associated with the fractured structures in the subsurface as possible traps of groundwater accumulation. However, due to the inherent ambiguity of indirect investigation by geophysical methods, there is another explanation of the observed low resistivity zone. This observation might be associated with the presence of carbonate phyllites from Canastra Group. The installation of two wells of medium priority are recommended, based on the presence of the observed anomalous features. This profile has two lithologies as dry soil and carbonate bedrock.

Figure 6 (a) The inverted resistivity and (b) lithological cross-sections along with the positions selected sites for deep tubular installation.

On profile SS03 (Figure 7), a medium to high resistivity anomaly was found which corresponds to a discontinuity coincident with relief lineage, which can store as well as recharge groundwater. Thus, the location for the installation of a deep tubular well at 175 meters from the beginning of this profile is suggested. The low resistivity anomaly near the end of the line may be related only to the presence of the carbonate phyllites from the rocks of Canasta Group, due to its horizontality. Therefore, this location does not present a structure of interest for groundwater accumulation. There are three lithologies found on this resistivity section as dry soil, saprolite and carbonate bedrock.

Figure 7 (a) The inverted resistivity and (b) lithological cross-sections along with the positions selected sites for deep tubular installation.

Figure 8 (profile SS04), the high resistivity geoelectric anomaly corresponds to the presence of saprolite derived from phyllites, the layer below being interpreted as the presence of carbonaceous phyllites in the region. It was not possible to identify any resistivity anomalies favorable for the investigation of groundwater occurrence, although the relief line on this geophysical section was investigated. Therefore, on this resistivity profile no site for the installation of tubular well is recommended.

Figure 8 (a) The inverted resistivity and (b) lithological cross-sections along with the positions selected sites for deep tubular installation.

Section SS05 (Figure 9) represents very similar hydrogeological conditions as observed on section SS04. It should be noted that the surface features of high resistivity, sometimes ellipsoidal which are associated with the presence of rainwater drainage network structures in the high resistive geoelectric layer which may be associated with the presence of saprolite. The section presents potential structures for the surface water accumulation, therefore, it is a recommended position for the installation of a tubular well in the region of lowest resistivity values, which is located at 190 meters from the beginning of the ERT profile. This profile presents a three-layered sub-surface lithology as dry soil, saprolite and carbonate bedrock.

Figure 9 (a) The inverted resistivity and (b) lithological cross-sections along with the positions selected sites for deep tubular installation.

In Section SS06 (Figure 10) the presence of Carbonaceous phyllites associated with the domain of low resistivity is shown. Therefore, this suggestion should be further confirmed by drilling (well) at the anomaly that lies at 240m away from the beginning of the profile SS06.

Figure 10 (a) The inverted resistivity and (b) lithological cross-sections along with the positions selected sites for deep tubular installation.

The discontinuities on section SS07 suggest the presence of structures of interests, and this hypothesis can be investigated at a distance of 170 meters from the beginning of profile SS07. Three subsurface lithologies are found as dry soil, saprolite and carbonate bedrock (Figure 11).

Figure 11 (a) The inverted resistivity and (b) lithological cross-sections along with the positions selected sites for deep tubular installation.

On Section SS08 (Figure 12), the rounded/ellipsoidal features of high resistivity occur on the surface, associated with the presence of structures of a rainwater flow network in the middle of the saprolite. Although the results presented in the inverted 2D model showed features of low resistivity, the horizontality of this domain suggests treating only a lithologic signature associated with the presence of non-weathered carbonaceous phyllites. The discontinuities observed along the low resistivity layer indicate probable zones of fractures/faults that are of low interest for the investigating of groundwater.

Figure 12 (a) The inverted resistivity and (b) lithological cross-sections along with the positions selected sites for deep tubular installation.

Site Selection and Rating for Tubular Wells Installation

Figure 13 shows the distribution of the tubular wells recommend based on the results obtained by the adopted methodology, i.e. the application of 2D models of resistivity by inversion at eight locations. In total, 8 (eight) tubular wells were suggested and classified against 5 different categories of priority for eventual construction and operation. The proposed locations were prioritized on a scale from 1 to 5, depending on the analyzed data. The well with the highest flow potential is given priority 1, i.e. indicates to the first to be built, and the well of priority 5 should be the one with the lowest flow potential.

Figure 13 The proposed locations for the installation of tubular wells in the Solar Condominium of Serra. The sites are prioritized on a linear scale varies from 1 to 5. A color scheme is used for the demonstration of site priorities.

Conclusions

In this paper, we presented a case study on identifying new potential tubular wells, which are recommended locations in the Federal District of Brazil. Based on the results obtained from the geophysical investigation (ERT) the following conclusions are drawn: (i) The site selection made on the basis of the investigation and prioritization criteria (for potential tubular wells) can increase the chances of success in the search for local groundwater, (ii) To exploit groundwater exclusively in the condominium tract, the maximum flow rate is expected to be 39.5 m^3/h (considering 20 hours of daily pumping). This flow can be achieved by a limited number of wells. If the new wells reach the average flow rate of the aquifer subsystem F, 5 to 6 tubular wells (correctly constructed and operated) will be sufficient to reach the safe considered flow. The approach presented in this study provides a promising framework for investigating and extracting groundwater in regions underlain by fractured aquifers.

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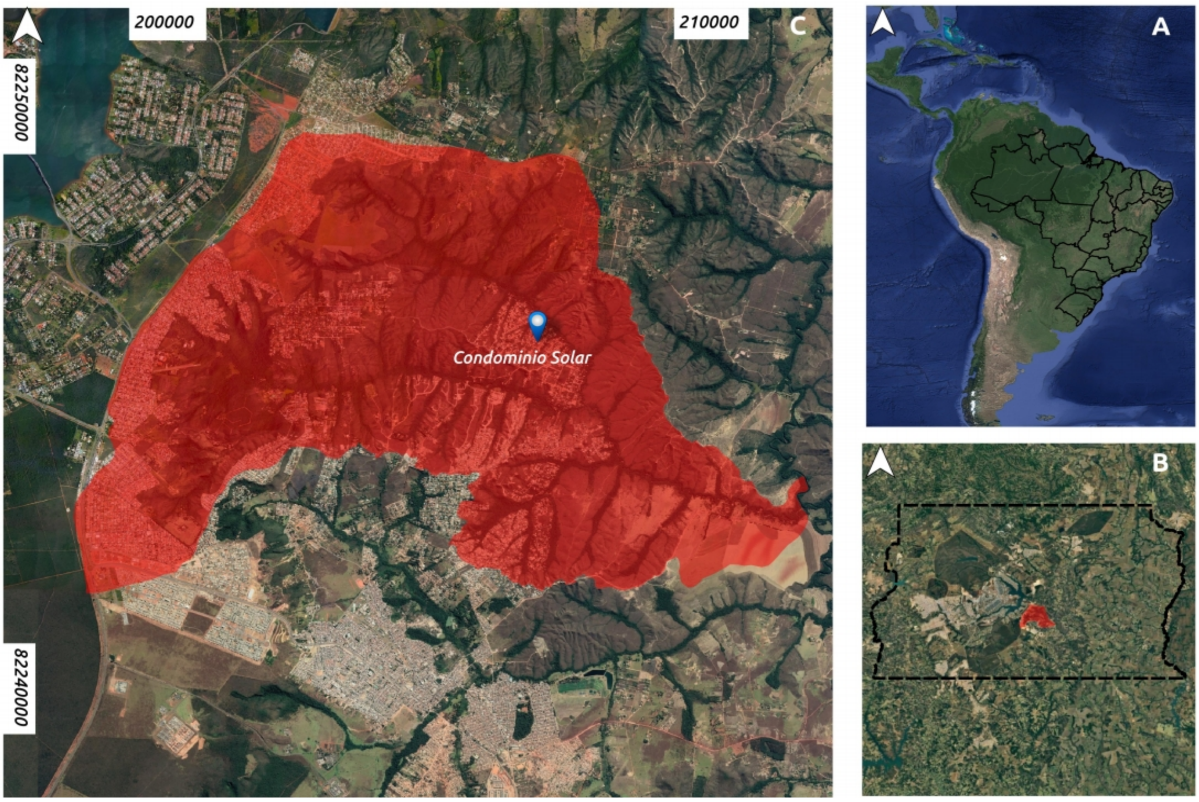


Figure 1

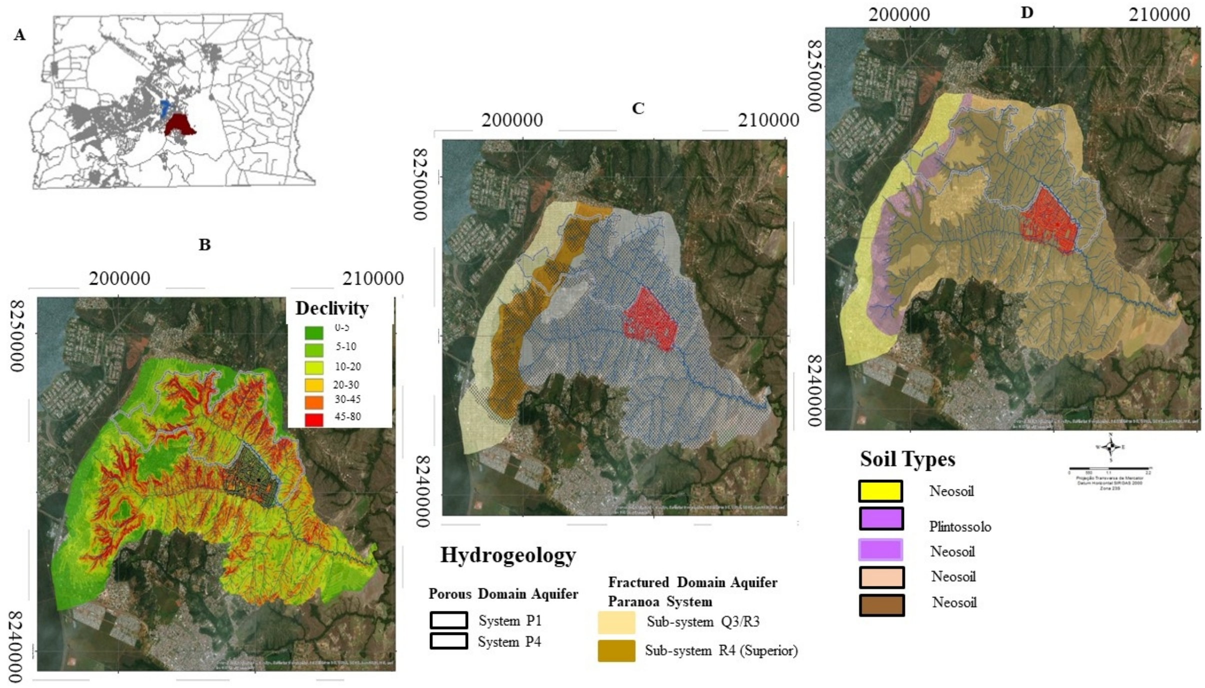


Figure 2

Table 1

Aquifer (System/Sub-systema)	*Average flow* (L/h)
Porous Domain Aquifer	
Systems P_1, P_2, P_3 e P_4	< 800
Fracture Domain Aquifer	
Paranoá System	
Sub-system S/A	12.000
Sub-system A	4.000
Sub-system Q_3/R_3	12.000
Sub-system R_4	6.000
Sub-system PPC	9.000
Canastra System	
Sub-system F	7.000
Sub-system F/Q/M	33.000
System BambuÍ	5.000
System Araxá	3.000

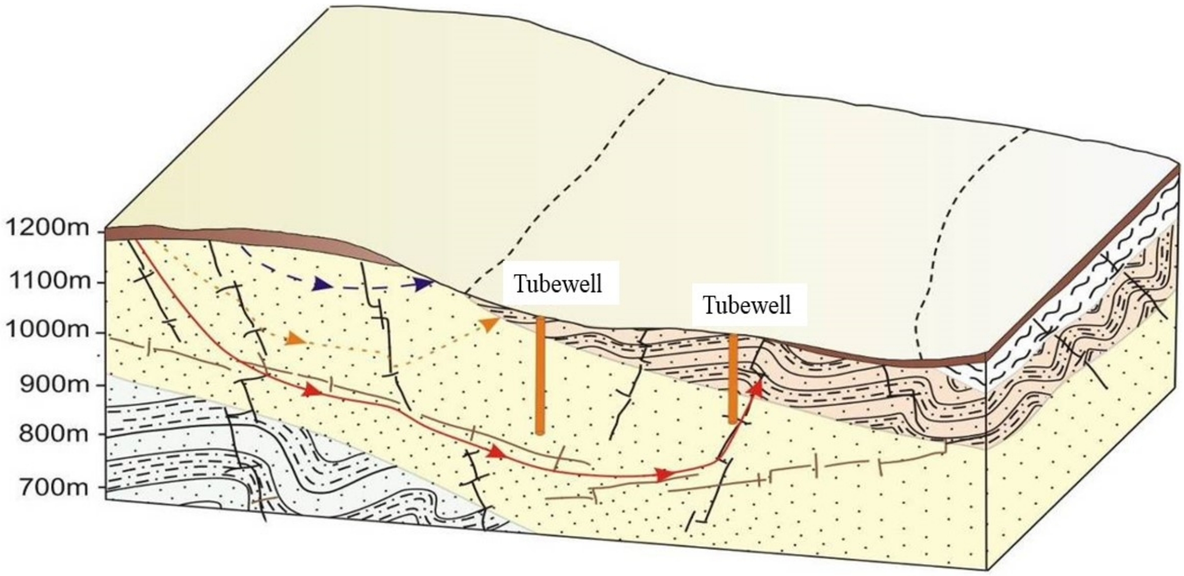


Figure 3

Figure 4

Table 2

Parameters	Value
Average annual precipitation	1450 mm
Porous domain area P4 - 20 meters thick	1400.000 m^2
Area of fractured system-F	1400.000 m^2
Effective recharge of the porous domain-P4 for the fractured system-F (percentage)	8%
Percentage of the permanent reserve available (annual)	9%
Thickness of the shallow fractured domain	70 m
Index of fractures interconnected in the short interval of the fractured subsystem	1%
Pore spacing of lower zone	60 m
Index of interconnected fractures of the deep interval of the fractured sub-system deep interval	0.5%

Table 3

Wells	Nome	UTM X	UTM Y	Time of operation (h)		Flow rate m^3/h	Depth (m)	Depth of pump (m)
1	Poço Solar 3	203908.87	8245181.94	18		2.9	150	70
2	Poço Praça B	205547.37	8245578.17	16		6.6	150	110
3	Poço Clube	205729.04	8244743.23	20		7.5	90	60
4	Poço Praça Colibri	205684.33	8245377.90	20		7.5	100	60
5	Poço do Trevo	204829.69	8245420.01	20		3.0	260	150
6	Poço da Portaria	203864.14	8245748.70	20		1.5	90	60
7	Poço Desativado	204549.00	8245907.00	20		2.4	150	90
Average						4.49		

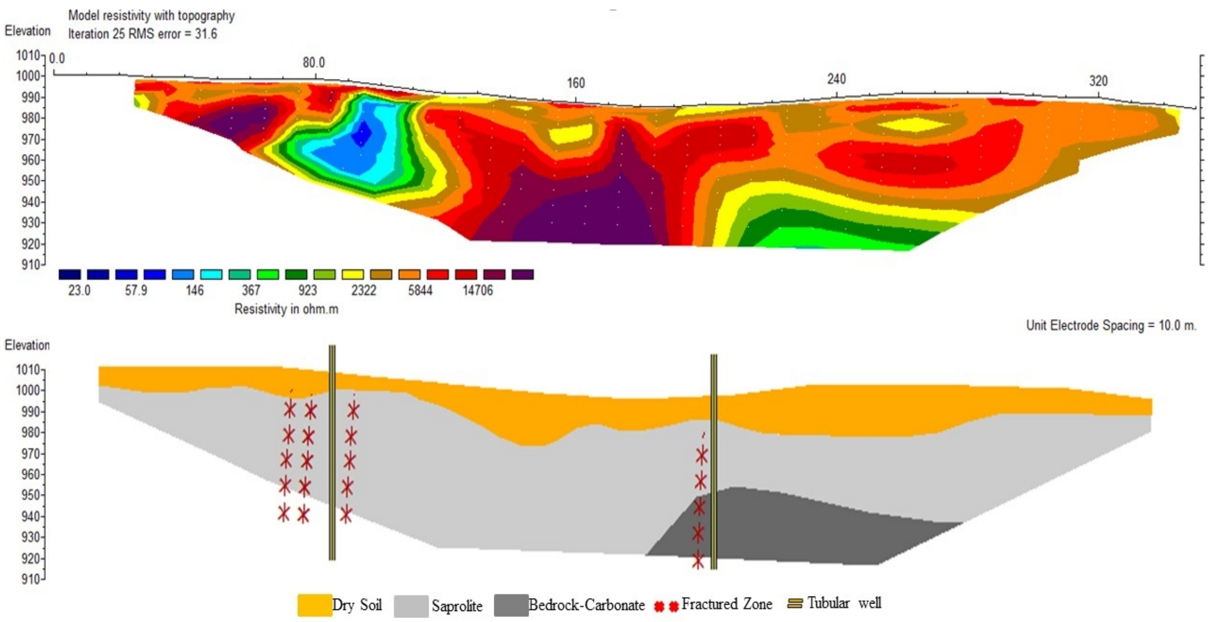


Figure 5

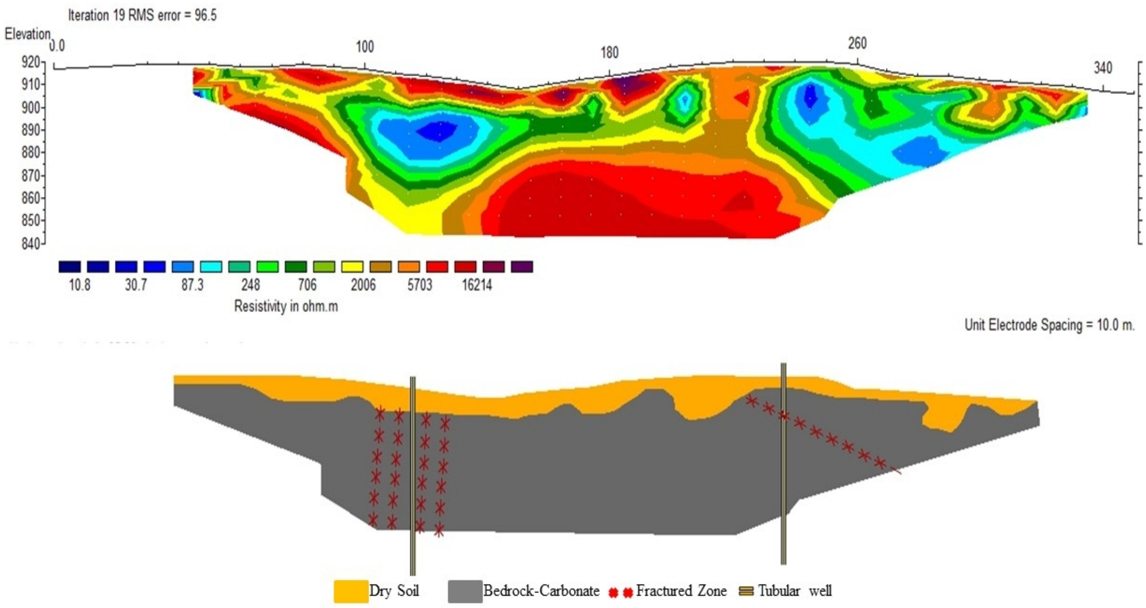


Figure 6

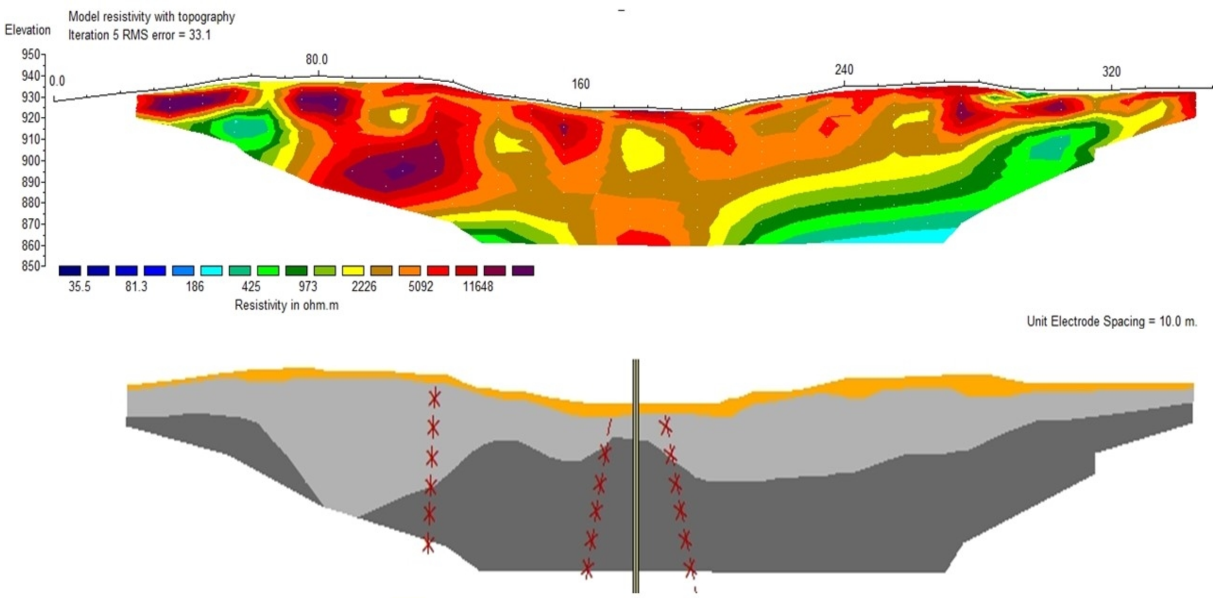


Figure 7

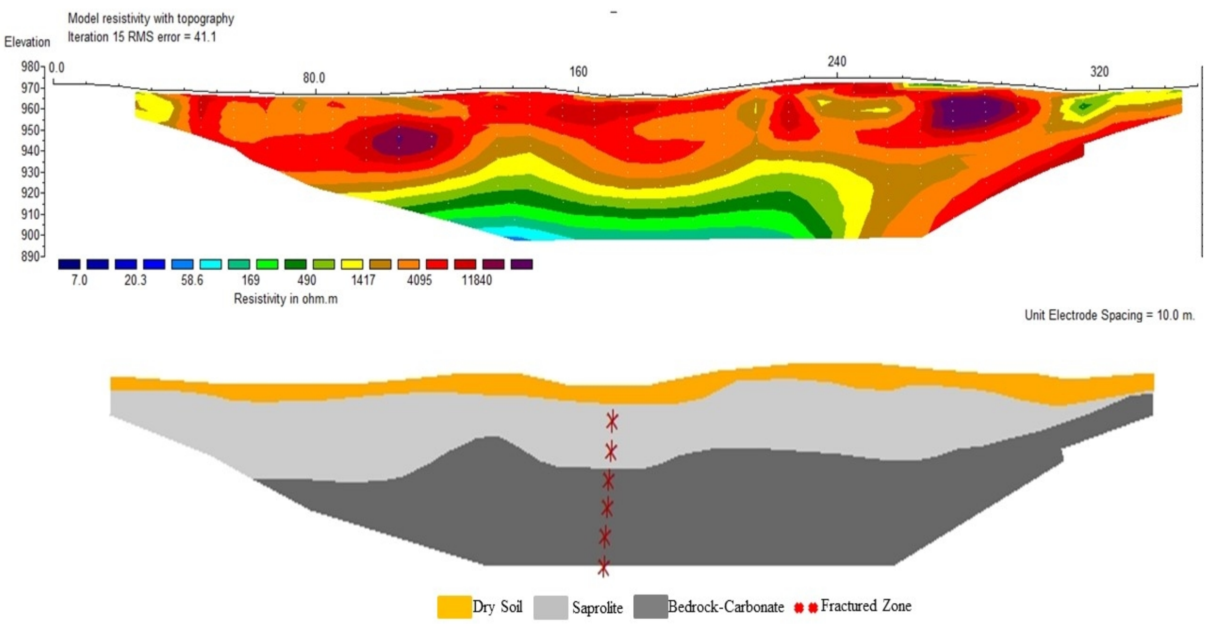


Figure 8

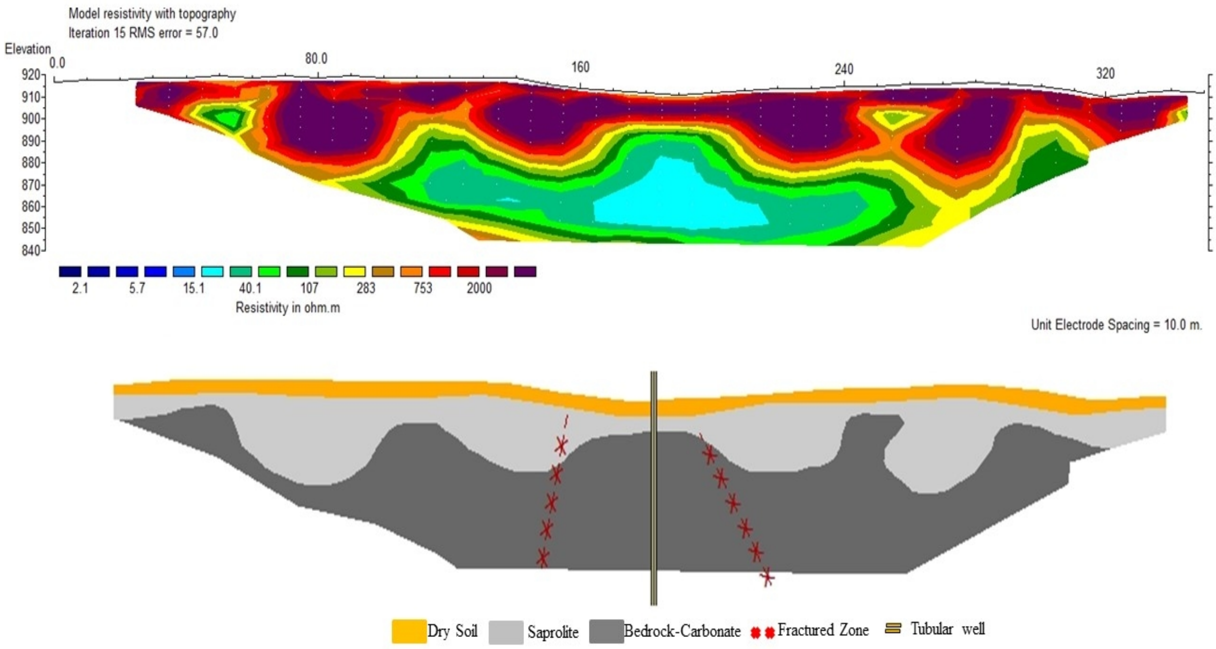


Figure 9

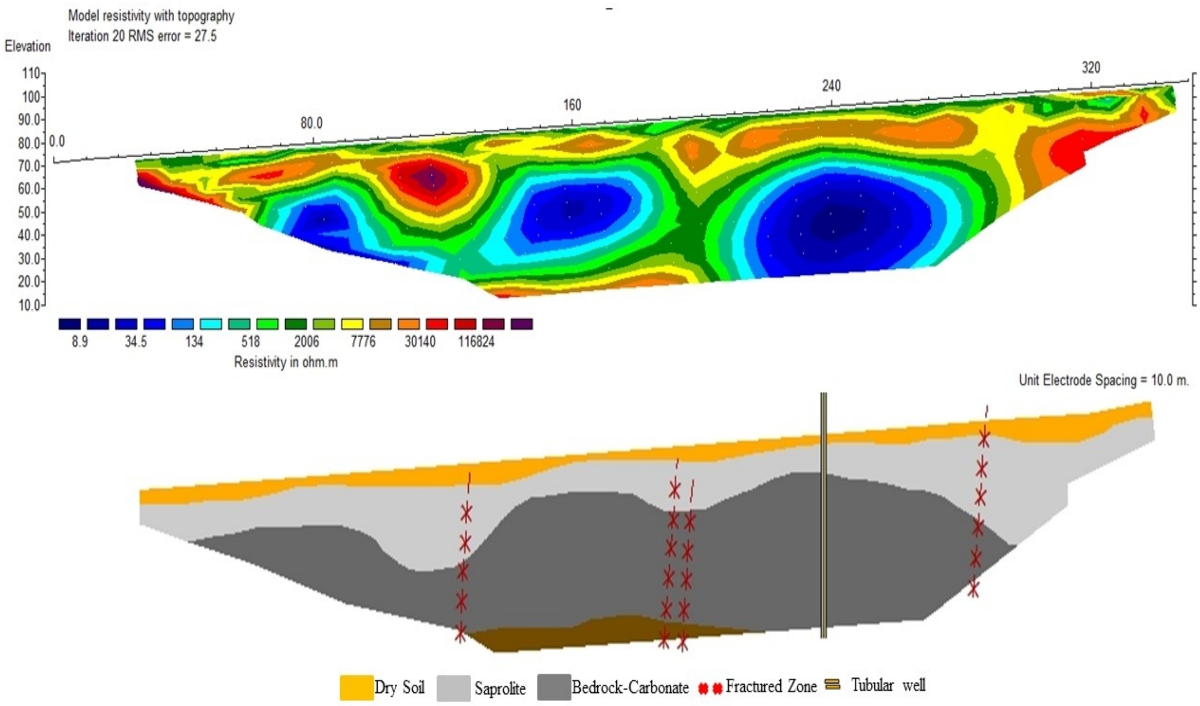


Figure 10

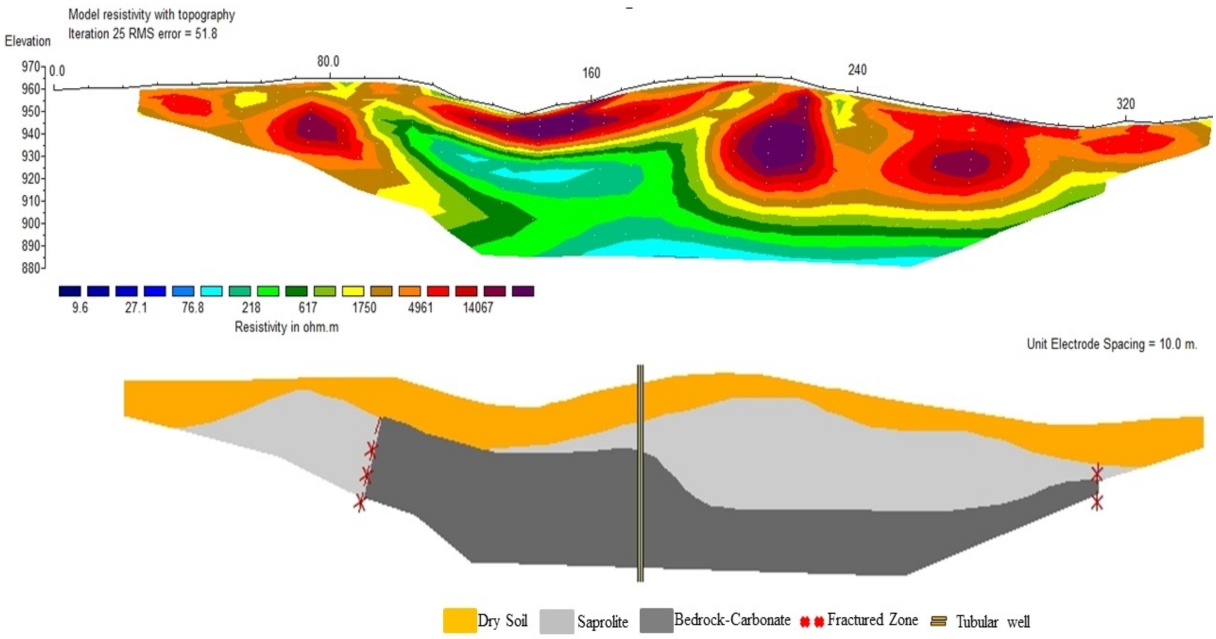


Figure 11

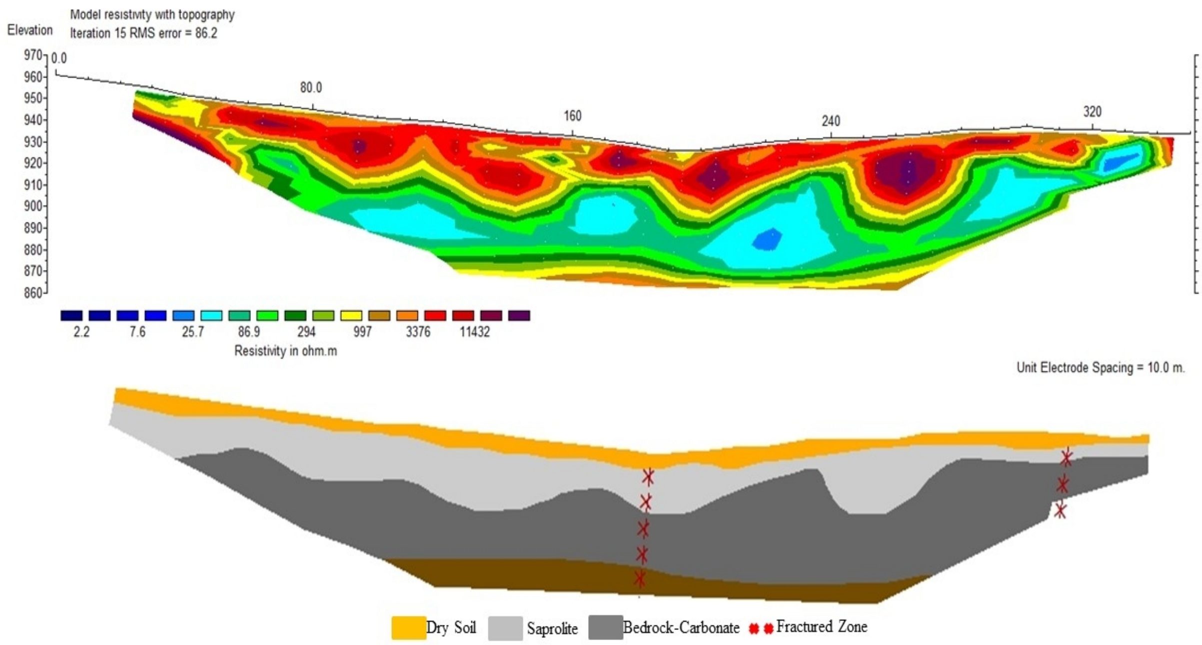
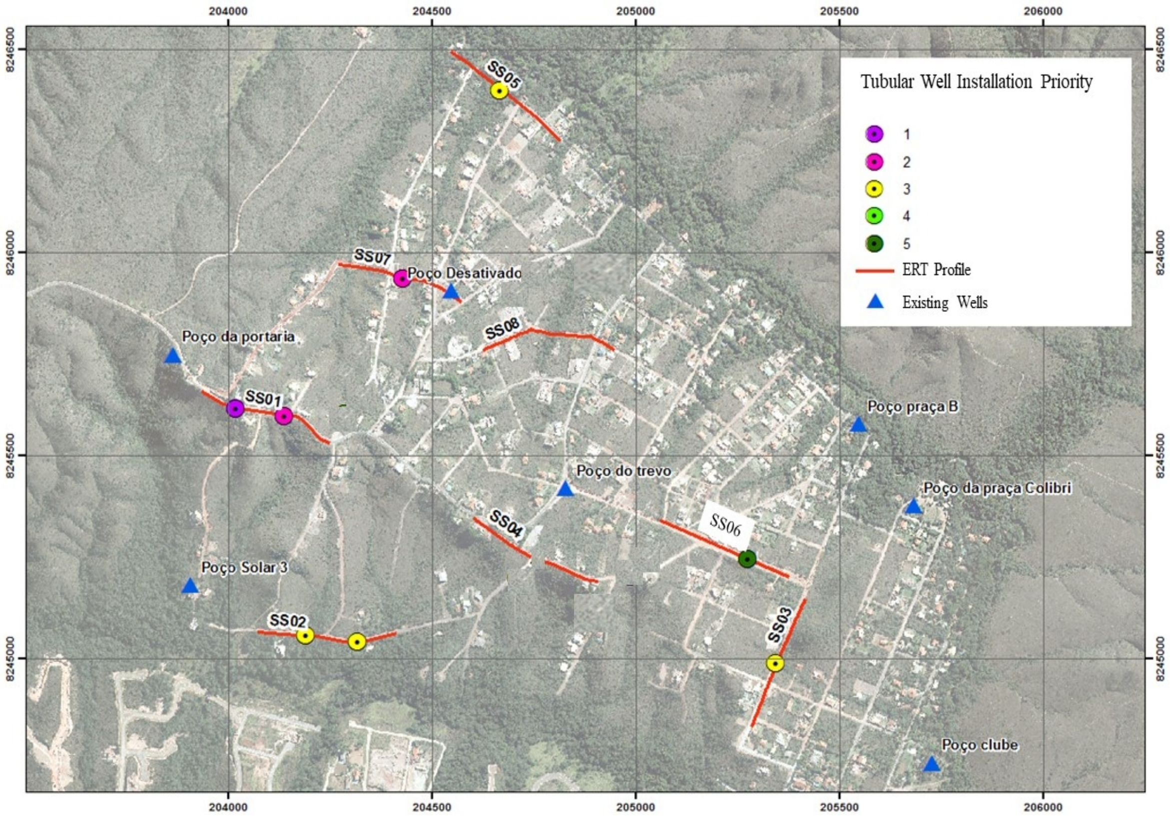


Figure 12



Tubular Well Installation Priority
1
2
3
4
5
ERT Profile
Existing Wells
SS01
SS02
SS03
SS04
SS05
SS06
SS07
SS08
Poço Desativado
Poço da portaria
Poço praça B
Poço do trevo
Poço da praça Colibri
Poço Solar 3
Poço clube
204000
204500
205000
205500
206000
8246500
8246000
8245500
8245000

Figure 13