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Conceptual geological model of the Ribeirão Tortinho Watershed, Federal District of Brazil

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A B S T R A C T

The increase of water consumption, associated with the disordered land occupation, lead to a scenario of overexploitation of surface and underground sources in the Federal District of Brazil. With the expansion of urban areas, the groundwater has played a major role in public supply, evidencing the need of deepening the knowledge of the local hydrogeologic framework. In this regard, this paper presents a conceptual hydrogeological model of the Córrego do Ribeirão Tortinho Watershed. The main goal of this report is to organize the available data and present it as a conceptual model that can subsidize the construction of a numerical groundwater flow model. In order to simplify the representation of the hydrogeologic framework, rocks and unconsolidated materials with similar hydraulic parameters and textural properties were grouped together to form hydrostratigraphic units. Six units were differentiated and their properties and attributes were discussed. The porous domain is represented by the hydrostratigraphic units I, II, III, and IV, characterized by oxisols, plintosols, cambisols, and gleisols, respectively. Rock units of the Paranoá Group were attributed to the other two hydrostratigraphic units. Quartzites and metarhytmites (Ribeirão da Contagem and Serra da Meia Noite Formations, respectively) form the hydrostratigraphic unit V, while slates (Ribeirão do Torto Formation) correspond to the unit VI. Through this systematic arrangement, an accurate and synthesized computational analysis can be successfully developed in order to access the groundwater flow of the study region.
Keywords: groundwater flow, conceptual geological model, water resources management.

Modelo geológico conceitual da Bacia do Ribeirão Tortinho, Distrito Federal, Brasil

R E S U M O

O aumento do consumo de água, associado à ocupação urbana desordenada, levou a um cenário de superexplotação de fontes superficiais e subterrâneas no Distrito Federal. Com a expansão das áreas urbanas, a água subterrânea tem desempenhado um papel importante no abastecimento público, evidenciando a necessidade de se aprofundar o conhecimento sobre o arcabouço hidrogeológico local. Neste sentido, este trabalho apresenta um modelo geológico conceitual da Bacia do Córrego do Ribeirão Tortinho. O principal objetivo deste relatório é organizar os dados disponíveis e apresentá-los na forma de um modelo conceitual que possa subsidiar a construção de um modelo numérico de fluxo de água subterrânea. Para simplificar a representação da estrutura hidrogeológica, rochas e materiais inconsolidados com parâmetros hidráulicos e propriedades texturais similares foram agrupados para formar unidades hidrostratigráficas. Seis unidades foram diferenciadas e suas propriedades e atributos foram discutidos. O domínio poroso é representado pelas unidades hidrostratigráficas I, II, III e IV, caracterizadas por latossolos, plintosolos, cambissolos e gleissolos, respectivamente. As unidades rochosas do Grupo Paranoá foram atribuídas às outras duas unidades hidroestratigráficas. Quartzitos e metarritmitos (Formações Ribeirão da Contagem e Serra da Meia Noite, respectivamente) formam a unidade hidrostratigráfica V, enquanto as ardósias (Formação Ribeirão do Torto) formam a unidade VI. Através deste arranjo sistemático, uma análise computacional precisa e sintetizada pode ser desenvolvida com sucesso para representar o fluxo de água subterrânea da região de estudo.
Palavras-chave: fluxo subterrâneo, modelo geológico conceitual, gestão em recursos hídricos.

Introduction

World water demand has been increasing at a rate of about 1% per year (WWAP, 2018), and will continue growing on the next decades with rising consumption in the agricultural, industrial and domestic sectors. The constant populational growth and the diversification of the land occupation patterns result in the reduction of surface and groundwater availability, leading to a scenario of overexploitation of the springs and aquifers.

The use of groundwater in the Federal District in Brazil presented a great increase in recent years due to the new model of land occupation adopted. With the expansion of urban centers, groundwater has come to play a major role in public supply through deep tubular groundwater wells.

The exploration of groundwater requires the in-depth knowledge of the hydrogeological characteristics of the aquifer systems, as well as the conditions of underground water circulation. In this context, groundwater flow models have shown to be particularly useful in the study and representation of aquifer formations, in the understanding of hydrodynamic processes, and in the better management of the water resources.

Groundwater flow modeling has been a quantitative tool widely used by hydrogeologists and water resource managers to evaluate aquifers and the impacts associated with the extensive use for human supply, irrigation, animal use, among other development activities (Kresic, 2006; 2010). Modeling attempts to capture real-world elements by integrating components of the hydrogeological characteristics of the physical environment, climate, and anthropogenic actions, were performed and thereby provided the variations in the conditions of an aquifer over time (e.g., Abdulla and Al-Assa'd, 2006; Alwathaf and El Mansouri, 2012; Masoud and El Osta, 2013, Jang et al., 2016). Several studies have been carried out in relation to underground flow modeling in order to understand several problems related to the use of groundwater. For instance, Chao et al. 2010, identified several measures to be taken to achieve the sustainable use of groundwater resources. In addition, many researchers have analyzed the flow dynamics of aquifers and the need to identify areas of groundwater exploitation through modeling methods (e.g. Jean et al, 2013; Lavigne et al., 2010; Okocha and Atakpo, 2013). Therefore, these underground flow simulations are useful for authorities to take corrective or remedial measures for the efficient use of the water resources.

Study site

The Córrego do Ribeirão Tortinho watershed is relatively small, but it is of great importance. It is a sub-basin inserted in the major Ribeirão do Torto basin and it is the main source of water for the Sobradinho rural area (Núcleo Rural Lago Oeste), located in the central portion of the Federal District (figure 1).

The Núcleo Rural Lago Oeste was supposed to be a controlled zone and mark the transition between urban occupation and conservation units. The proposed idea was to deal with low urban density and not to generate impacts for the basin. Nevertheless, the irregular land occupation allied to the lack of a land use planning potentiated the negative impacts with direct reflexes in the quality and quantity of the available surface and groundwater resources.

The creation of the Brasília National Park in the year of 1961 had as a major goal to preserve and protect the water resources of the Ribeirão do Torto and Santa Maria watersheds, in order to supply the city of Brasília. However, the defined national park boundaries do not coincide with the physical limits of the watershed; instead, the boundary was delimited based on the major existing roads that cross the region, especially the DF-001 road, which is oriented NW-SE and transects de Córrego do Ribeirão Tortinho watershed, dividing it into a northeastern and a southwestern portions. In the northeastern portion is located part of the Núcleo Rural Lago Oeste, where the land use is intensive, especially in terms of small-scale family agriculture. In addition, land cover is marked by the intense removal of the natural native vegetation and degradation of water resources due impermeabilization. On the other hand, the land cover of the southwestern portion of the watershed is represented by the preserved native vegetation inside the Brasília National Park.

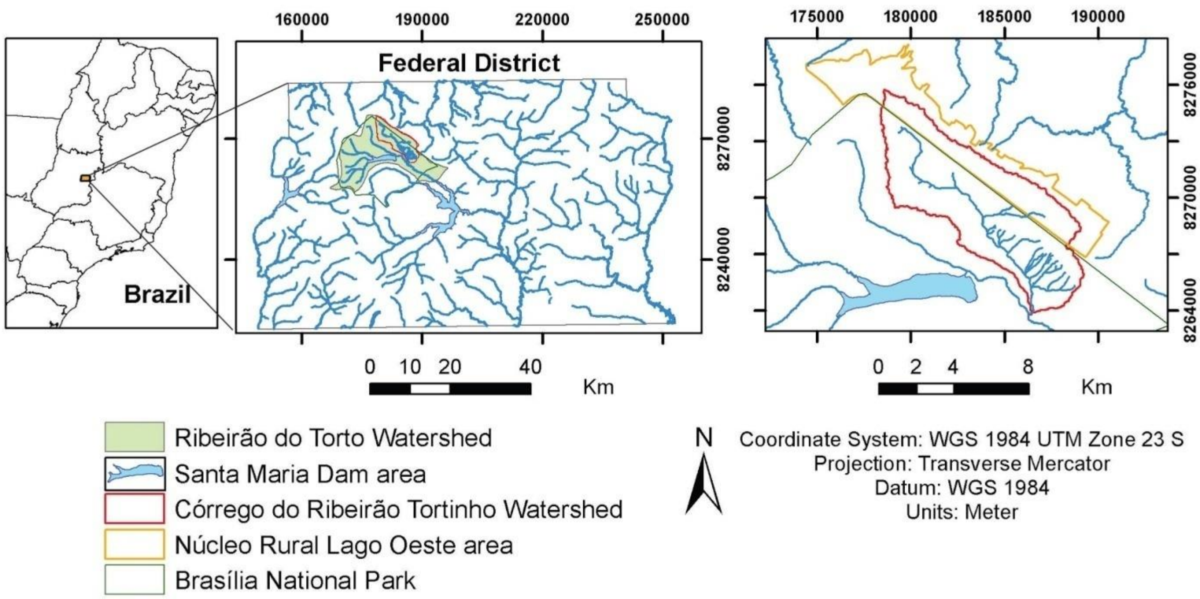

Figure 1 - Location of the Córrego do Ribeirão Tortinho watershed in the Federal District of Brazil.

Objectives

The objective of this work is to study the behavior of water circulation in the subsurface of the Córrego do Ribeirão Tortinho watershed. The review and compilation of available information, the development of a conceptual geological model, and the construction of a three-dimensional groundwater flow model that represents the elements of the conceptual geological model are necessary tools in order to achieve an understanding of the groundwater flow system.

To achieve the proposed objective, the following goals will be completed: (i) identify, acquire and review all available data from previous studies concerning the study area in the field of hydrogeology; (ii) develop a spatially referenced database of information using GIS to characterize the aquifers across the study area; (iii) identify regional and local boundaries for groundwater flow and develop a conceptual geological model that is consistent with the previous studies.

Materials and methods

Many studies related to the geology, pedology, geomorphology, and hydrogeology of the study area have been published in the past years. Relevant academic papers and reports were compiled and reviewed in order to develop an understanding of the geologic and hydrogeologic setting of the watershed area. The purpose of this research, aiming to gather the existing data, is to develop the conceptual geologic model.

The geological model was constructed using information such as the geological structure, hydraulic conductivity, and layer properties. Data from wells provided by ADASA (Agência Reguladora de Águas, Energia e Saneamento Básico do Distrito Federal) and SIAGAS (Sistema de Informações de Águas Subterrâneas) were also reviewed and include measured groundwater levels and flow rates. The conceptual geologic model of the Córrego do Ribeirão Tortinho watershed was developed using a number of existing data sets and maps, including thematic maps and parameter distributions. The data was compiled in a GIS mapping system. The GIS database used in this present study include: topography (DEM – Digital Elevation Model); geology; surface water features (e.g. streams, basin and sub-basin boundaries, wetlands, dams, lakes); pedology; recharge potential; municipal features (e.g. roads, land use); groundwater wells information (monitoring and human supply wells).

The following topics will describe the available data of the study area, and how it relates to the development of the conceptual geologic model such as geology, pedology, climate, geomorphology, hydrogeology, and groundwater well data.

Geological setting

The geological context of the Córrego do Ribeirão Tortinho sub-basin is defined by the rocks of the Paranoá Group. According to Campos (2004), the Paranoá Group is represented by rocks characterized in eleven correlated lithostratigraphic units, from the base to the top, with the depositional sequences SM, R1, Q1, R2, Q2, S, A, R3, Q3, R4, and PPC. A more recent work by Campos et al. (2013) proposes to formalize these units as Formation Ribeirão São Miguel, Cordovil Formation, Serra da Boa Vista Formation, Serra Almécegas Formation, Serra do Paranã Formation, Ribeirão Piçarrão Formation, Ribeirão do Torto Formation, Serra da Meia Noite Formation, Ribeirão Contagem Formation, Córrego do Sansão Formation and Córrego do Barreiro Formation, respectively. The bedrock beneath the Córrego do Ribeirão Tortinho watershed area is defined by the Ribeirão do Torto, Serra da Meia Noite, and Ribeirão da Contagem formations. These formations are described below (Campos et al., 2004; Campos et al., 2013).

Ribeirão do Torto Formation

The Ribeirão do Torto Formation outcrops in the proximities of the Santa Maria Dam boundaries. This lithofacies is characterized by purplish slates when altered, or greenish gray when fresh and homogeneous. Close to the limit with the upper unit, there are millimeter-to-centimeter siltic-clayey intercalations, with red to pink tonalities. The passage to the metarythmite unit that covers it is gradual. These rocks are intensely fractured and, due to its pelitic character, the metamorphic foliations are more easily developed in this unit. Particularly, two surfaces are quite penetrative, characterizing typical slaty cleavages. The only sedimentary structure observed is flat-parallel lamination near the top of the unit. Occurrences of white to yellowish quartzites are rare within the set of slates, always characterized by metrical or lenses that are generally irregular and massive.

Serra da Meia Noite Formation

Alternation of centimetric to metric layers of fine to medium quartzites with thin layers of metapelitic rocks characterize the Serra da Meia Noite Formation, defining this package as a sandy metarhytmite. The lenticular aspect of the stratification is quite a common feature. Parallel stratification, ripple marks, lenticular stratification and sand dikes are frequent sedimentary structures in this formation, while cross-stratification and hummockies are less frequently observed. The contact between the upper unit and the Serra da Meia Noite formations is abrupt.

Ribeirão da Contagem Formation

Fine to medium quartzites define the Ribeirão da Contagem Formation and characterize the high topographies of the study area, where the Núcleo Rural Lago Oesteisestablished. This unit varies from white to light gray (dark gray when fresh) rocks, well sorted, mineralogically mature, silicified and when less recrystallized show rounded grains. In altered outcrops, it is possible to observe decimetric to metric scale parallel layering. Intense fracturing is also described in this unit. Other structures present are cross-stratification and ripple marks. Herring bone structures are rare. Meatarhytmite lenses are common next to the base and the top of this unit.

Structural setting

The Córrego do Ribeirão Tortinho watershed is inserted in the Dome of Brasilia structural window, where the Ribeirão do Torto, Serra da Meia Noite, and Ribeirão da Contagem formations occur and are stratigraphically positioned in the top of the Paranoá Group (figure 2). The regional structure of the dome is related to progressive shortening oriented NE-SW and NW-SE, which resulted in different folding styles and fold interference patterns. The wavelengths of these folds are kilometer scale and its geometry defines the configuration of the domes and basins observed in this region (Kumaira, 2016). The borders of the dome are high topography areas sustained by the quartzites of the Ribeirão da Contagem Formation, while the nucleus is characterized by metarhytmite lenses and slates of the Ribeirão do Torto Formation in low topography areas. Metarhytmites of the Córrego do Sansão Formation represent the flanks of the dome.

The watershed is located in the northeastern portion of the dome, where the structural configuration is characterized by a low-angle flank dipping to the northeast direction.

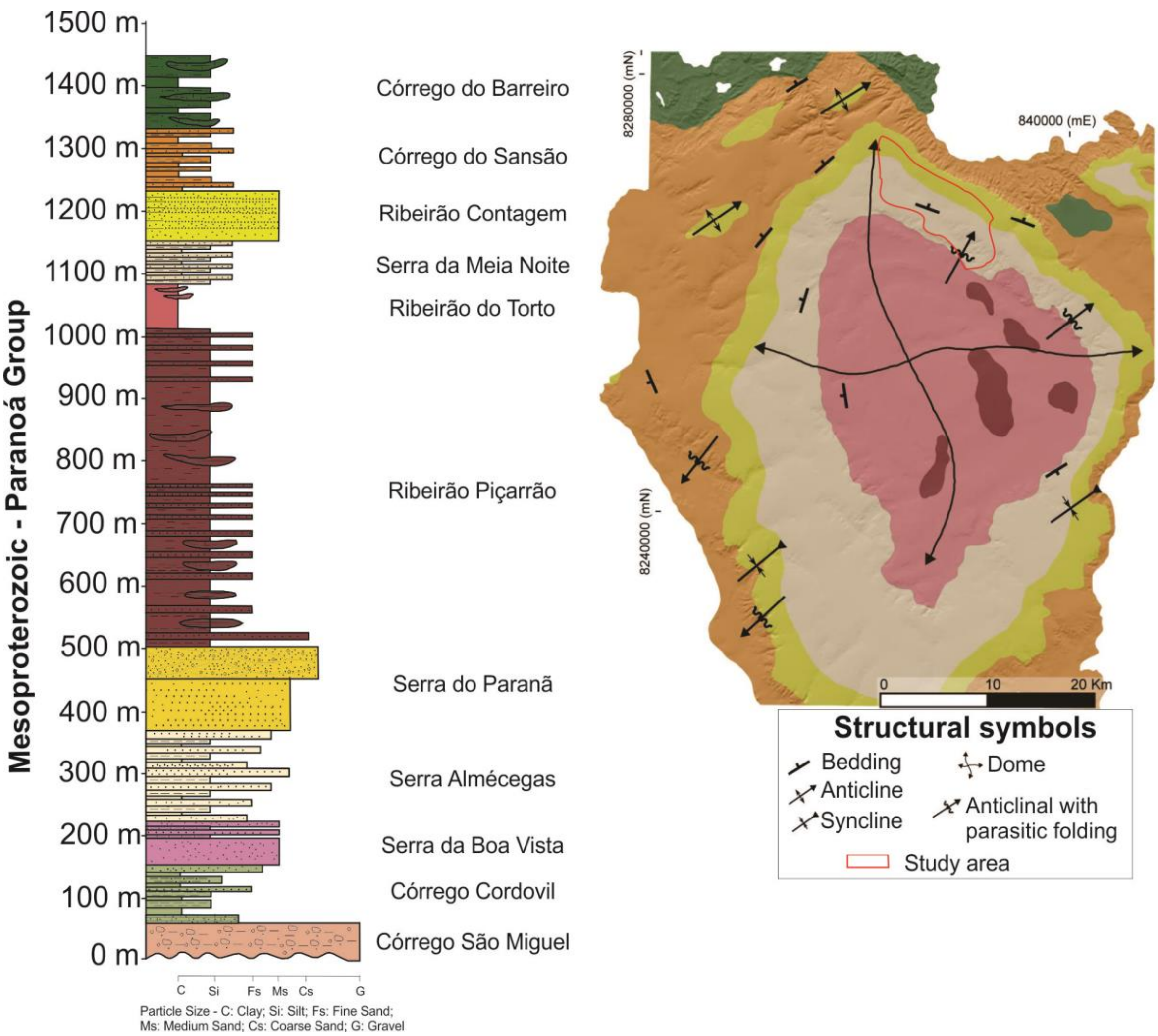

Figure 2 - Stratigraphic column proposed for the Paranoá Group and a simplified geological map of the Brasília Dome highlighting the structural setting and study area (modified from Campos et al., 2013 and Kumaira, 2016).

Climate

A strong seasonality (figure 3) with two well defined periods characterizes the climate in the study region. In the period between December to March, the precipitation is concentrated in 57.9% (INMET, 1992). The interval between the months of May and September, there is a low precipitation rate and a high evaporation rate, leading to a dry season. The average annual rainfall is 1540 mm. According to the Köppen classification, the current climate in the region falls between tropical (Aw) and tropical altitude (Cwa and Cwb) (In: CODEPLAN, 1984).

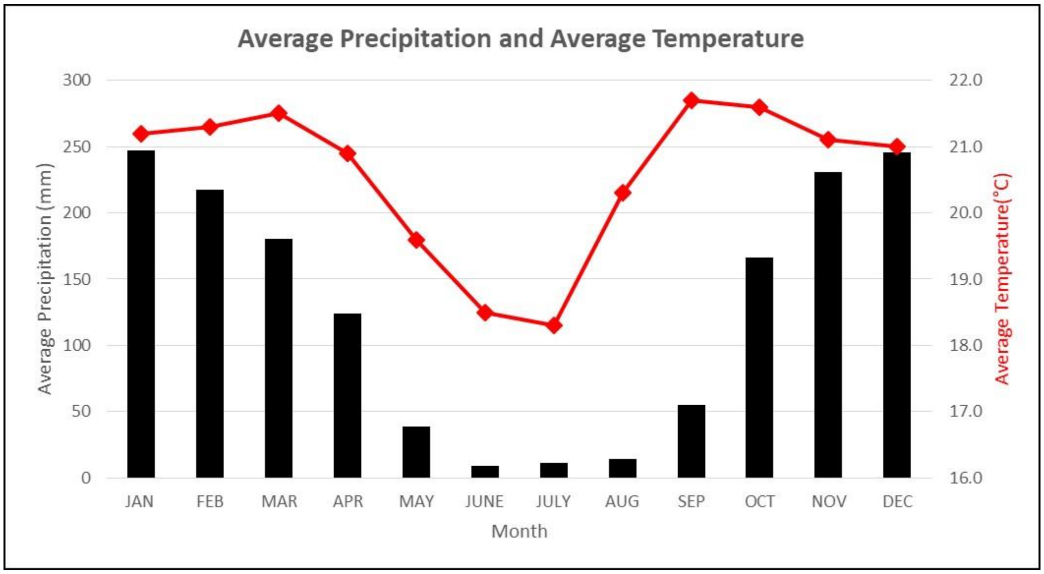

Figure 3 - Diagram of the average temperature and course of precipitation for the capital Brasília. The graphs are based on data from the years 1961 to 1990 (modified after Instituto Nacional de Meteorologia 2013).

Pedological setting

The pedological context of the study area (figure 4) is predominantly related to oxisols (reddish and reddish yellow) and cambisols, with limited occurrences of petroferric plintosols, and haplic gleisols. The oxisols are related to residual relief forms of flat surfaces in high topographies where water infiltration is favorable. The haplic cambisols are described in steep relief areas where surface runoff predominates. Petroferric plintosols are restricted and associated with oxisols, but infiltration is minimum due to its low permeability (Reatto et al., 2004). The soils present in the study area are described below.

Reddish oxisol and reddish yellow oxisol

The oxisols are highly weathered and have oxidized subsurface horizons. The clayey texture, dystrophic character, associated with granular structure in the superficial horizon and lumpy structure in depth are common characteristics described for the reddish oxisols. The reddish-yellow oxisols have similar properties, although it is described with a sandy texture. These soils are associated with high plateau topographies.

Petroferric plintosol

Petroferric plintosols are also related to high plateau areas of the Córrego do Ribeirão Tortinho watershed. Common features are gravel texture, dystrophic to alic character, and the presence of a ferric horizon.

Haplic cambisol

Haplic cambisols occur in the steep relief areas within the watershed; these soils present poorly developed horizons. Silty-clayey, clayey, clayey-gravelly are frequently observed textures. Fragments of the underlying rock units are common features.

Haplic Gleisol

Haplic gleisol within the watershed occurs along the Ribeirão Tortinho stream and it is described as very clayey texture, dystrophic character, and with a granular structure in the superficial horizon. Moreover, these soils are poorly drained with its properties resulting from the influence of a water-saturated environment related to the presence of the water table near the surface.

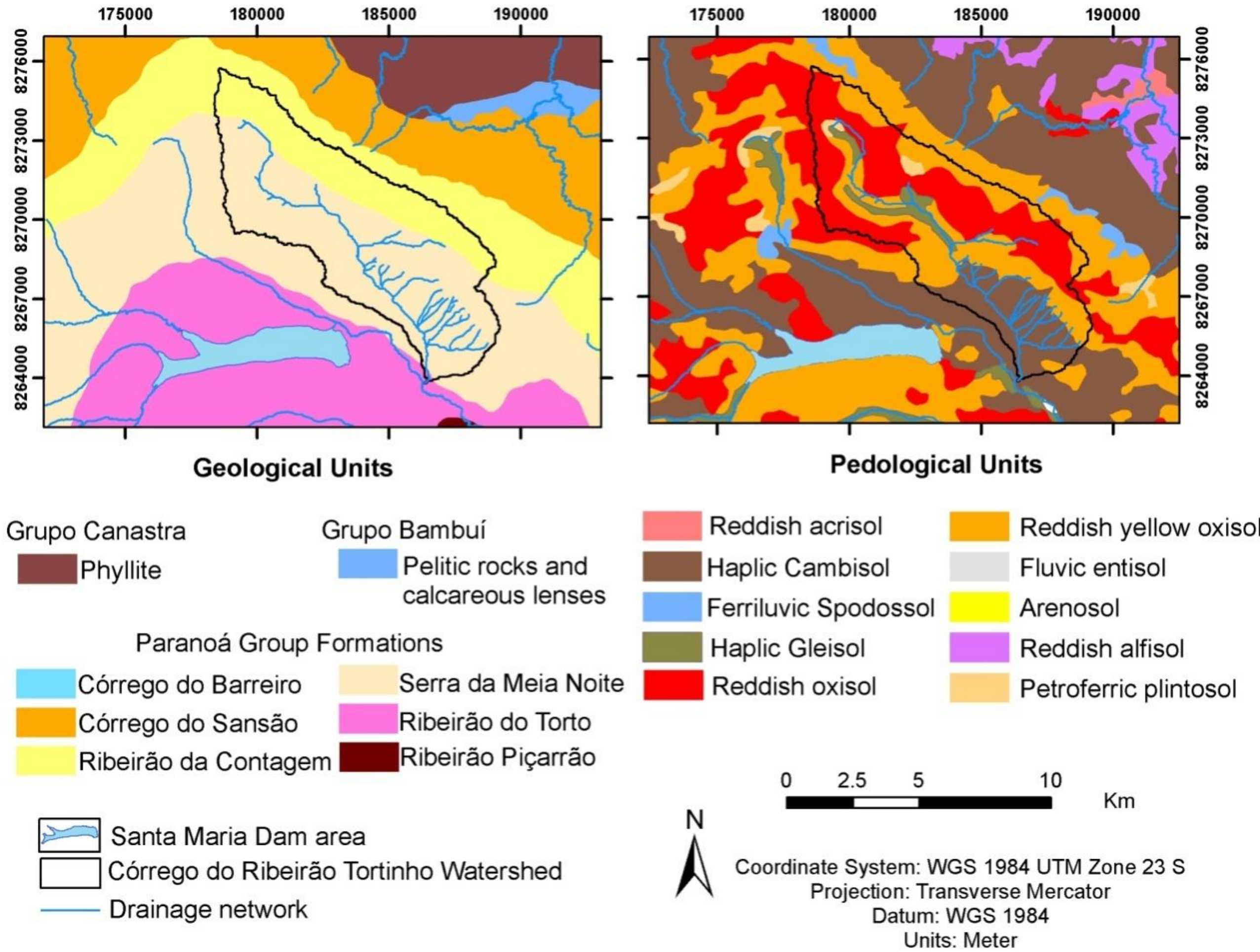

Figure 4 – Geological and pedological units of the Córrego do Ribeirão Tortinho watershed.

Geomorphology/Bedrock topography

The bedrock geology exerts a remarkable control over the compartmentalization of the surface topography (Martins and Baptista, 1998; Campos, 2004). The highest elevation areas in the study area are found in the Núcleo Rural do Lago Oeste, on the northeastern portion of the Córrego do Ribeirão Tortinho watershed. These areas lie mostly on the Ribeirão da Contagem Formation, characterized by quartzites. Regions of intermediate dissection are controlled by the Serra da Meia Noite and Ribeirão do Torto formations, composed of metarhytmites and slates, respectively.

A digital elevation model (DEM) with a resolution of 12.5 meters was obtained from the ALOS PALSAR Global Radar Imagery (© JAXA/METI 2007) (figure 5).

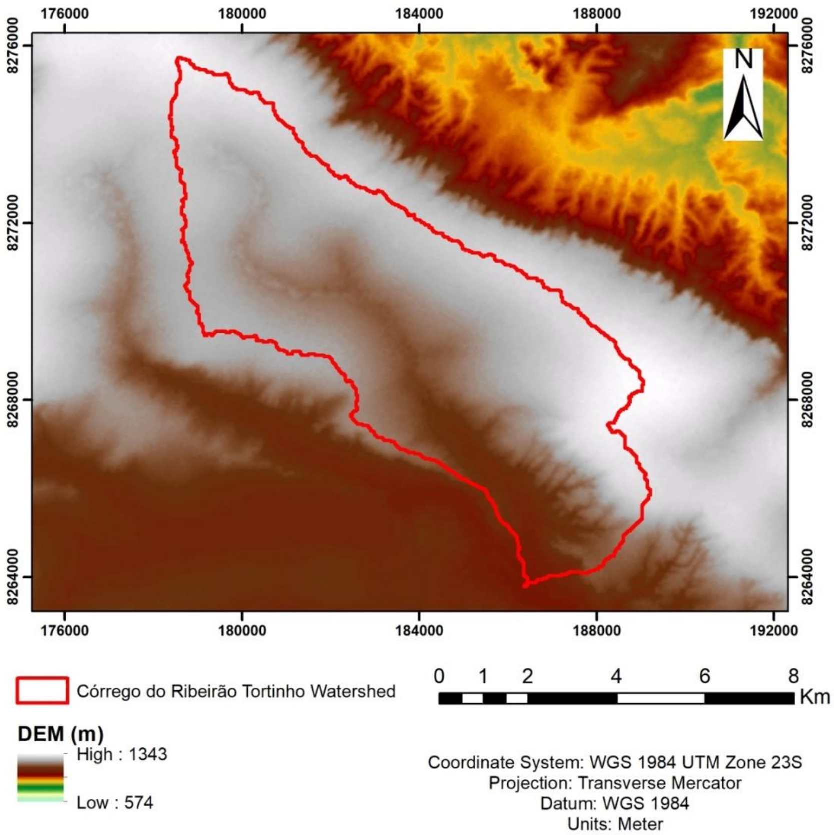

Figure 5 – Digital Elevation Model obtained from the ALOS PALSAR Global Radar Imagery (© JAXA/METI 2007).

Hydrogeological setting

In the Federal District, where the geology is characterized by metamorphic rocks covered by thick soils, two groups of aquifers can be differentiated and correspond to underground water reservoirs: the Porous Domain (upper aquifers) and the Fractured Domain (lower aquifers) (Freitas-Silva and Campos, 1998; Campos, 2004).

The Porous Domain is represented by the unconsolidated geological media characterized by the association of soils and saprolite or regolith. In situ infiltration tests performed in different sites of the Federal District (Souza and Campos, 2001) permit a classification of the soils and regolith associations from a hydrogeological point of view in four systems: P1, P2, P3, and P4. This classification method takes into account the predominance of certain soil classes, their depths and preliminary measurements of vertical hydraulic conductivities. P1 and P4 are the major systems found in the Córrego do Ribeirão Tortinho watershed. The P1 system includes the oxisols (reddish and reddish yellow), with a thickness approximately between 20 and 40 meters and values of vertical conductivity varying from 0.1 to 8.5 m/day. The P4 system is predominated by the haplic cambisols with thickness varying around 2 meters and low infiltration potentials.

The Fractured Domain is characterized by the bedrock material where the spaces occupied by water are represented by planar discontinuities, fracture planes, joints, shear zones, and faults. The bedrock is represented by metasediments, and the intergranular spaces are filled during lithification and metamorphism, thus the porosity of the water reservoirs being classified as secondary porosity. The metasedimentary rocks of the Paranoá Group underneath the Porous domain correspond to the fractured aquifer systems with the following sub-systems: S/A, A, R3/Q3 and R4 sub-systems. In the study site, the A and R3/Q3 sub-systems are present. The A sub-system is characterized by the slates of the Ribeirão do Torto formation while the R3/Q3 sub-system corresponds to the Serra da Meia Noite (sandy metarhytmites) and the Ribeirão da Contagem (medium quartzites) formations, respectively. These aquifers sub-systems are strongly anisotropic and heterogeneous and are described as free or confined aquifers with variable lateral extent. The R3/Q3 system of the Paranoá Group (Fractured Domain), represented by metasedimentary rocks, is characterized by free or semi-confined fissure aquifers, with transmissivity varying from 1.3 to 43.2 m^2/day (Souza and Campos, 2001; Campos, 2004; Cadamuro and Campos, 2005; Lousada and Campos, 2005).

The area of the present study fits the conceptual schematic aquifer model of Two Potentiometric Surfaces Model (figure 6) of Lousada and Campos 2005, a configuration that occurs in the interior of the high plateau regions (Martins and Baptista, 1998), of flat and high topographies, being a recharge area for the associated aquifers.

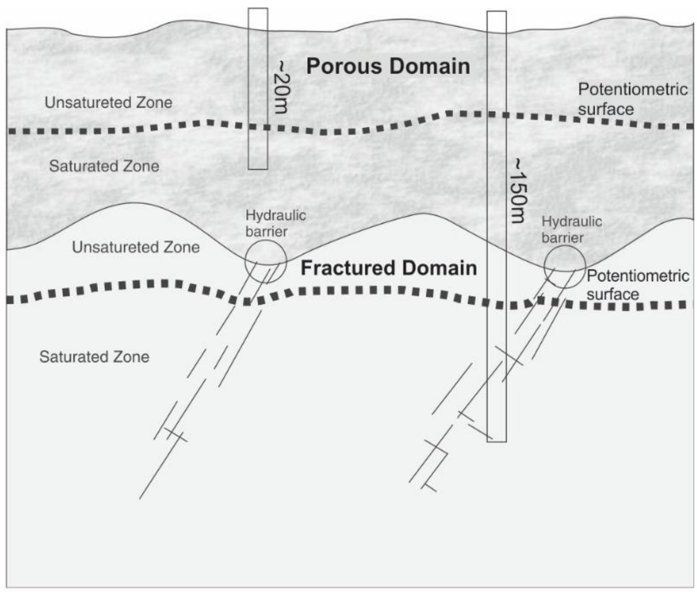

Figure 6 - A schematic model of the Two Potentiometric Surfaces Model. Situation present in flat relief associated with high topography areas, as in the case of the Córrego Ribeirão Tortinho watershed. The average thickness of the regolith is 40 meters (dark grey color). The average depth of the potentiometric surface of the fractured domain is 70 meters. The tubular groundwater well has a depth of approximately 150 meters, while the excavated groundwater well has a depth of 20 meters. Adapted from Lousada and Campos 2005, Gonçalves et al. 2013.

The natural recharge of the systems P1overlying the R3/Q3 in the high plateau areas obey two stages of natural infiltration (Souza, 2001). The first stage occurs through the soils to the saturated zone of the porous domain. The other stage starts from the moment the system P1 reaches a condition of maximum storage and the hydraulic load becomes capable of infiltrating and overcoming the hydraulic barrier formed by the air/clays in the fractures toward the saturated zone of the R3/Q3 aquifer system of the fractured domain.

According to the Management Plan of the Brasília National Park report (ICMBio, 1998), the Brasília National Park area presents two groups of unconsolidated material responsible for the separation into two regions of the porous domain. The first one is characterized by covers of sandy and quartzose metarhytmites (Serra da Meia Noite Formation), inserted in the Córrego do Ribeirão Tortinho watershed area, which present hydraulic conductivity in the order of 10^{-6} m/s and transmissivity in the order of 10^{-5} m^2/s. The second is represented by materials originated from the slate unit (Ribeirão do Torto Formation), with a hydraulic conductivity of about 10^{-9} m/s and transmissivity of 10^{-6} m^2/s.

Groundwater Wells

Data provided by ADASA show the evolution of the static level of the tubular monitoring well located at 8th street in the Núcleo Rural Lago Oeste (table 1; figure 7) during the periods of April 2013 to April 2017. The deep groundwater well reaches the bedrock and represents the fractured domain. The shallow groundwater well is inserted into the porous domain, characterized by the soil and regolith. The monitoring of the static levels indicates a lowering in relation to the surface over the four years of measurement in the two domains, starting from measurements in April 2013 close to 11 meters and reaching values around 15 meters in May 2017.

Two other wells in the study area were built by SIAGAS, associated to the Brazilian Geological Survey (CPRM). One of the wells with 100 meters of depth is also on 8th street and in February 1997 (date of its construction) it presented a static level measurement of 14 meters. The other well, located at the eastern boundary of the Núcleo Rural Lago Oeste (Vila Basevi) is 142.50 meters deep and had a static level of 7.2 meters at the time of its implementation in August 2002. The location of the wells provided by ADASA and SIAGAS are shown in figure 8.

Table 1 – Groundwater static levels measured for the two wells located in the 8th street of the Núcleo Rural Lago Oeste. One deep tubular well is installed in the fractured domain, while the other one is shallower and is inserted in the porous domain. The data was obtained from ADASA.

ADASA Groundwater Monitoring Wells	**Domain** Groundwater Static Level (m)	
Date	**Fractured**	**Porous**
April 2013	11.30	11.00
September 2013	14.00	11.10
April 2014	18.00	11.50
October 2014	13.00	16.00
February 2015	14.30	17.60
March 2016	15.00	14.00
July 2016	15.25	14.30
August 2016	15.34	14.08
September 2016	15.53	14.55
October 2016	13.63	14.62
November 2016	14.77	14.75
December 2016	15.14	14.30
January 2017	15.16	14.40
February 2017	15.34	14.34
March 2017	15.36	14.61
April 2017	15.25	14.46
May 2017	15.30	14.47

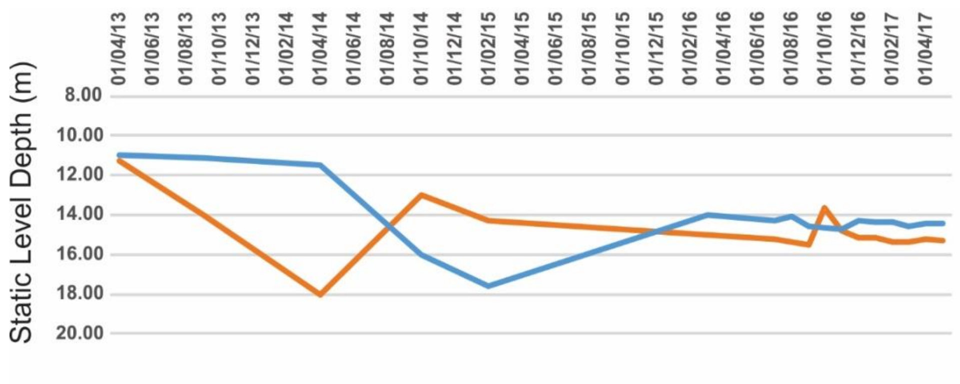

Figure 7 - Static Water Level Measurement History in the Fractured and Porous domains between the years 2013 and 2017 of the Groundwater Monitoring Well number 16 of the Núcleo Rural Lago Oeste located at 8th Street and within the watershed. Measurements provided by ADASA. The blue line represents the measurements of the Fractured Domain, while the orange line refers to the Porous Domain.

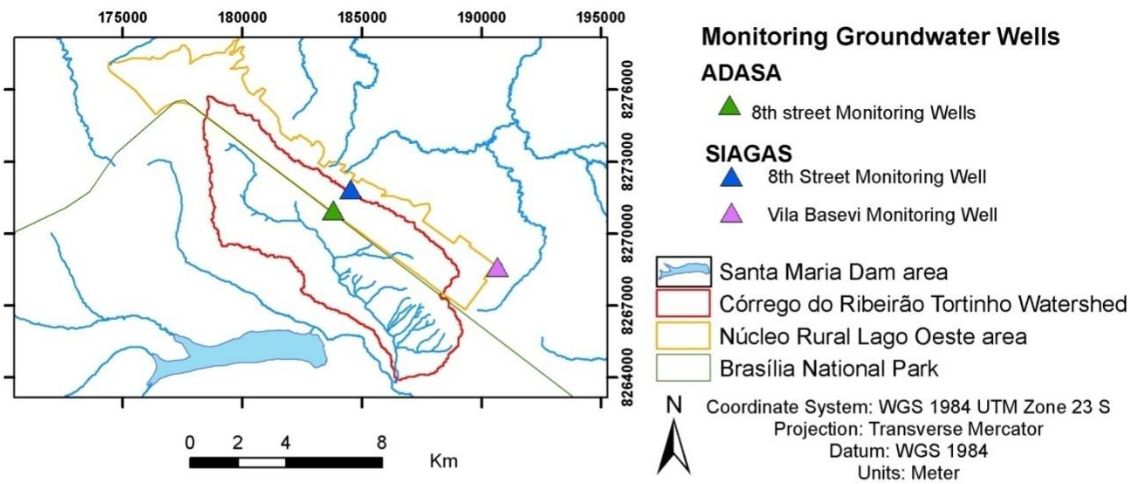

Figure 8 – Location of the monitoring groundwater wells of ADASA and SIAGAS in the Núcleo Rural Lago Oeste.

Results and discussion

Hydrostratigraphic Units

Complex geologic or pedologic units with similar hydrogeologic properties and textural characteristics can be grouped together to form a hydrostratigraphic unit. The different characteristics of the hydrostratigraphic units allow the subsurface to be divided into aquifers and aquitards (Waterloo Hydrogeologic Inc, 2004). The separated 'packages' with distinct properties can be examined for the analysis of groundwater flow.

Within the study area, two distinct aquifer units were identified: (i) the porous domain aquifers and the (ii) fractured domain aquifers.

Porous Domain

The aquifers that represent the porous domain are associated with the combination of the soil and the regolith portion, defined as the layer of unconsolidated material covering the bedrock. These aquifers can be classified as continuous intergranular and unconfined. Within the Córrego do Ribeirão Tortinho watershed, five different types of soils are described as reddish oxisol, reddish yellow oxisol, petroferric plintosol, haplic cambisol, and haplic gleisol. Each type of soil and the associated regolith (layer of unconsolidated material covering the bedrock) represents a specific hydrostratigraphic unit with specific hydraulic parameters and other physical properties. These shallow aquifers are commonly used in private and domestic water; however, these aquifers are highly susceptible to groundwater contamination.

Fractured Domain

The second aquifer unit includes fractured aquifers associated to the metasedimentary rocks underlying the soil/regolith layer. These aquifer systems are characterized to be semi-confined or fissure aquifers. Each type of bedrock underlying the soil/regolith layer represents a different hydrostratigraphic unit and behaves differently when considering the analysis of groundwater flow. These hydrostratigraphic units are represented by the Paranoá Group metasedimentary rocks: Ribeirão da Contagem, Serra da Meia Noite, and Ribeirão do Torto formations.

Conceptual Hydrostratigraphic Units

Mapping of the distribution of each of these hydrostratigraphic units in the study area was undertaken by reviewing and interpreting the subsurface geology within the region. The following topics will describe each defined hydrostratigraphic unit and its properties. The conceptual geological model of the study region is shown in figure 7.

Hydrostratigraphic unit I (HU I) - Porous Domain

The HU I includes the reddish oxisol and the reddish yellow oxisol and associated saprolite. The distribution of these soils is shown in figure 4and it is associated with high plateau areas with low declivity rates. The thickness of this hydrostratigraphic unit varies from 20 to 40 meters due to its well-developed pedum. The HU I represents the alteration product of the quartzites of the Ribeirão da Contagem Formation and part of the metarhytmites of the Serra da Meia Noite Formation.

Hydrostratigraphic unit II (HU II) – Porous Domain

The HU II is represented by the petroferric plintosols, a result of the localized segregation of iron, which acts as a cementation agent and forms a petroferric horizon. The thickness of this unit varies from 1 to 2 meters and it is related to the periodical soaking by the groundwater level. Due to its low permeability character, this unit behaves as a physical barrier to water percolation in the direction of the groundwater level. Values of hydraulic conductivities are variable, from 10^{-5} to 10^{-9} m/s.

Hydrostratigraphic unit III (HU III) – Porous Domain

The HU III is defined by the haplic cambisols that occur in the steeper relief areas within the watershed. The thickness of this unit varies from 1 to 3 meters due to its poor pedum development. Hydraulic conductivities on the surface are high, with values varying from 10^{-4} to 10^{-5} m/s; however, there is a rapid tendency to lower values with depth, reaching 10^{-7} to 10^{-8} m/s.

Hydrostratigraphic unit IV (HU IV) - Porous Domain

The HU IV is associated with the haplic gleisol occurrences along the Riberão Tortinho stream. It comprises poorly drained soils with its properties resulting from the influence of permanent or temporary excess moisture due to the presence of the water table near the surface during a given period of the year. The thickness of this unit varies from a few centimeters to approximately 2 meters. Hydraulic conductivities are naturally low due to its high water saturation, varying from 10^{-8} to 10^{-9} m/s.

Hydrostratigraphic unit V (HU V) – Fractured Domain

The HU V comprises the metasedimentary rocks of the Serra da Meia Noite and Ribeirão da Contagem formations, corresponding to the R3/Q3 sub-system described by Freitas-Silva and Campos, 1998. Both of these geological units are mainly composed by psammitic lithotypes and exhibit resembling hydrogeological properties, which enable their inclusion in the same hydrostratigraphic unit.

This hydrogeological setting is essentially composed by discontinuous aquifers, where the groundwater occurrence is exclusively related to the presence of secondary planar structural elements such as faults, fractures, and joints, due to the brittle behavior of the host rocks. Therefore, these reservoirs show a highly variable pattern of physical and hydrodynamic parameters, constituting a heterogeneous and anisotropic system.

The HU V covers almost the entire extension of the study area, with a thickness of approximately 150 meters, and hosts a productive aquifer for domestic water supply.

Hydrostratigraphic unit VI (HU VI) - Fractured Domain

Lithotypes associated to the Ribeirão do Torto formation define the HU VI, which corresponds to the A aquifer system of Freitas-Silva and Campos, 1998. This unit covers just a narrow area in the most downstream region of the watershed. The HU VI shows limited water availability, being mainly composed of discontinuous and anisotropic aquifers with low values of hydraulic conductivity.

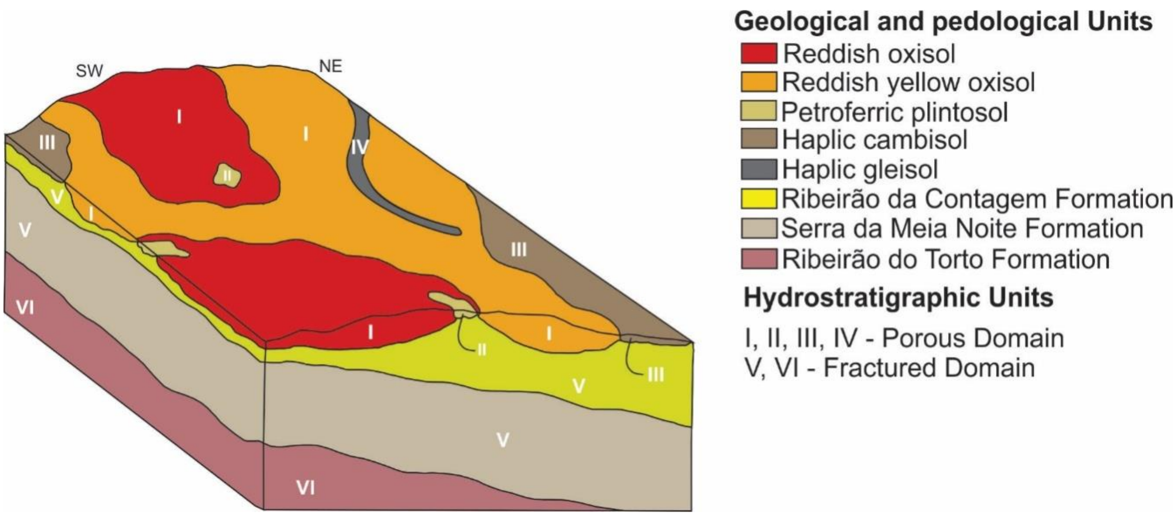

Figure 9 - Three-dimensional schematic view of the hydrostratigraphic units of the conceptual geological model of the Córrego do Ribeirão Tortinho study area.

Hydraulic Conductivity

The estimates of hydraulic conductivities (permeability) are typically derived from aquifer test data, literature values, or from previous groundwater flow studies and models. Typically, the vertical hydraulic conductivity is assumed to be one order of magnitude less than the horizontal hydraulic conductivity. The discrepancies associated to the hydraulic conductivity measurements in the existing studies are reflections of the degree of heterogeneity of the hydrostratigraphic unit and the large variations that lie in the bedrock aquifers, where the bedrock formation is intensely fractured across the study region (Waterloo Hydrogeologic Inc, 2004).

Within a groundwater flow model, for each hydrostratigraphic unit, there is an assigned hydraulic conductivity parameter value. For example, values assigned for the haplic cambisol (HU III) are different compared to the reddish and reddish yellow oxisols (HU I) due to its different subsurface properties to transmit water. It is a property that can vary significantly from one unit to another. During the development of the groundwater flow model, the hydraulic conductivity values used in the model will aim to be consistent with the geologic/pedologic settings and also values cited in the literature and obtained in aquifer tests.

Table 2 below shows the estimate values for hydraulic conductivities (Kx, Ky, and Kz) for each assigned hydrostratigraphic unit and its associated thickness. The values were obtained and adapted from the literature review (Freitas-Silva and Campos, 1998; Souza and Campos, 2001).

Table 2 – Estimate values for hydraulic conductivities for each assigned hydrostratigraphic unit and its associated material and thickness.

	Hydrostratigraphic Unit	**Pedological and Geological Units**	**Estimated Hydraulic Conductivity (m/s)**			**Average Thickness (m)**
			Kx	Ky	Kz	
Soils	I	Reddish oxisol and reddish yellow oxisol	$1x10^{-5}$	$1x10^{-5}$	$1x10^{-6}$	30
	II	Petroferric plintosol	$1x10^{-6}$	$1x10^{-6}$	$1x10^{-7}$	5
	III	Haplic cambisol	$1x10^{-7}$	$1x10^{-7}$	$1x10^{-8}$	1
	IV	Haplic gleisol	$1x10^{-7}$	$1x10^{-7}$	$1x10^{-8}$	5
Paranoá Group	V	Ribeirão da Contagem Fm.	$1x10^{-5}$	$1x10^{-5}$	$1x10^{-6}$	50
	V	Serra da Meia Noite Fm.	$1x10^{-5}$	$1x10^{-5}$	$1x10^{-6}$	150
	VI	Ribeirão do Torto Fm.	$1x10^{-6}$	$1x10^{-6}$	$1x10^{-7}$	150

Recharge

The recharge process occurs throughout the entire extension of the study area and is controlled by a wide range of factors that includes not only the climate components and their spatial distribution but also the particularities of the physical environment. Among these aspects, some must be highlighted, such as the hypsometry and geomorphic setting of the watershed, the properties of the regolith cover and the underlying rocks (and their interaction), as well as the anthropic interventions on the land use and occupation.

The geomorphological compartmentation of the Ribeirão Tortinho Watershed comprises two distinct patterns of landforms: high plateau areas and associated dissected valleys produced by stream erosion and incision. The infiltration rates tend to progressively decline from the upper plane areas, where it reaches its maximum, to the steeper slopes, where surface runoff predominates.

The highest elevations of the study area are located over an extensive flat area with declivity rates lower than 10%, covered by mature soil profiles developed from the quartzites of the Ribeirão da Contagem Formation. These pedologic covers, mainly composed by reddish oxisols and reddish yellow oxisols, display high values of hydraulic conductivity, corresponding to the main local recharge area, and also represent an important regional recharge zone. Moreover, these regions are also being studied for the application of artificial recharge (Cadamuro and Campos, 2015).

The growing urbanization of the Núcleo Rural Lago Oeste has reduced recharge as water flows over concrete and other urban elements rather than recharging the groundwater system and the associated aquifer. On the other hand, the Brasília National Park area within the watershed with mature soil profiles has the greatest recharge potential, where water infiltrates rapidly into the deep groundwater system.

Conclusion

The present study describes the characteristics of the Córrego do Ribeirão Tortinho watershed and includes the following: a compilation of available geologic, pedologic, hydrogeologic, and climatological data; information about groundwater wells in the study site; and the development of a three-dimensional conceptual geological model for the basin. The geological model will be used to build and calibrate the groundwater flow model. Through this approach, the data presented could be used to develop predictive hydrogeologic models of the basin and serve as a guide for water resources managers.

The conceptual geological model consists of six hydrostratigraphic units. The upper aquifer hydrostratigraphic units (porous domain) are represented by HU I to HU IV: (I) reddish oxisols; and reddish yellow oxisols, (II) petroferric plitonsols; (III) haplic cambisols, and (IV) haplic gleisols. The lower aquifer units, representing the fractured domain, corresponding to the R3/Q3 and A sub-systems. The first one is formed by the associations of the Ribeirão da Contagem and the Serra da Meia Noite formations (HU V). The A system, named HU VI, is represented by slates of the Ribeirão do Torto Formation. Each of these hydrostratigraphic units has singular properties such as hydraulic conductivities and thickness, that together with the associated relief form, will constitute and behave differently within the groundwater flow model.

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