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REGIONAL CHARACTERIZATION OF THE ENTRE RIBEIROS AQUIFER, NORTHWEST OF MINAS GERAIS STATE, BRAZIL

CARACTERIZAÇÃO REGIONAL DO AQUÍFERO ENTRE RIBEIROS, NOROESTE DO ESTADO DE MINAS GERAIS

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ABSTRACT - The Entre Ribeiros Aquifer is a virtually unknown groundwater reservoir located in the northeastern portion of the Paracatu County, northwest of Minas Gerais State, Central Brazil. The reservoir rocks are limestone, marl, siltstone and shale from the base of the Bambuí Group, including the Sete Lagoas and Serra de Santa Helena formations. Karstification processes are limited, since de limestone rocks are lenses interfingered with siltstone, marl and shale. The aquifer is classified as a fissure-karstic type, anisotropic and heterogeneous, confined by a shale layer. The main data obtained from wells dataset include: mean well discharge of 56 m^3/h (and outliers up to 100 m^3/h), hydraulic conductivity about 10^{-7} m/s, transmissivity varying from 10^{-3} to 10^{-5} m^2/s and average storage coefficient 10^{-4}. The fracturing-karstification interconnected index is estimated about 5% and the saturated thickness is considered as 100 meters. The total area of distribution of the Entre Ribeiros Aquifer is estimated at 5,500 km², what demonstrates its regional importance. In present days, the main use of the water in the region is for irrigation, which arises the concern of overexploitation risk. In this sense, it is important to apply management assessment actions, including water level monitoring, water availability estimations, combined use of groundwater and surface water sources and increase of surficial reservoirs (dams construction and tanks installation). The sustainability of the Entre Ribeiros Aquifer is important to keep the baseflow that feeds the Paracatu River in the rain recession period, and consequently, the São Francisco River discharge.
Keywords: Bambuí Group. Pumping test data. Fissure-karstic confined aquifer.

RESUMO - O Aquífero Entre Ribeiros é um reservatório de águas subterrâneas praticamente desconhecido, localizado na porção nordeste do município de Paracatu, noroeste do estado de Minas Gerais, Brasil Central. As rochas do reservatório são calcário, marga, siltito e folhelho da base do Grupo Bambuí, incluindo as formações Sete Lagoas e Serra de Santa Helena. Os processos de carstificação são limitados, uma vez que as rochas calcárias são lentes intercaladas com siltito, marga e folhelho. O aquífero é classificado como físsuro-cárstico, anisotrópico e heterogêneo, confinado por uma camada de folhelho. As principais informações obtidas a partir do conjunto de dados de poços incluem: vazão média de poço de 56 m³/h (e valores discrepantes de até 100 m³/h), condutividade hidráulica em torno de 10^{-7} m/s, transmissividade variando de 10^{-3} a 10^{-5} m²/s e coeficiente de armazenamento médio de 10^{-4}. O índice de fraturamento-carstificação interconectado é estimado em cerca de 5% e a espessura saturada é considerada como 100 metros. A área total de distribuição do Aquífero Entre Ribeiros é estimada em 5.500 km², o que demonstra sua importância regional. Atualmente, o principal uso da água na região é para irrigação, o que levanta a preocupação com o risco de sobrexplotação. Nesse sentido, é importante desenvolver ações de avaliação e gestão, incluindo monitoramento de níveis d'água, estimativas de disponibilidade hídrica, uso combinado de fontes subterrâneas e superficiais e aumento de reservatórios superficiais (construção de barragens e instalações de tanques). A sustentabilidade do Aquífero Entre Ribeiros é importante para manter o fluxo de base que alimenta o Rio Paracatu no período de recessão das chuvas e, consequentemente, a vazão do Rio São Francisco.
Palavras-chave: Grupo Bambuí. Dados de testes de bombeamento. Aquífero físsuro-cárstico confinado.

INTRODUCTION

The northwest region of Minas Gerais State, Brazil, presents extensive agricultural development, with the replacement of areas previously used for extensive livestock farming by irrigated agriculture. This process of changing pattern of land use is accompanied by an increase in water demand, since irrigation is the main consumptive use of water with around 50% of the withdrawal of water resources (Althoff & Rodrigues, 2019; ANA, 2021; Embrapa, 2024).

The center pivot system was the technique that had the greatest increase in area in the last two decades, being responsible for 40% of the total annual increase in irrigation systems. The total area occupied by center pivots in 2020 in the Cerrado Biome was 1,253,792 hectares, and the Minas Gerais State is the federation unit with the largest number, with 7,933 units at the beginning of the decade (ANA, 2021).

The Paracatu County, in the northwest of Minas Gerais, is delimited by 8,231 km² (IBGE, 2024). Due to the intense occupation by large rural properties, this region demands extensive water consumption and has an area of 72,727 hectares occupied with center pivots for irrigation (Embrapa, 2024). In the northeast portion of the county, the region named Entre Ribeiros stands out, with flat relief, predominance of thick soils, and low drainage density.

The period of rainfall recession characteristic of the Cerrado Biome presides as a water stress phase of the hydrological year, with low soil humidity, decreased flow rates in streams and springs, and a natural lowering of aquifer levels.

A large part of the surface water resources in the region is already compromised by the implemented irrigation systems, including the construction of dams and reservoirs in the largest watercourses. Therefore, the expansion of water supply in the Entre Ribeiros region has been achieved through the construction of wells with depths varying from 100 to greater than 200 meters. The flow rates of these wells vary from 8 to 100 m³/h and specific capacities vary from 0.14 to 12.85 m³/h/m.

The Entre Ribeiros Aquifer is the main aquifer in the northwest of Minas Gerais and extends along the left bank of the Paracatu River, which is the main tributary of the São Francisco River in the upper watercourse of the Basin. It is a mixed aquifer, represented by carbonate rocks associated with non-carbonate rocks (mainly pelitic rocks) from the base of the Bambuí Group that presents, simultaneously, secondary planar porosity and secondary porosity due to karst dissolution. Its exploitation occurs jointly, being a single hydrostratigraphic unit (Campos et al., 2022).

The Bambuí Group makes up an extensive cover over the São Francisco Craton and throughout the entire outer portion of the Brasília Fold Belt, generating distinct hydraulic behaviors in each context. In the first case, the facies of the Sete Lagoas and Serra de Santa Helena formations are exclusively carbonate (Dardenne, 1978) and occur as thick and continuous layers, composing classic karst aquifers.

However, in the Brasília Fold Belt the same formations constitute fissure-karstic aquifers, where limestone lenses are associated with pelitic rocks, which can be homogeneous or heterogeneous. When homogeneous, they are composed of continuous layers of impure limestone rocks (marls) and once heterogeneous, are formed by lenses of carbonate rocks with restricted lateral continuity, interfingered vertically and laterally with poorly permeable rocks, such as siltstone, shale, phyllite or schist (Rodrigues et al., 2023).

Commonly, the geological unit linked to the aquifer is used to name the aquifer. However, there are some cases in which the choice is associated with regional issues, such as the transboundary Guarani Aquifer (Araújo et al., 1999), Mangue de Pedras Aquifer (Albuquerque et al., 2022), the Floridan Aquifer (Plummer, 1977), among others.

Since there is already a groundwater reservoir named as the Bambuí Aquifer (Souza et al., 2014 and Theodoro et al., 2019), Campos et al. (2022) named as Entre Ribeiros Aquifer the groundwater reservoir, in reference to the Entre Ribeiros region, the area where most of the aquifer occurs. The Bambuí Aquifer is located in the cratonic region with hydraulic behavior different from that observed in the study area.

When considering the high potential of this groundwater reservoir, the increased sensitivity and vulnerability in relation to the pumping of its waters, this work aims to formalize the name of the Entre Ribeiros Aquifer and characterize it in all its aspects, from its geographic distribution area, hydraulic interactions, circulation conditions from recharge to discharge, its water availability and exploration conditions.

The characterization of the Entre Ribeiros Aquifer is necessary and justified due to the limited knowledge about this groundwater reservoir, which shows good exploitation conditions, and is at the beginning of intensive pumping. Furthermore, analyzing the sustainability of aquifer exploitation is essential for maintaining the integrity of the water resources. Excessive water pumping from this aquifer can cause the lowering of the potentiometric surface, decrease in surface water flows, drought of springs, and interference in surface watercourses, overexploitation and collapses in supply systems.

Preliminary information indicates that the discharge of the Entre Ribeiros Aquifer occurs directly into the Paracatu River, and its eventual overexploitation or pumping pressure could affect the flow of this important tributary of the São Francisco River, responsible for maintaining a large part of its flow during the period of rain recession (Campos et al., 2022).

The main objective of this research is the regional description of the Entre Ribeiros Aquifer, including hydrodynamic parameters, thickness, conceptual model, distribution area and potential.

MATERIAL AND METHOD

This research was developed based on a set of actions that are traditionally applied to hydrogeological studies, including geological and pedological description, interpretation of pumping test data, evaluation of deep well logs, description of gutter samples, soil infiltration tests and flow characterization.

To determine local recharge conditions, infiltration tests were carried out in each mapped soil class. The techniques adopted were the "concentric rings" and the "open end hole" methods to determine the vertical hydraulic conductivity on the surface and in depth, respectively.

To distinguish the hydrochemical signature, *in situ* measurements of physicochemical parameters were made, including pH, temperature, oxidetion-reduction potential and electrical conductivity, with the aid of portable multi-parameter equipment.

The data on the water points, considered essential for the aquifer characterization were obtained from the registry of the Geological Survey of Brazil (Groundwater Information System Platform - SIAGAS) and from companies specialized in well construction. All the wells in the dataset were visited in fieldwork. The main information is listed below:

- Inventory of water points consisting of 87 deep tubular wells, distributed along all the aquifer extent;

- Detailed assessment of pedo-geological and construction wells logs (available for the majority of the study wells);

- Gutter samples, whose study and description were fundamental for understanding the lateral distribution of rock types and their depth projection;

- Data from long period pumping tests (with drawdown and recovery information) carried out in the final stages of well construction. This dataset allowed getting data on discharge rates, static and dynamic level, drawdown and specific capacity. These data were conducted by specialized companies and are considered coherent and reliable.

The wells report data include both, pedo-geological log (rock and soil description, fractures depth, size of the fragments, presence of calcite veins and units contacts) and construction log (total depth, diameter, screen depth, casing section, and depth of open well). Besides the material and construction information, the well data includes hydrodynamic facts, as static and dynamic levels, discharge rates, and pumping test data).

The hydraulic parameters (hydraulic conductivity, transmissivity and storage coefficient) were determined by interpreting the results of pumping tests data using the *Aquifer Test Pro* software. To the treatment of pumping test data, the following procedures were adopted:

i) Distance of 1 meter between the pumping and the observation well, since the lowering measures were carried out in the pumping well itself;

ii) The methods of Theis (1935), Hantush (1956) and Warren & Root (1963) were applied, since they presented the best fit between the theoretical and the drawdown data curve. Likewise, they are also the methods that best fit to the conceptual model of the aquifer.

The knowledge of the information on the pedo-geological and construction wells logs is fundamental for classifying the aquifer in a conceptual model and, thus, evaluating the coherence of the results obtained.

The soil taxonomy was assigned after fieldwork profiles description based on the techniques and classification purposed by Embrapa (2018).

After opening and cleaning the profiles (in roads cuts), the horizons are distinguished and the color, texture, structures, consistencies, biological activities and parental material are described.

The delimitation of the aquifer occurrence area was conducted by the integration of different source information, including wells data or wells battery data (main information), relief pattern (lowlands with small topographic range), soil types distribution (main reddish and yellow oxisol) and drainage pattern and density. Due to the heterogeneous data availability, two polygons were purposed: defined and inferred limits.

CHARACTERIZATION OF THE STUDY AREA

The distribution area of the Entre Ribeiros Aquifer is located in the northeast portion of the Paracatu County, Minas Gerais State, Central Brazil, and makes up an irregular polygonal in the Paracatu River Plain, including the valley of its tributaries on the left bank: Rico Creek and the São Pedro Stream, Preto River and Entre Ribeiros Stream (Figure 1).

The climate is typical of the cerrado region, associated to the alternation of two seasons, characterized by a dry winter and a rainy summer. The average annual precipitation is 1,400 mm (Climatedata, 2025), strongly concentrated between the months of December and April, with a significant water deficit between the months of May and September.

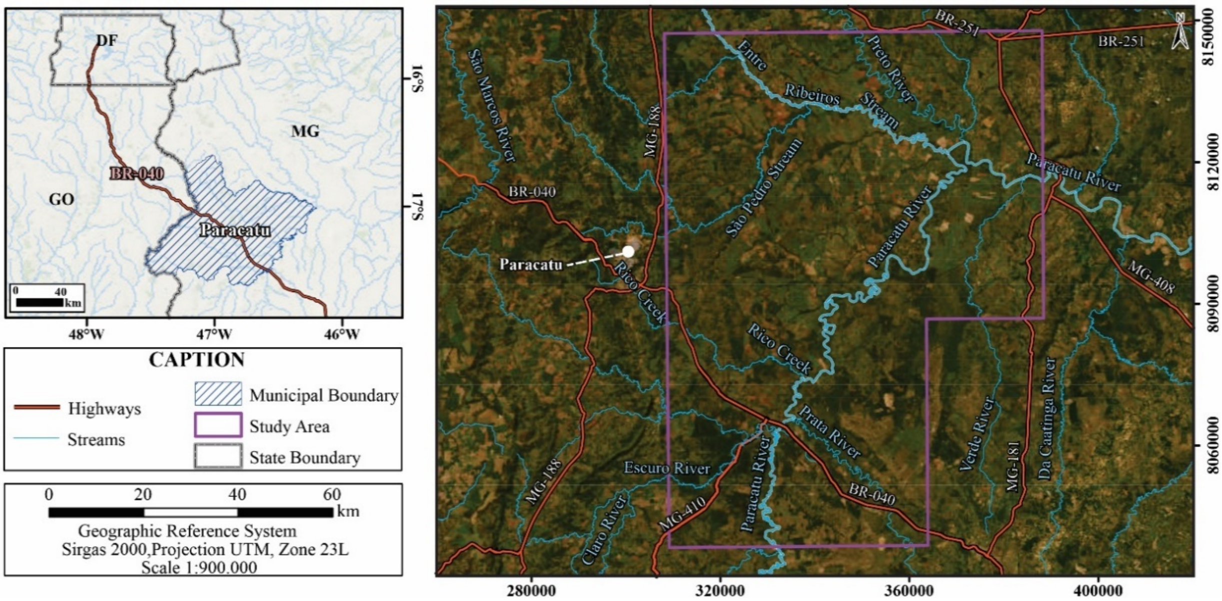

Figure 1 - Location of the study area (northwest of Minas Gerais State, Central Brazil).

This aquifer is located in the São Francisco Hydrogeological Province, in the external zone of the Brasília Fold Belt (Pessoa et al., 1980; Almeida et al., 1981). It is composed of carbonate lenses interbedded and interfingered with pelitic rocks from the Sete Lagoas and Serra de Santa Helena formations at the base of the Bambuí Group. Regionally, the aquifer is located east of the regional thrust fault that marks the contact between the sediments of the Vazante and Bambuí groups (Dardenne, 1978).

The regional distribution of the Entre Ribeiros Aquifer is estimated at 5,500 km². To delimit the area of occurrence of the aquifer, data from deep wells distributed mainly in the central and northern portions were used. In the southernmost, the absence of well data did not allow the precise delimitation.

The geomorphology in the aquifer region occurrence is homogenous with a plain pattern (with altitude ranging from 560 to 500 meters), low watercourses density, small streams controlled by structures and major rivers showing a regional meandering pattern. Regionally the area represents the left margin (northwest margin) of the Paracatu River Valley.

Figure 2 presents the distribution of the aquifer from two perspectives: i) the area whose delimitation has the largest number of wells and which, in association with the relief pattern, soils and geological context, allowed a safe delimitation (yellow line); ii) the limit considered inferred, which is proposed based on the correlation of physiographic features and continuity of the geological setting (blue line).

The following classes of soil cover were identified: oxisols (Latosol), plinthosols, inceptsols (Cambisol) and gleysols. Oxisols are reddish and yellow-reddish, have a clayey texture and coarse aggregate and micro aggregate structures.

They originate from the pedogenesis of pelitic materials from the disintegration of shales and

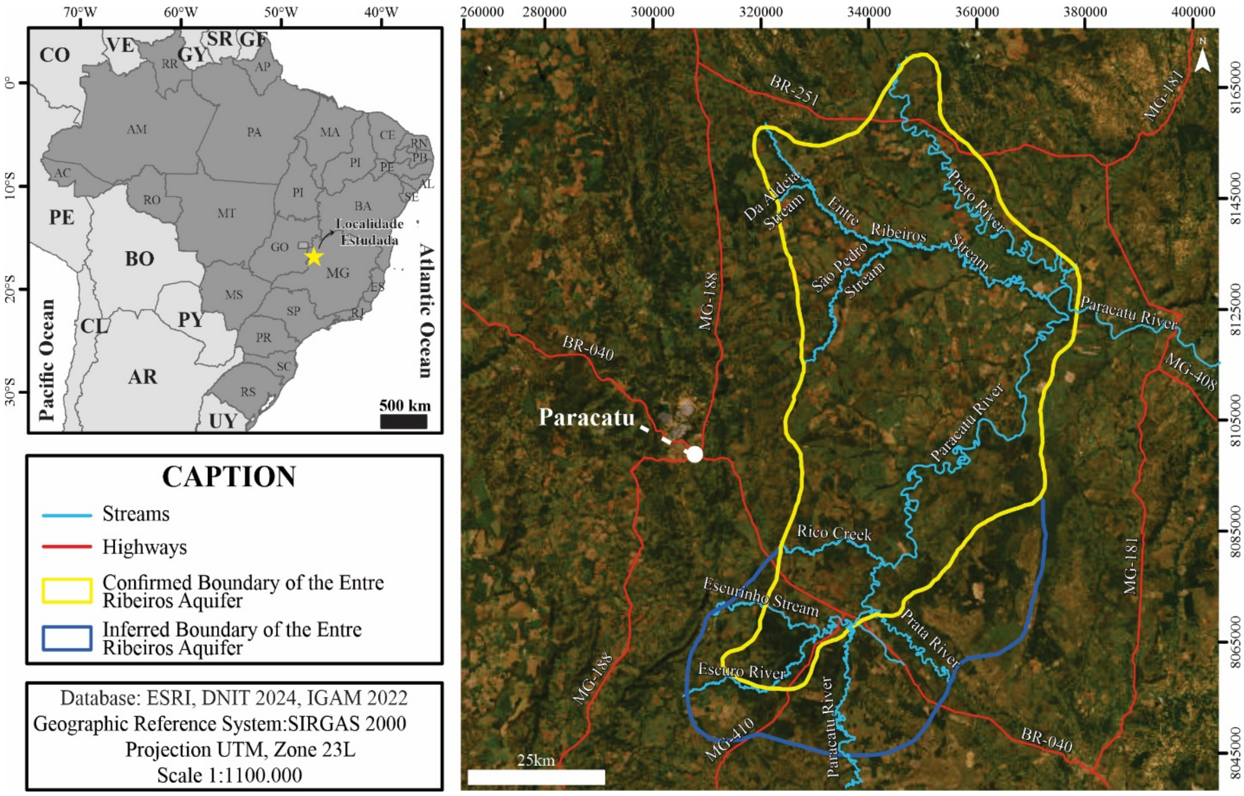

Figure 2 - Regional distribution of the Entre Ribeiros Aquifer. Area delimited in yellow, established limit: 4,087 km². Area defined in dark blue, inferred limit: 1,369 km².

marls from the Serra de Santa Helena Formation of the Bambuí Group. These soils are associated with the interior areas of the plateaus with a flat to gently wavy relief pattern, with great lateral continuity and largely predominate in area.

The widespread distribution of oxisols is a favorable factor for water resources, since these soils have a large capacity for infiltrating precipitation water, being an excellent regulator of surface and groundwater systems.

Plinthosols occur in small areas where plintic horizons are exposed or present at shallow depths. Inceptsols occur on slopes of watercourses with deeper valleys and are restricted in area.

Gleysols are characterized by poor drainage and strong hydromorphism. They occur in relief depressions or in marginal areas of shallow lakes. The grayish or whitish color of the Bg horizon, the clayey texture and coarse aggregate structure are diagnostic of this soil class.

RESULTS AND DISCUSSIONS

The Entre Ribeiros Aquifer

The Entre Ribeiros Aquifer is described as a single reservoir once it shows a heterogeneous behavior and a unique hydraulic functioning over all the occurrence distribution. Groundwater reservoirs are treated as an Aquifer System (like the Guarani or the Urucuia) when there are different subtypes or contrasting flow conditions (confined, unconfined, perched setting, intergranular or double porosity media, regional and flow systems and so one).

Although, it is related to a heterogeneous geology, the study reservoir is defined as a particular aquifer, because there is no significant contrasting in the transmissivity and storage coefficient over the different areas of occurrences. In this sense, the study groundwater reservoir cannot be described as an aquifer system, but must be defined as an individual aquifer.

Conceptual Model

Classifying an aquifer in an appropriate conceptual model is important not only from a theoretical point of view, but also for validating hydraulic parameters, understanding the water level fluctuations, preparing processes for granting rights, estimating water reserves, developing artificial recharge projects and, ultimately, for the groundwater management (Rodrigues et al., 2023).

Direct access to the aquifer is carried out through sampling in deep or monitoring wells, and in springs (Rodrigues & Campos, 2024). Therefore, the hydrogeological model of the aquifer study area is proposed based on the descriptions of the pedo-geological and construction of wells logs, as well as the analysis of the hydraulic parameters (hydraulic conductivity, transmissivity and storage coefficient) obtained from the pumping tests data.

Campos et al. (2022) indicate the existence of two overlapping aquifers in the study area: i) intergranular, unconfined aquifer, hosted in clayey oxisols and saprolites arising from the weathering of pelitic rocks from the Sete Lagoas and Serra de Santa Helena formations of the Bambuí Group and ii) aquifer classified as semiconfined fissure-karstic (overlap by a siltstone layer) associated with limestone lenses interfingered with siltstones, shales and marls (Figure 3).

The confining layer is represented by siltstones and clayey siltstones with variable thickness, depending on folding, erosion and pedogenesis, averaging 50 meters.

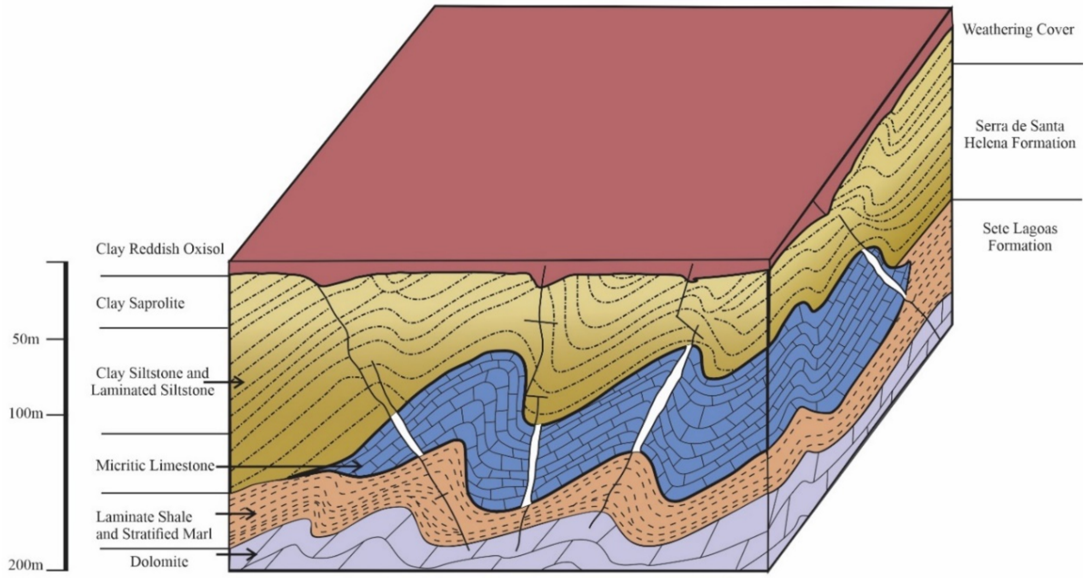

Figure 3 - Diagram block with schematic representation of the different types of rocks that make up the Entre Ribeiros Aquifer. This groundwater reservoir fits the conceptual model of fissure-karstic aquifer and occurs under siltstones and soils attributed to the weathering of pelitic rocks at the base of the Bambuí Group (Sete Lagoas and Serra de Santa Helena formations).

Intergranular Phreatic Aquifer

It is represented by a cover of structured clay oxisols and saprolite, which generate a continuous and unconsolidated, relatively homogeneous layer with a thickness varying from 10 to 20 meters. As it goes deeper into the soil profile, the hydraulic conductivity values decrease, ranging from 10^{-4} to 10^{-6} m/s.

This phreatic aquifer plays an important role in the recharge processes of the underlying aquifers, as it functions as a layer that retains a large part of the rainwater and transmits it to the deep aquifer by descending vertical flow.

It also has a regulatory function for surface watercourses and lakes in the region, since its base flow feeds the superficial water bodies (springs, streams and lakes).

Fissure-Karstic Aquifer

The outcrops in the study area are very restricted, so it was necessary to interpret information from the correlation between regional stratigraphy and geomorphology with the descriptions of wells logs. With the data from the pedo-geological logs and the descriptions of the gutter samples, it was possible to identify the heterogeneity of the aquifer, which is composed of limestone and dolomite lenses of a few kilometers in length and tens of meters in thickness, interfingered vertically and laterally with siltstone, shale and marl (Figure 4).

Despite the existence of carbonate rocks in the region, karstic features are rare and poorly developed, with only elongated lakes and humid lands being observed, which are interpreted as residual karstic features, represented by ancient subsidence depressions and soil collapses. Karstic cavities are rare in well descriptions, and when wells intersect dissolution voids, they are small. Other karstic features such as speleothems, sinkholes, springs and others are not present, as there are no exposures of carbonate rocks throughout the aquifer entire area of occurrence.

The deep wells show specific capacities ranging from 0.1420 to 3.6363 $m^3/h/m$ (and an outlier value of 12.8571 $m^3/h/m$) and an average of 2.1465 $m^3/h/m$, in addition to flow rates of 8 to 100 m^3/h with an average of 56 m^3/h (Table 1 and Figure 5).

These contrasting values show the great heterogeneity of the aquifer and show favorable

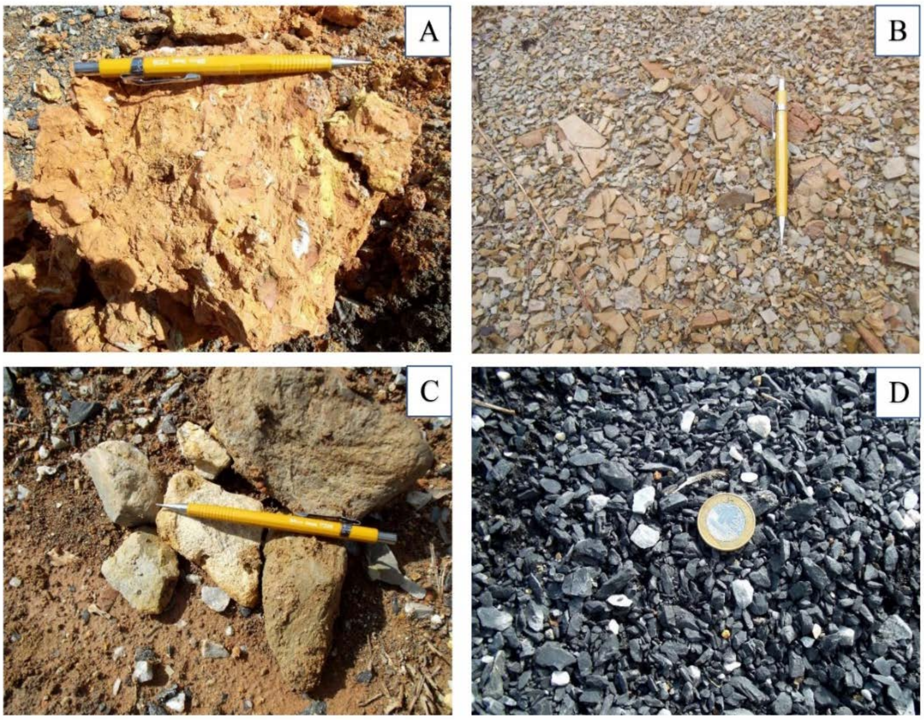

Figure 4. A. Weathered shale of the confining layer (about 30 meters depth). **B.** Weathered siltstone correlated to the Sete Lagoas Formation. **C.** Marls fragments, after carbonated dissolution. **D.** Black micritic limestone related to the main reservoir rock.

Table 1 - Main wells data. **Q** = Pumping rate; **WLPB** = Water level before pumping; **SL** = Stabilized level; **Sw** = Drawdown; **Spec. Cap.** = Specific Capacity. Well ID: **VPD** = Vale do Paracatu Distillery; **IF** = Imperial Farm; **SRF** = Santa Rosa Farm; **SBF** = São Bento Farm; **TSF** = Terra Santa Farm.

Well	Depth (m)	Q (m^3/h)	WLBP (m)	SL (m)	Sw (m)	Spec. Cap. ($m^3/h/m$)	Recover time (min)	Regolith thickness (m)
VPD-1	258	8	7	40	33	0.242424	-	48
VPD-2	150	15.2	9	107	107	0.142056	60	17
VPD-3	144	84	13	100	87	0.965517	30	39
VPD-4	150	44	13	120	107	0.411214	30	34
VPD-5	150	58	16	90	104	0.557692	32	42
VPD-6	162	44.6	11	100	89	0.501123	30	42
VPD-7	150	27	15	105	90	0.30	35	37
VPD-8	138	100	17	90	73	1.36986	35	52
VPD-9	132	61	14	84	70	0.885714	29	42
VPD-10	192	15	17	80	63	0.238095	50	40
IF-1	61.5	135	27	45	18	7.5	40	31
IF-2	142	75	5	95	90	0.8333	55	41
IF-3	114	95	4	70	66	1.4393	48	42
IF-4	84	96	3	55	52	1.8461	24	37
IF-5	72	97	5	52	47	2.0638	34	34
SRF-1	160	18	9	80	71	0.2535	70	36
SRF-2	48	90	23	30	7	12.8571	14	41
SRF-3	160	35	23	110	87	0.4022	20	39
SRF-4	160	22	15	50	35	0.6285	20	37
SRF-5	54	90	12	20	8	11.25	22	29
SRF-6	72	80	19	40	21	3.8095	20	40
SBF-1	105	40	5	16	11	3.6363	50	62
SBF-2	96	37	6.5	29	22.5	1.68	60	42
SBF-3	102	51	5	12	7	7.4	35	58
SBF-4	96	44	3	42	39	1.1282	60	42
SBF-6	90	45	6	29	23	1.9565	50	60
SBF-7	82	80	3	68	65	1.2307	60	38
SBF-8	102	30	1	42	41	0.7317	50	35
SBF-9	60	80	11	45	34	2.3529	65	41
TSF-1	128	36	9.37	78.50	69.13	0.52	48	30
TSF-2	140	45	11.38	72.43	61.05	0.74	63	30
TSF-3	120	35	10.54	70.53	59.99	0.59	52	30
TSF-4	100	51	16.05	56.11	35.02	1.45	60	45
TSF-5	100	45	16	58	42	1.07	101	45
Average	120	56	11.2	64.1	54	2.1465	44	40

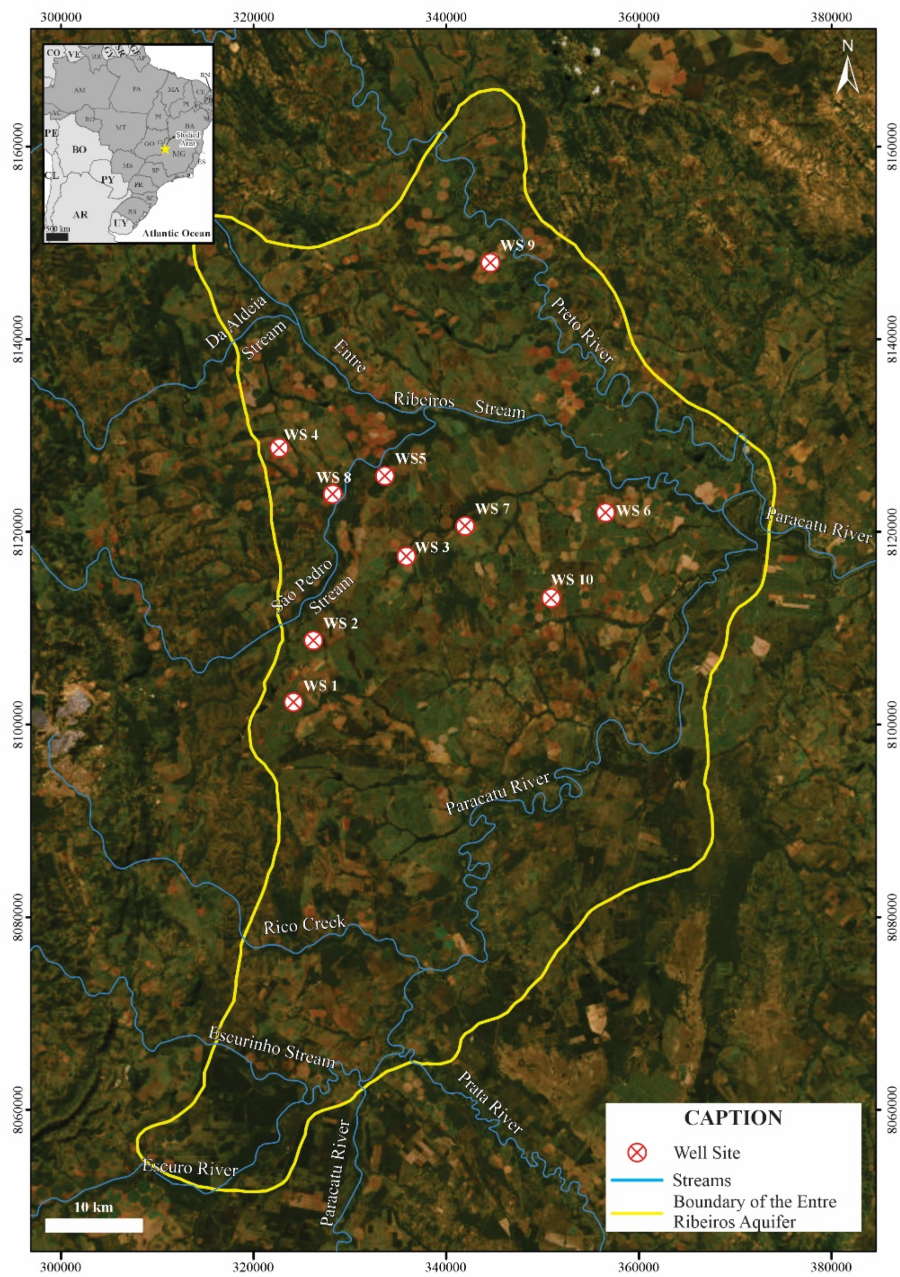

Figure 5 - Location of wells applied to the hydraulic characterization of the Entre Ribeiros Aquifer. Each well site represent a group of 6 to 10 wells.

exploitation conditions, in which the average specific capacity, which can be considered the reference value for the aquifer as a whole, is of the order of 2.0 $m^3/h/m$.

The fissure-karstic conceptual model was constrained due to significant differences from the classical karstic medium (Rodrigues, 2022). The main contrasts from the Entre Ribeiros and karstic aquifers are the absence of karstic features and landscapes (as caves, sinkholes, speleothems, blind streams) and the dimensions of the carbonate rocks. In classic karsts terrains the carbonate rocks occur in thick and continuous layers, the water shows higher hardness, alkaline pH and higher water total dissolved solids (Rodrigues et al., 2023).

The main difference of the mixed fissure-karstic from de karstic systems is the dissolution rates and the size of the conduits. In fissure-karstic medium, the porosity is due to vugs and small dissolution holes, while in the karstic aquifers the cavities are larger and more continuous. The karstification is higher because of the greater thickness and lateral continuity of the carbonate rocks.

The hydrodynamic parameters that characterize the Entre Ribeiros Aquifer were obtained from data long pumping tests (minimum 24 hours) with a constant and continuous flow.

It is important to highlight that the data used to estimate the parameters were obtained from wells with a high level of knowledge, when pedo-geological and construction logs are available.

The hydraulic conductivity is variable between orders of magnitude ranging from 10^{-5} to 10^{-7} m/s, with the modal value in the order of 10^{-7} m/s. The transmissivity varies between orders of magnitude from 10^{-3} to 10^{-5} m²/s, with the saturated thickness considered as the depth reached by the well subtracting the confining layer thickness.

The storage coefficient varies between 10^{-3} and 10^{-5}, with the modal value around 10^{-4} (Table 2).

Table 2 - Hydrodynamic parameters of reference wells distributed over the Entre Ribeiros Aquifer.

Well	K (m/s)	T (m²/s)	S
VPD-1	1.60×10^{-7}	6.88×10^{-6}	8.53×10^{-4}
VPD-2	1.18×10^{-6}	5.06×10^{-6}	8.89×10^{-4}
VPD-3	6.15×10^{-7}	3.88×10^{-5}	3.90×10^{-3}
VPD-4	3.28×10^{-7}	1.74×10^{-5}	3.16×10^{-3}
VPD-5	5.90×10^{-6}	4.16×10^{-5}	5.55×10^{-3}
VPD-6	4.15×10^{-7}	2.20×10^{-5}	3.27×10^{-5}
VPD-7	3.13×10^{-7}	1.97×10^{-5}	3.54×10^{-3}
VPD-8	3.27×10^{-7}	2.06×10^{-5}	5.78×10^{-3}
VPD-9	3.42×10^{-7}	2.15×10^{-5}	6.96×10^{-3}
VPD-10	1.60×10^{-7}	4.13×10^{-6}	2.09×10^{-3}
IF-1	8.86×10^{-6}	5.41×10^{-4}	3.14×10^{-4}
IF-2	2.12×10^{-6}	3.00×10^{-4}	1.74×10^{-5}
IF-3	3.34×10^{-6}	3.81×10^{-4}	2.21×10^{-3}
IF-4	4.58×10^{-6}	3.85×10^{-4}	2.23×10^{-5}
IF-5	5.40×10^{-6}	3.89×10^{-4}	2.26×10^{-3}
SRF-1	3.11×10^{-7}	4.98×10^{-5}	4.48×10^{-5}
SRF-2	5.25×10^{-5}	2.52×10^{-3}	1.98×10^{-3}
SRF-3	4.80×10^{-7}	7.68×10^{-5}	1.74×10^{-4}
SRF-4	7.82×10^{-7}	1.25×10^{-4}	4.37×10^{-5}
SRF-5	4.11×10^{-5}	2.22×10^{-3}	1.31×10^{-3}
SRF-6	1.05×10^{-5}	7.53×10^{-4}	4.16×10^{-4}
SBF-1	1.18×10^{-5}	1.24×10^{-3}	5.06×10^{-5}
SBF-2	4.82×10^{-6}	4.63×10^{-4}	5.11×10^{-5}
SBF-3	1.30×10^{-5}	1.32×10^{-3}	1.48×10^{-2}
SBF-4	2.35×10^{-6}	2.26×10^{-4}	6.35×10^{-4}
SBF-6	3.64×10^{-6}	3.27×10^{-4}	5.09×10^{-3}
SBF-7	4.66×10^{-6}	3.82×10^{-4}	6.45×10^{-5}
SBF-8	2.44×10^{-6}	2.49×10^{-4}	1.10×10^{-5}
SBF-9	1.53×10^{-5}	9.17×10^{-4}	4.17×10^{-6}

K = hydraulic conductivity; **T** = transmissivity; **S** = storage coefficient; Well ID: **SRF** = Santa Rosa Farm; **VPD** = Vale do Paracatu Distillery; **IF** = Imperial Farm; **SBF** = São Bento Farm.

The wells production and hydrodynamic parameters contrasting values observed in the Entre Ribeiros Aquifer are coherent with the conceptual model of a fissure-karstic aquifer, which presents a high degree of anisotropy and heterogeneity (Rodrigues et al., 2023).

Figure 6 shows graphical distribution of hydraulic and dimensional constraints that discriminate the fractured, karstic and fissure-karstic aquifers types. The mixture aquifer category displays transitional hydraulic conductivity and specific capacity of wells when compared to the fractured and classical karstic reservoirs.

The same behavior is observed in the assessment of total porosity and diameter of pores and conduits. In this sense, the open spaces are much smaller in the fissure-karstic media in comparison to the classical karstic observed in thick and continuous carbonate rocks successions.

The storage coefficient values confirm the conceptual model, which demonstrates that, it is an aquifer with a high degree of confinement, varying from semiconfined to fully confined, with the confining layer represented by shale and clayey siltstone of the Sete Lagoas and Serra de Santa Helena formations.

The confining layer is overlain by soil and saprolite that form an unconfined, relatively homogeneous and isotropic intergranular aquifer (Figure 7). Thus, the Entre Ribeiros Aquifer is classified as fissure-karstic, semiconfined to confined, with strong anisotropy and heterogeneity.

This information can be corroborated by analyzing the behavior of dynamic levels and the reestablishment of the potentiometric surface after the pumping system is turned off. The wells have static levels between 1 and 27 meters and very deep dynamic levels, reaching up to 120 meters.

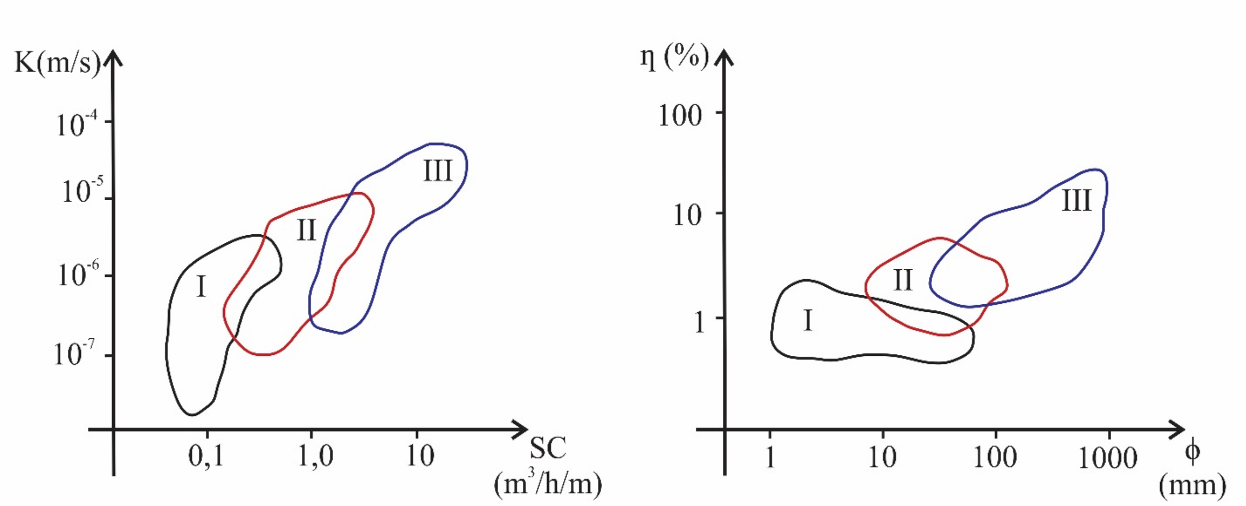

Figure 6 - Graphical distribution comparing fractured (**I**), fissure-karstic (**II**) and karstic (**III**) aquifers. **K** - Hydraulic conductivity; **SC** - Specify capacity; .**η** - Total porosity and **ϕ** - Porous or conduits diameter. Values achieved from different database: Freeze and Cherry (1979), Custódio and Llamas (1983), Driscoll (1995), Fetter (2001), White (2002), Singhal and Gupta (2010), Robineau et al. (2018), Valigi et al. (2021); Rodrigues et al. (2023); Ma et al. (2024); Ostad et al. (2024).

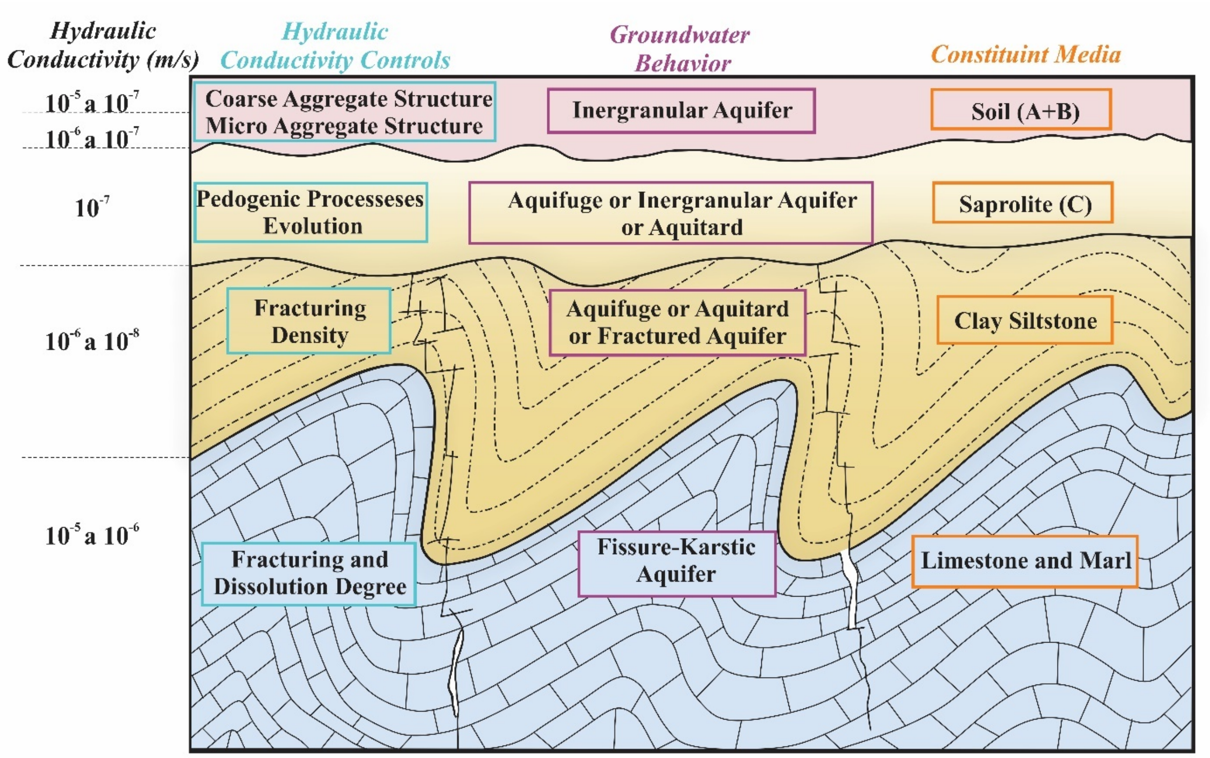

Figure 7 - Schematic illustration showing the hydrogeological functioning of the different layers that make up the Entre Ribeiros Aquifer and the controls on hydraulic conductivity. Magnitude orders values for hydraulic conductivity are proposed from different sources: *in situ* infiltration tests, pumping tests and analogy with similar systems.

The storage coefficient values confirm the conceptual model, which demonstrates that, it is an aquifer with a high degree of confinement, varying from semiconfined to fully confined, with the confining layer represented by shale and clayey siltstone of the Sete Lagoas and Serra de Santa Helena formations.

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This information can be corroborated by analyzing the behavior of dynamic levels and the reestablishment of the potentiometric surface after the pumping system is turned off. The wells have static levels between 1 and 27 meters and very deep dynamic levels, reaching up to 120 meters.

However, the recovery of static levels, after the end of continuous 24-hour pumping, occurs between 24 and 101 minutes (with an average of

44 minutes).

The upper unconfined aquifer is composed of the weathering soil cover that includes the pedum horizons and the saprolite. The upper portion is represented by the horizons of thick oxisols, where hydraulic conductivity is controlled by the structuring of the constituent material.

The A horizon has a well-developed coarse aggregate structure and a hydraulic conductivity value between 10^{-5} and 10^{-6} m/s. As it goes deeper into the soil profile, the structure of the B horizon becomes micro aggregate and, as a result, there is a reduction in the permeability coefficient to 10^{-7} m/s.

The saprolite belong to the upper unconfined hydrostratigraphic unit and it is the result from the siltstone alteration that occurs underneath.

This portion of the soil profile can also play as an aquitard as the degree of weathering increases. As there is no longer any preserved structure in the saprolite, the hydraulic conductivity is influenced by the clayey texture, reaching variable values between 10^{-7} and 10^{-8} m/s.

The confining layer consists of folded and fractured clayey siltstone and shale, 20 to 40 meters thick. Based on its petrographic characteristics, its hydraulic conductivity is variable, with values between 10^{-6} and 10^{-8} m/s and, therefore, it can present different hydrogeological behaviors, depending on its thickness and fracturing degree.

Places where shale and siltstone show greater thickness, massive or slightly fractured, the confining layer must play as an aquifuge and the Entre Ribeiros Aquifer will be classified as fully confined. In portions where clayey and silty rocks are very fractured and with maximum connection of these structures, the confining layer should play as an aquitard and, in this case, the Entre Ribeiros Aquifer will be classified as a semiconfined aquifer.

The fracturing degree will be responsible for determining leakage by vertical downward flow of water from the aquitard towards the confined aquifer. In addition, to playing as an aquitard or an aquifuge, the clayey siltstone and shale layer also represents an independent aquifer classified as fractured, anisotropic and heterogeneous.

The aquifer confined portion fits into the conceptual model of a fissure-karstic aquifer composed of lenses of carbonate rocks of limited thickness (including limestones and dolomites) laterally and vertically interfingered with pelitic rocks (marls and shales).

The hydraulic conductivity of this portion of the aquifer is controlled by the fracturing degree of clayey rocks and the dissolution degree of carbonate rocks.

Physical-Chemical Conditions of Water

Water was sampled at deep wells and dig wells used to supply the Vale do Paracatu Distillery, Imperial Farm and a lake (UTM coordinate 332.216 W and 8.114.631 S). The parameters were obtained using portable multiparameter equipment to determine electrical conductivity, temperature, pH and oxidation-reduction potential (Table 3).

The data shows a strong contrast between shallow groundwater and surface water, compared to the deep aquifer. The electrical conductivity of the fissure-karstic aquifer is moderate, typical of the proposed hydrogeological model. In case of a greater contribution of pure carbonates and a smaller contribution of marls, higher values would be predicted. In the phreatic aquifer the reduced value indicates that rainwater is in contact with inert material, represented by oxisols.

Table 3 - In situ measure of physical-chemical data of water samples from different media.

Wells Parameter	VPD-3	VPD-6	VPD-8	VPD-9	IF-1	Shallow Well	Lake
EC (μS/cm)	91.1	83.3	100.6	107.8	109.4	25.7	15.5
Temp. (°C)	29.3	26.2	28.8	25.6	27.3	24.9	27.6
pH	8.27	8.32	8.36	8.38	7.98	5.8	5.4
Eh (mV)	-78.0	-80.2	-83.4	-84.5	-57.30	+66.4	+73.3

EC = Electrical Conductivity; **Temp**. = Temperature; **VPD** = Vale do Paracatu Distillery; **IF** = Imperial Farm.

The pH rates follow the same pattern, with an alkaline value for deep wells and an acidic value for the dig wells and lake waters. The value close to 8 is consistent with the dissolution of carbonate rocks associated with the fissure-karstic aquifer. Values lower than 6 for groundwater and surface water also reflect the pH close to the rainwater.

The water electrical conductivity has a strong relationship with the total dissolved solids, and, for a general approximation, the relationship EC = 1,8 x TDS can be applied. Therefore, it can be stated that the waters of the Entre Ribeiros Aquifer present low to moderate mineralization, and can be applied to any type of application, including human consumption and irrigation.

The contamination risks of the Entre Ribeiros Aquifer are considered restricted, since it is covered by a thick weathering soil cover, and a confining layer, and therefore infiltration waters must percolate approximately 40 meters before reaching the saturated zone of the fissure-karstic aquifer.

Preliminary proposition of recharge and discharge areas

The entire aquifer exposure projection, regardless of the type of soil or outcropping rock, is considered a potential recharge area for the underlying aquifers (Campos et al., 2022). In the study region, the potential recharge zone corresponds to the polygon itself, delimited by the occurrence of the unconfined phreatic aquifer that overlaps the Entre Ribeiros Aquifer. The phreatic aquifer has good recharge conditions, as it is located in a region with moderate rainfall with 1400 mm/year average, soils with high hydraulic conductivity and flat relief.

During the rainy season (November to March), part of the water that infiltrates the shallower aquifer can migrate by downward vertical drainage towards the deep fissure-karstic aquifer, which characterizes its potential recharge. The effective recharge of the Entre Ribeiros Aquifer will depend on the behavior of the confining layer.

Areas where siltstone perform an aquifuge function, recharge is considered null. In areas where the confining layer is an aquitard, there may be recharge from leaking or vertical flow towards confining aquifer, and part of the water stored in the aquitard can represent effective recharge. It is estimated that this process should be more active along regional fault zones that are capable of connecting porosity to the confined aquifer in a more effectively way (Fetter, 2001).

The regional discharge zone is defined by the Paracatu River itself, based on lateral and upward flow. The altimetric relations between the phreatic aquifer and the confining layer base (550 m) prove that the valley occurs at elevations close to the interface of the outcrop of the limestone lenses at the base of the Bambuí Group, causing direct discharge of the Entre Ribeiros Aquifer into the Paracatu River (500 m). The confining layer and the phreatic aquifer thickness is about 40 to 50 meters, and the river valley erosion is enough to expose the confined aquifer.

The local discharge is related to the phreatic aquifer and is represented by the surface drainage network, linked to the oxisols and by the lakes connected to the gleysols that occur in topographically depressed regions. Despite the low drainage density in the Paracatu Plain, specific flow values are high, even during the dry season, which demonstrates the importance of the phreatic aquifer for maintaining perennial and regularizing flows.

CONCLUSIONS AND FINAL REMARKS

Aquifer exploitation sustainability assessing is fundamental for water resources maintenance in an integrated point of view. The Entre Ribeiros Aquifer is practically unknown, both from a scientific and exploitation standpoint (Campos et al., 2022). This aquifer fits into semiconfined to fully confined fissure-karstic conceptual model and its exploitation is mainly used for irrigation by center pivot system.

Dataset applied to the aquifer assessment and parameters definition is coherent, mainly composed of well informations in which the pedo-geological and constructive logs are established and reliable.

The pumping test with drawdown and recovery water levels data were applied to the hydrodynamic parameters acquisition. Transmissivity variability and storage coefficient are coherent to the conceptual model of a confined fissure-karstic aquifer, hosted in lenses of carbonate rocks interfingered with siltstone, shale and marls. The rocks and facies arrangement are suitable with the Sete Lagoas and Serra de Santa Helena formations, base of the Bambuí Group.

Rodrigues (2022) and Rodrigues et al., (2023) presented the main controls, definitions and differences between the karstic and fissure-karstic aquifers. In these research results of many case studies and examples were described.

One of the examples applied to this issue was the contrast of the carbonate aquifers of the base of the Bambuí Group, comparing the occurrences in the craton and in the Brasília Fold Belt area. In the cratonic region the limestone occurs in thick and continuous layer and determine classic karstic environment. In the Brasília Fold Belt area the carbonate is in discontinuous lenses and in this condition generates fissure-karstic aquifers.

The differences of karstic and fissure-karstic aquifers are relevant and must be considered to development of management practices. The fissure-karstic aquifer shows intermediate conditions when compared to fractures and karstic media.

Depending on the dissolution rates, these aquifers can be similar to fractured rocks, or when the carbonate rocks surplus the non-carbonated, can be more comparable to the karstic reservoirs.

Water demands seasonal factor favors the aquifer sustainability, since in the regular and intense water rain period; the demand for irrigation is minimized. In this way, during some months of the hydrological cycle, it is possible to reduce pumping to favor the recharge and the recovery of potentiometric levels.

The Entre Ribeiros Aquifer has high hydrogeological potential, with a great water production capacity. Paracatu River Valley region on its west bank (between the confluence of Prata River and Preto River) has low drainage density, due to the natural environment itself, characterized by flat relief covered by oxisols. Thus, the use of groundwater is the best option for irrigation, and in case of pumping rates are considered consistent with the aquifer capacity, production can result in a sustainable system.

The Entre Ribeiros Aquifer sustainable exploitation is important to prevent future interference and reduction in the flow of the Paracatu River, which is the main tributary of the São Francisco River in upper watercourse of the Basin. Preliminary information indicates that the Entre Ribeiros Aquifer discharge occurs along the Paracatu River Valley, as the carbonate rocks outcrop in the river thalweg.

Future studies must focus on hydrology issues to understand the relations between groundwater and surface water, the regional flow system and recharge-discharge questions. Dating water residence time also will be important to answer management subjects and to define technical criteria to assay user's grants volumes.

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