Environmental Research 202 (2021) 111756

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Geological and hydrogeological review of a semi-arid region with conflicts to water availability (southeastern Brazil)

Apolo P. Bhering [a,*], I.M.H.R. Antunes [a], Eduardo A.G. Marques [b], Rodrigo S. de Paula [c]

[a] Institute of Earth Sciences (ICT), Pole of University of Minho, Campus de Gualtar, 4710-057, Braga, Portugal
[b] Civil Engineering Department, Federal University of Viçosa, Viçosa, Brazil
[c] Geosciences Institute, Federal University of Minas Gerais, Belo Horizonte, Brazil

ARTICLE INFO

Keywords:
Groundwater
Water supply
Karst aquifers
Bambuí Group
Montes Claros

ABSTRACT

Groundwater consumption has become increasingly relevant for urban development. The city of Montes Claros (Minas Gerais, Brazil) is located in the border region of the Brazilian semi-arid polygon and has registered conflicts of water use for decades ago. The study area contains a complex karst system responsible for the heterogeneous permeability of water recharge and groundwater flow. The urban area of Montes Claros is located in the Vieira River watershed and contains different groundwater wells used to agro-industrial and human consumption. Almost groundwater captions have a low specific capacity with a consequent groundwater depletion. On the region, there are significant areas with a negative water balance concerning to water recharge and groundwater exploitation. Groundwater flow has a regional dominant direction of SW-NE, however locally, groundwater flow varies and could be identified some clusters with high hydrological potential. The contrast between hydrogeological features of the outcropping lithotypes added to the geological structures contribute to variations in the potentiometric level and in the productivity of aquifers.

The main aim of this study is a reviewer of the regional hydrogeology of the municipality of Montes Claros to evaluate a potential groundwater availability on the urban area and minimize a groundwater overexploitation and scarcity. A detailed characterization of the local hydrogeology from Montes Claros region will be crucial to a definition of more efficient water supply policies on the management of water resources, particularly in a scenario of climate change and water scarcity in semi-arid areas.

1. Introduction

Economic development promotes agro-industrial expansion and urbanization. Despite several positive effects, there are also different environmental impacts, particularly on water resources (Schirmer et al., 2013). Water is the principal natural resource that living beings depend on, regarding both quantity and quality, and are closely linked to urban and rural development.

Climate changes, population growth, and complex economic activities increase the pressure on water resources, compromising runoffs and the quality of the world's large freshwater ecosystems (Grafton et al., 2013; Mattos et al., 2018). Water scarcity can be defined as an excess of water demand over available supply (FAO, 2012), and it is characterized by unsatisfied demand, over exploitation of groundwater resources and vulnerability of natural resources (Vairavamoorthy et al., 2008; Kharraz et al., 2012; Acharyya, 2014; Selby and Hoffmann, 2014; Mattos et al., 2018).

Societies in semi-arid areas are specifically vulnerable to climate variability and water availability and therefore potentially vulnerable to climate change conditions (Krol and Bronstert, 2007). Semi-arid regions frequently have consequent hydrological years of below-average rainfall and severe drought. Despite being among the top ten countries in the world relatively to water resources availability, Brazil has a spatial distribution of water resources highly non-uniform, particularly in semi-arid regions (Herrera-Pantoja and Hiscock, 2015; Montenegro and Ragab, 2012).

Geological settings, land use and occupation, or the existence of underground infrastructures such as water catchment and sewage systems, contribute to water availability (Schirmer et al., 2013). Karst aquifers have a high heterogeneity mainly associated to groundwater flow (Bakalowicz, 2005; Goldscheider and Drew, 2007).

Relatively to porous and fractured aquifers, karst aquifers present

* Corresponding author.
E-mail address: apolopb@yahoo.com.br (A.P. Bhering).

https://doi.org/10.1016/j.envres.2021.111756
Received 10 March 2021; Received in revised form 22 March 2021; Accepted 16 July 2021
Available online 27 July 2021

additional variables which difficult groundwater flow models, such as the high heterogeneity of spatial permeability, non-linearities and threshold effects (White, 2002; Bakalowicz, 2011; Pereira et al., 2019; Lucon et al., 2020). This heterogeneity is related to some typical features of karst regions, such as sinks, dry valleys, and caverns (Legrand and Stringfield, 1973), and a consequent scarcity of available data and not sufficient to a detailed hydrological model on karstic systems (Hartmann et al., 2014). Aquifer karts systems present specific features, particularly a groundwater scarcity and lower predictability of groundwater supplies (Legrand and Stringfield, 1973), local subsidences associated to groundwater pumping (Wang et al., 2007; Galvão, 2015), natural or anthropic induced events, as sinkholes (Salvati and Sasowsky, 2002; Gutiérrez et al., 2014; Kaufmann and Romanov, 2016).

The present research aims to present a review of geological, hydrological and hydrogeological features of the urban area of Montes Claros, a Brazilian municipality with a population of 400,000 inhabitants, located in the north of Minas Gerais state. The city has a predominant semi-arid climate (Brazilian National Water Agency - ANA, 2018a), and is located in the official limit of Brazilian semi-arid polygon (Sudene, 2019). All the region has a history of conflicts related to water availability, since the 1980s (Brazilian Geological Survey - CPRM, 2018a). This review will allow addressing preliminary issues related to water availability, especially groundwater, highlighting an eventual over exploitation in the urban area. An integrated spatial analysis of groundwater data obtained from public and domestic wells, overlayed with hydrography, regional aquifer specific capacity and groundwater level variation, will allow to the identification of potential regions for groundwater availability in the region. The obtained results will promote a sustainable groundwater management and water resources crucial in semi-arid areas with water scarcity and a climate change scenario.

2. Study area

2.1. Location and general description

The municipality of Montes Claros (16°44′06″S, 43°51′43″W; WGS84) is located in the north of the state of Minas Gerais (Fig. 1a), in the southeastern region of Brazil, about 422 km from the state capital, Belo Horizonte. Montes Claros (Fig. 1b) is the largest city in the northern region of Minas Gerais, with a population of over 400,000 inhabitants, constituting an important regional economic pole. The city is the ninth economy in the state of Minas Gerais, and one of its bases is the retail trade, which employs most of the inhabitants. After 1965, associated to the implementation of the electric power by the Brazilian CEMIG (Companhia Energética de Minas Gerais), and the active participation of Sudene (Government Development Organization) in the local development, the regional industry achieves a relevant activity. The industrial park from Montes Claros is dominated by food production, health services, civil construction and textile sectors (Leite, 2006; Leite et al., 2011).

Brazil has different types of climate regions, mainly due to its territorial extension and great variations in relief. Despite the predominance of tropical and subtropical climate zones, there are also semi-arid climate regions, concentrated in the northeast and the southeast of the country (particularly on the north of Minas Gerais). As in other semi-arid regions, conflicts over restrictions on water availability are quite common. Some studies in Tunisia (Lacombe et al., 2008), Iran (Mohammadinezhad and Mostafa Ahmadvand, 2020), Afeghanistan and Pakistan (Atef et al., 2019), Niger (Boubacar et al., 2020) and Brazil (Krol et al., 2006; Braga et al., 2010) are relevant cases about groundwater management and minimization of water scarcity in semi-arid regions.

Montes Claros municipality area is predominantly located in a semi-arid climate zone (ANA, 2018a), exactly at the limit of the Brazilian semi-arid proposed by the Development Agency responsible for Brazilian semi-arid climate regions (Sudene, 2019). Groundwater exploitation

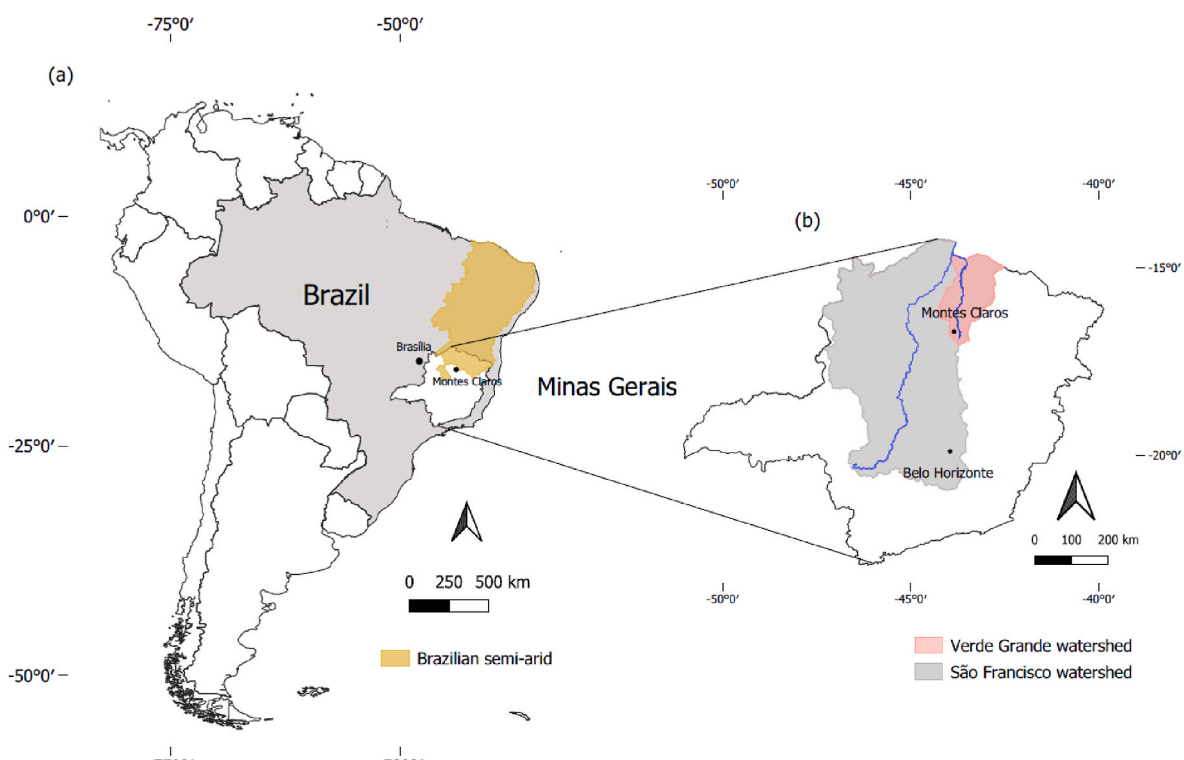

Fig. 1. (a) Geographical setting of Montes Claros and Brazilian semi-arid area (adapted from Sudene, 2019); (b) Minas Gerais State including the river of São Francisco and Verde Grande watersheds and Montes Claros.

from local aquifers has become increasingly important for supplying the population. Water public supply of Montes Claros is mainly associated to surface water and locally from the catching system of groundwater, particularly in critical periods of water scarcity (Sousa, 2013). The water supply system has an annual water capacity of 18 hm^3, while the municipal demand is around 28 hm^3 (ANA, 2018b). Consequently, Montes Claros urban area corresponds to a region with water rationing, and some local areas show a negative balance between recharge and exploitation (ANA, 2018a).

2.2. Hydrography

The municipality of Montes Claros is mostly inserted in the Verde Grande River watershed, an important affluent on the East side of São Francisco River (Fig. 2a). During the 1970s, the region had a significant development supported by public policies related to agricultural irrigation and other incentives, which contributed to the agro-industrial development. However, those policies were responsible for the conflicts related to water use in the following decade (ANA, 2013). The Verde Grande River basin provides a significant agricultural production for supplying important cities, such as Montes Claros, primary through agricultural irrigation (Vieira and Sandoval-Solis, 2018).

The São Francisco River watershed represents the largest watershed located exclusively in the Brazilian territory, covering approximately an area of 630,000 km^2, representing about 8 % of the national territory. The river with an extension of 2,860 km long, cuts different climatic regions, with the longest extension in the northeast region of the country. The average flow rate is about 2850 $m^3 s^{-1}$, representing about two/thirds of surface waters from northeast of Brazil. Almost the region is located in a semi-arid climate influence, with consequent prolonged and severe droughts, a situation aggravated with the increment of groundwater exploitation on a regional scale (Maneta et al., 2009; Teixeira et al., 2009; Santos et al., 2020). Groundwater management is particularly relevant in the São Francisco River watershed, mainly due to historical difficulties in social and economic development of the Brazilian semi-arid area, with a particular emphasis on karst and karst fissured aquifers.

The Vieira River watershed encompasses almost all the urban areas from the municipality of Montes Claros. The annual rainfall is about 1000 mm/year, and decreasing gradually to the northeast, on the direction of the semi-arid limit (Fig. 2a). The river watershed area has an altitude ranging from 561 m (at Montes Claros) to 1036 m (on the opposite side of the river valley) (Fig. 2b). The soil occupation is mostly distributed between forest and rural areas, in a total of 90% of the area. Urban area occupies less than 10% of Vieira River watershed, while agricultural activities occur in approximately 1% of the area (ANA, 2018b). The expansion of the urban area, promotes a decrease in agricultural areas, and a consequent decrease in groundwater irrigation consumption. However, the negative water balance still remains on local areas of the urban zone (ANA, 2018b, c).

2.3. Geology

The region of Montes Claros is inserted in the São Francisco craton (Almeida, 1977), near the transition with the Araçuaí fold belt (Fig. 3). São Francisco craton basement is formed by Archean and Paleoproterozoic rocks overlapped by Proterozoic and Phanerozoic sedimentary units (Alkmim and Martins-Neto, 2012). The Bambuí Group corresponds to these Proterozoic units and outcrops almost the study area, while Phanerozoic coverings, represented by sandstones of the Urucuia Formation and alluvial and colluvial deposits, also occur in the area.

The Bambuí Group represents a late Neoproterozoic sedimentary cover that outcrops over 300,000 km^2 of the São Francisco basin (Caxito et al., 2018) composed by carbonate to siliciclastic deposits, with up to 3000 m thick (Martins-Neto et al., 2001). The classic stratigraphy was defined by Dardenne (1978) and consists of five sedimentary units: Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, Serra da Saudade and Três Marias formations.

In the Vieira river watershed, the Bambuí Group is represented by Serra da Santa Helena, Lagoa do Jacaré and Serra da Saudade formations

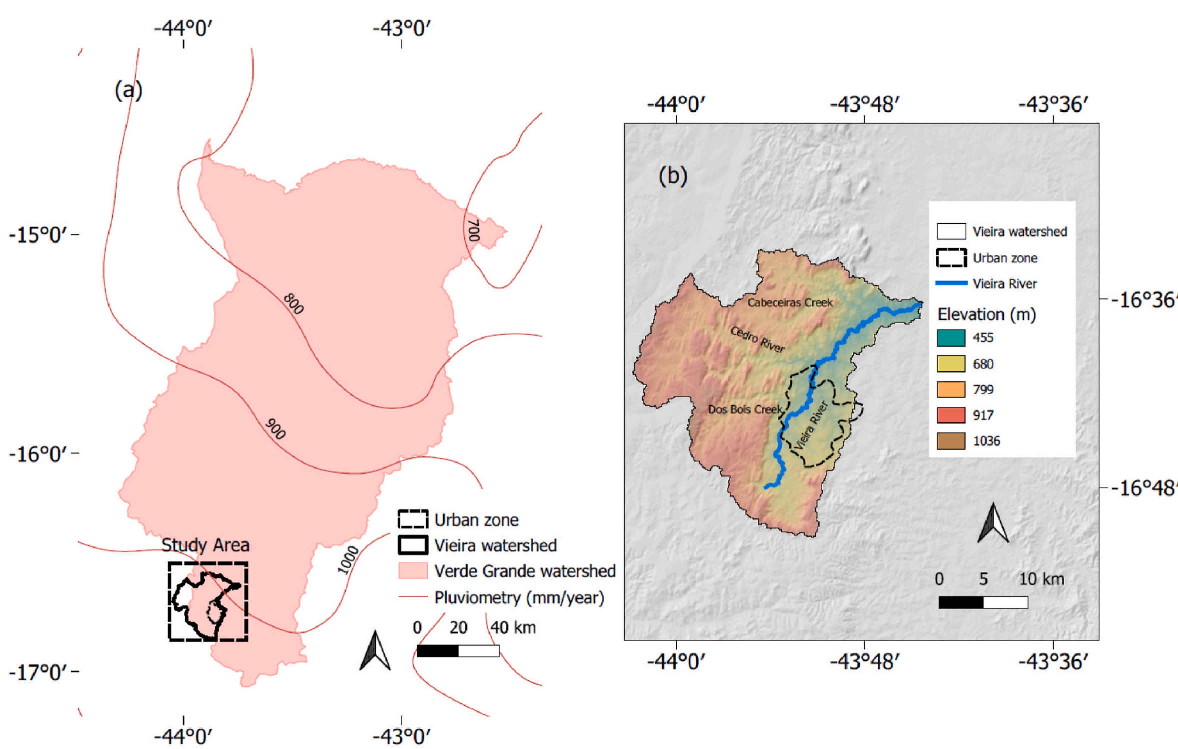

Fig. 2. (a) Pluviometry of the Verde Grande River watershed, including Vieira watershed and the urban area of Montes Claros (adapted from CPRM, 2013); (b) Vieira river watershed hypsometry. Datum: WGS 84.

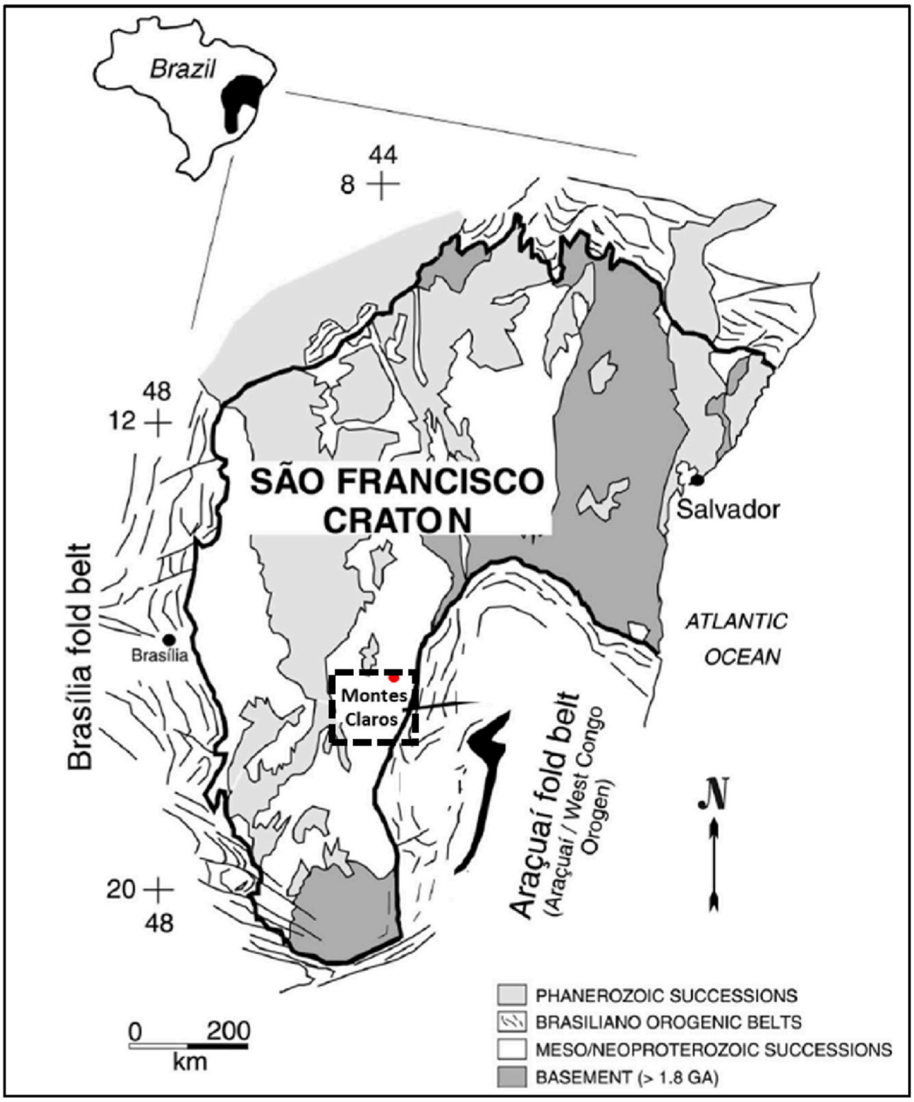

Fig. 3. Montes Claros in São Francisco craton (adapted from Martins-Neto et al., 2001).

(Fig. 4).

The carbonate sequence is composed, on the base, mainly by metasiltstones from the Serra de Santa Helena Formation; limestones and metasiltstones in the intermediate portion belonging to the Lagoa do Jacaré Formation; and metamudstones and metasiltstones from the Serra da Saudade Formation at the top (Chaves and Andrade, 2014b). In structural features, there are large folds, corresponding to kilometric synclines and anticlines structures, with its limbs plunging to southeast and showing smoother dip than those that plunge to northwest. Brittle structures include normal mid-size faults and large fractures according to general direction NNE-SSW (Chaves and Andrade, 2014b).

2.4. Hydrogeology

In Brazilian karst systems, several studies on the aquifer characterization, groundwater flow modeling and water availability have been developed (e.g. da Silva, 1982; Karmann, 1994; Auler, 1999; Pessoa, 2005; Braga et al., 2010; de Paula and Velásquez, 2013; Soares and Velásquez, 2013; Ninanya et al., 2018; de Paula, 2019), and some of these studies also include an interface with urbanized areas (e.g. da Silva, 1988; Galvão, 2015). Almost results were obtained in the North of Minas Gerais region, coincident with the water scarcity of the semi-arid region, and showing the relevance and higher productivity of the wells located in karstic aquifer systems compared to fissured aquifers (Costa et al., 2018; Santos and Velásquez, 2018). The aquifer developed in the karst system of the Bambuí Group is also frequently considered as a karstic fissured system due to pelitic intercalations and the occurrence of large extensions without well-developed karstic features, increasing the importance of fractures to groundwater flow, as highlighted by the results obtained in the Jaíba region, around 200 km north of Montes Claros (Atman et al., 2011).

In the Vieira river watershed, two types of aquifer systems were developed, corresponding to a granular and karstic fissured, and also an aquitard system (Fig. 5). The Lagoa do Jacaré Formation is the dominant geological unit and constituted mostly by limestones, corresponding to the karstic fissured aquifer. On this formation, there is an important local karstic system - Lapa Grande State Park - with the occurrence of several structures and characteristic features, such as caves, lakes, swallets and sinkholes (Fig. 5). Lapa Grande State Park is an environmental conservation unit located at west of the urban zone, with an area of more than 15,000 ha, and that was classified due to the hydrological relevance as a recharging area, besides providing an important water supply source for the urban area of Montes Claros. This conservation unit has around 70 caves mapped, with a highlight on Lapa Grande, which has more than 2000 m of galleries (Barbosa et al., 2015). Vieira river watershed has more than 250 cavities mapped (CECAV, 2019),

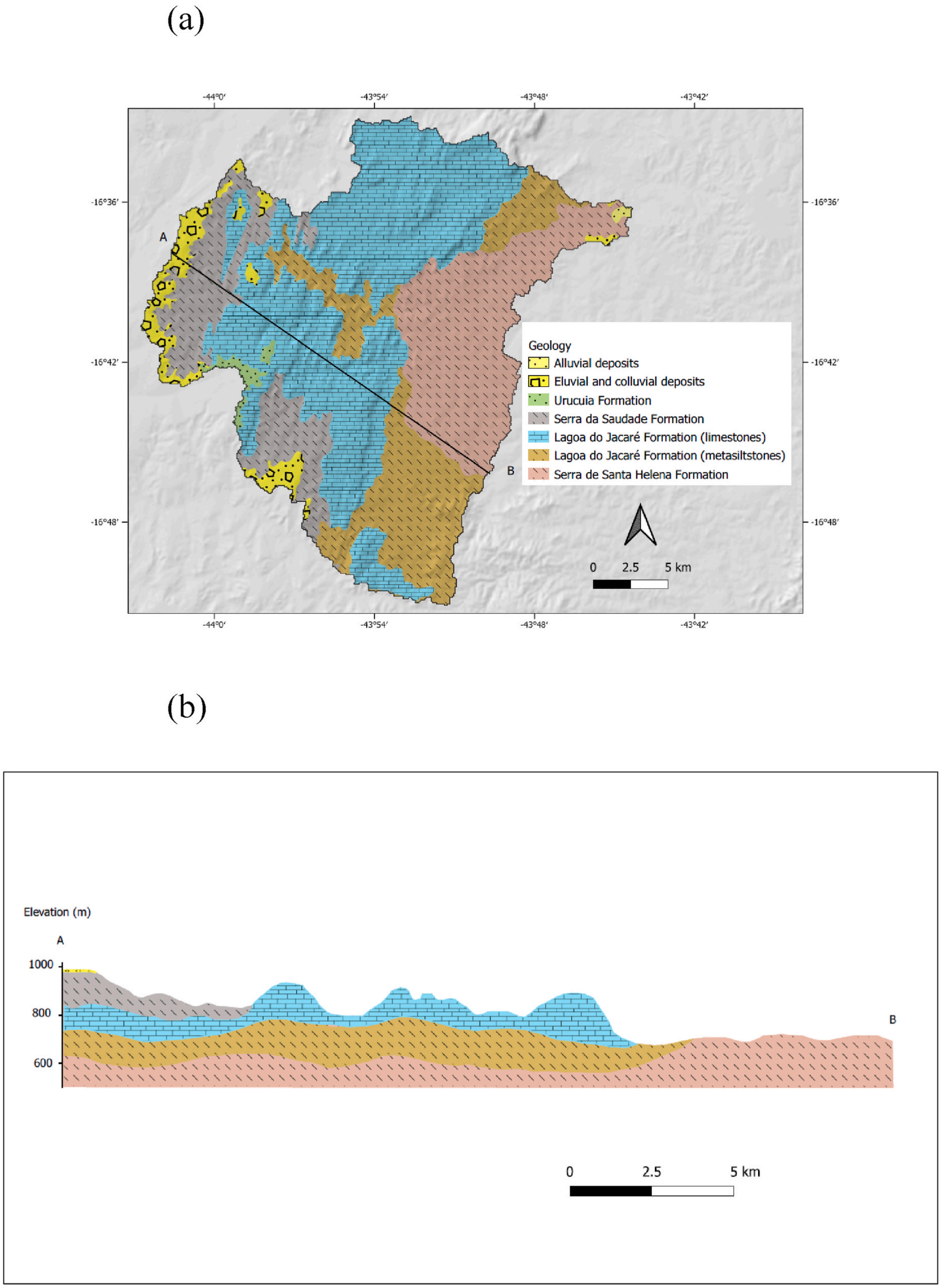

Fig. 4. (a) Geologic map of Vieira river watershed (adapted from Chaves and Andrade, 2014a, b); (b) geological cross section (A-B from Fig. 4a). Datum: WGS 84.

with a preferential NNE-SSW trend, as well as other karstic structures (Fig. 5).

The aquitards are represented by metasiltstones and metamudstones from the Serra da Santa Helena and Serra da Saudade formations, and are characterized by a low hydraulic transmissivity pelitic layers. Locally, is similar as a karstic fissured aquifer system with carbonate intercalations or a low thickness, as in the region of Lagoa do Jacaré Formation. The urban zone of Montes Claros is located above these units, which could support the low groundwater productivity region. Even located in a pelitic domain, karstic features are also frequent, since

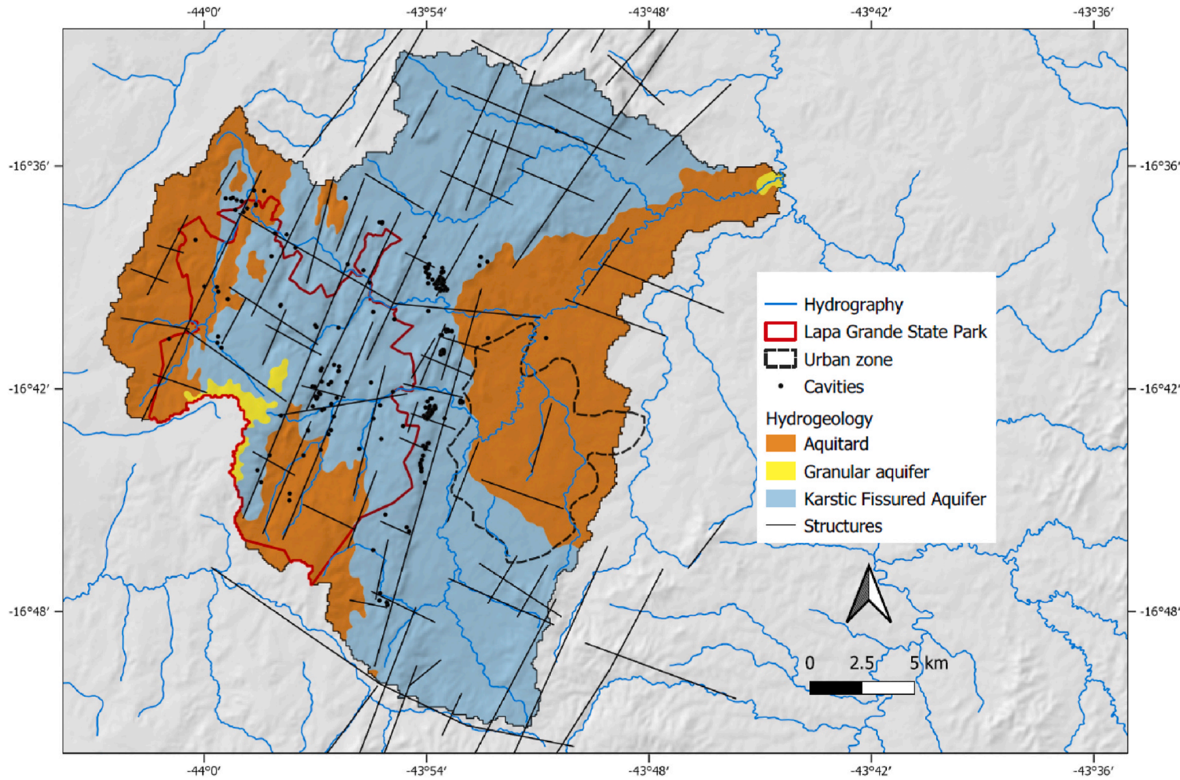

Fig. 5. Vieira river watershed aquifer systems, main structures and cavities (adapted from CECAV, 2019) and Lapa Grande State Park area location. Datum: WGS 84.

the base of the Lagoa do Jacaré Formation presents carbonate intercalations (Chaves and Andrade, 2014b). The alternation between pelitic and carbonate sediments is also found in the region of Serra da Santa Helena Formation, as obtained in 35 well depth logs (ANA, 2018b).

Granular aquifers are represented by the Urucuia Formation - as a clastic plateau caprock - and alluvial soils. Despite the local occurrence of the Urucuia Formation in the Vieira river watershed, this sedimentary unit represents an important national aquifer system, with approximately 500 km length, located between the north of the Minas Gerais state and the Brazilian Northeast region. Generally, this aquifer system occurs in the contact with the Bambuí Group, as an erosive discordance surface, which the rainwater infiltration is the dominant recharge source, feeding directly the Bambuí karst aquifer (ANA, 2018d; Marques et al., 2020).

3. Groundwater availability

Actually, there are more than 700 registered groundwater wells in the Vieira river watershed, according the information from SIAGAS - Groundwater Information System (CPRM, 2020) - a public wells database. However, some of these wells are abandoned. The data of specific capacity (m^3/h/m) and groundwater information of 400 groundwater wells were used and processed in a geographical information software (QGIS).

Almost, groundwater wells have an average depth of 86 m reaching up to 240 m depth. The average of groundwater level is about 14.5 m depth with a maximum of 60 m depth. Most of these groundwater wells are hosted in limestones and metapelites belonging to the Lagoa do Jacaré and Serra da Santa Helena Formation. More than 70% of the groundwater wells are located in the urban area of Montes Claros, mainly associated to water resources for domestic consumption and industrial activities (Fig. 6 (a)). In this area, the groundwater level is deeper, around 600 m, and is associated mainly to geomorphological features and also to possible dewatering caused by the large concentration of groundwater wells in the urban area.

Regionally, the underground flow occurs from SW to NE (IGAM, 2007). However, the topography and hydrogeology of Vieira river watershed maximize the hydraulic gradient difference, in the NW/SE direction, promoting a local flow, which percolates in another fracturation direction (WNW/ESE), evidenced by the groundwater water level isolines (Fig. 6 (a)). The specific capacity data (m^3/h/m) was obtained mainly from pumping tests developed during groundwater well abstraction. Montes Claros urban area is coincident with the lower specific capacity values for the aquifer, mostly represented by the aquitard and karstic fissured units (Fig. 6 (b)). This lower productivity is mainly associated to the occurrence of intercalated metasiltstones and metamudstones layers from the Lagoa do Jacaré and Serra da Santa Helena Formations, resulting as an aquitard. In the urban area, the higher water specific capacity zones are related to NNE-SSW alignment intersections, represented by the regional structure and the main direction of orthogonal fractures (WNW-ESE), commonly represented by the confluence of watercourses, as the example of the Vieira River and Dos Bois Creek.

Locally, the groundwater wells are located close to the rivers and the higher groundwater productivity could also suggest a direct connection between surface water (stream) and groundwater (well). On the Vieira river watershed, the region with higher groundwater specific capacity occurs near the contact between the metapelitic unit and the karst from Lagoa do Jacaré, which is associated with preferential structures for meteoric water infiltration and the occurrence of caves and karst features (e.g. sinkholes). These areas occur mainly in the confluence between Cedro River and Cabeceiras Creek, which cut the carbonate layer of the Lagoa do Jacaré Formation (Fig. 6 (b)).

Although water public supply is almost exclusive from surface water resources, this study allows to the identification of possible potential groundwater resources, that could be used as local population supply. The integration of geological and hydrogeological local characteristics correlated with areas of higher water specific capacity also contributes to new prospecting possibilities on the delimitation of productive

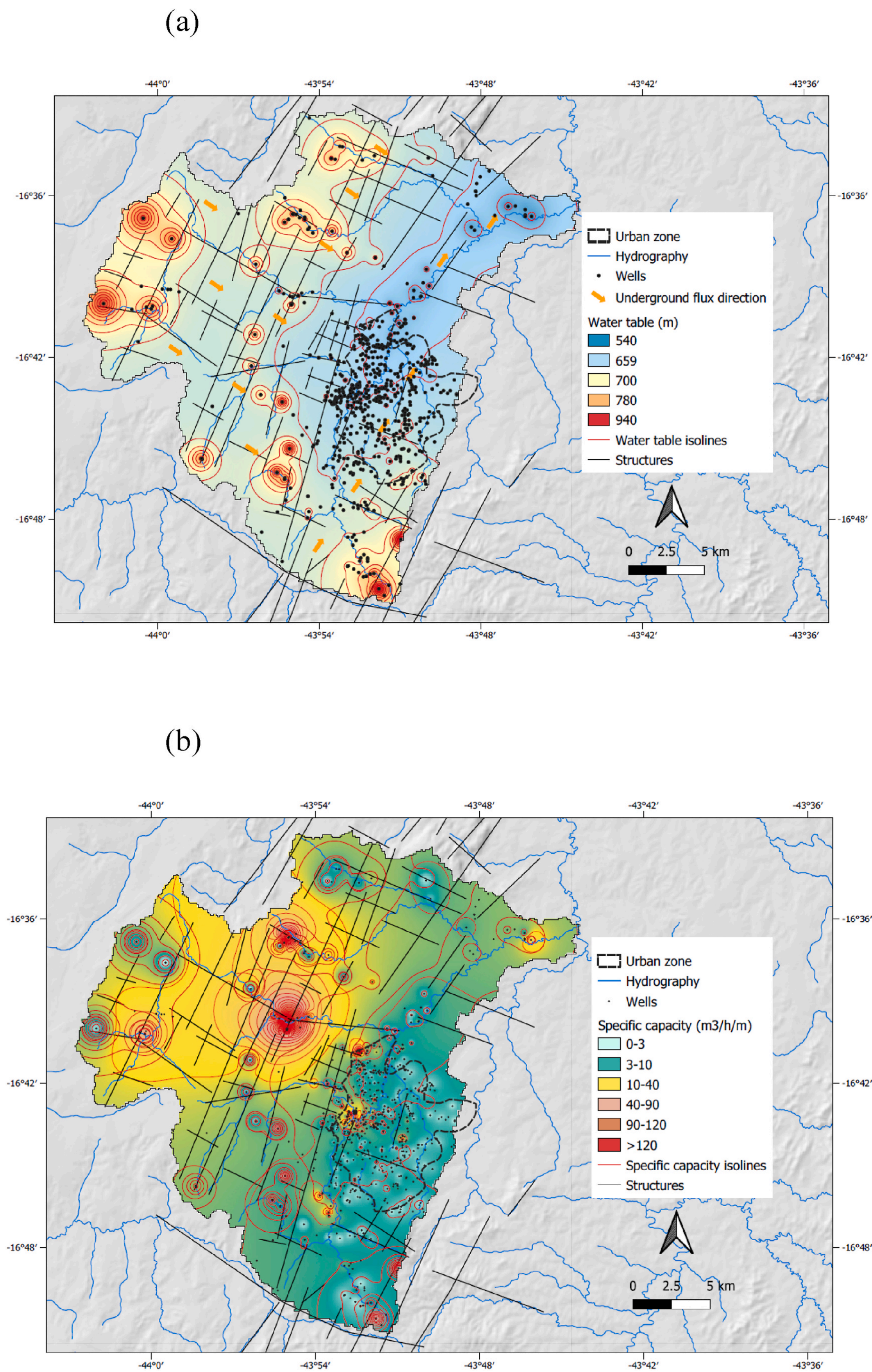

Fig. 6. (a) Groundwater flow direction; (b) Specific capacity in Vieira river watershed. Datum: WGS 84.

aquifer system zones.

A water balance zoning investigation was carried out and the river watershed was divided into equal 18 square cells, and in each one a balance was generated with the difference between the *flow in* and the *flow out* (ANA, 2018b). The *flow in* is defined as the calculated pluviometric recharge and the *flow out* is obtained from the registered total groundwater production (well). Of the 18 cells, 3 of them presented a negative water balance, with a higher well groundwater exploitation than the calculated pluviometric water recharge. These data were interpolated and presented in Fig. 7, illustrating the negative water balance to the Montes Claros urban region.

A negative water balance, relatively to natural recharge and discharge, associated to the pumping of wells have been obtained for specific regions (ANA, 2018a, b; CPRM, 2018b). These results were developed on a regional and local scale, including small watersheds around Montes Claros and Vieira River. Relatively to the Verde Grande River watershed, which encompasses the Vieira River, other studies have been developed, including results of potential productivity for groundwater wells (Costa et al., 2018); potential of local aquifer systems (Santos and Velásquez, 2018); and water resources sustainability indexes (Vieira and Sandoval-Solis, 2018), highlighting the criticality of (ground)water management on the region of Montes Claros.

4. Discussion

A review of the hydrogeology of Montes Claros region was presented, as an assessment of groundwater availability. The Montes Claros region is located mainly on a karst fissured aquifer system predominantly represented by a Neoproterozoic geological unit (Lagoa do Jacaré Formation, Bambuí Group), showing a heterogeneous permeability, as evidenced by the well-developed local karstic system. This formation is characterized by thick limestone layers and also intercalations of metasiltstones and metamudstones, especially on the bottom, a condition that will increase the relevant contribution of secondary porosity, associated to the brittle structures from the rock mass.

The groundwater regional flow has a dominant direction NNE/SSW, in the lower topographic region of the watershed, mainly on the Vieira River borders. However, there is a clear orthogonal groundwater flow related to the regional structural direction and that percolates through the second main geological structures family (WNW/ESE). The groundwater flow is conditioned by a large morphological and hydraulic gradient variation in this direction and the local geology.

As expected in karstic zones, the regional groundwater level and some hydrogeological properties, as water specific capacity, present local concentrated clusters and high variability. In some cases, the higher groundwater specific capacity may be affected by the direct connection between surface water and groundwater. Otherwise, geological characteristics of Montes Claros region will promote areas with higher aquifer production parameters. These areas with higher aquifer productivity are mainly associated to the main structural NNE-SSW and orthogonal directions (intersections), karst dissolution and conduits connections. Morphologically, these conditions are represented by regional lineaments, watercourse confluences, cave alignments, sinkholes and swallets.

5. Conclusions

The integration of hydrogeological characteristics and regional structures will promote the delimitation of areas with higher groundwater specific capacity, which could contribute to higher local hydrogeological productivity and to the definition of more efficient water supply policies. Some of the main points that represent these geological conditions, with higher groundwater specific capacity in confluence zones, are present in the Cedro River and Cabeceiras Creek. Other regions, such as on the west and south of Dos Bois Creek, present a higher probability of obtaining a better groundwater aquifer productivity. However, the reduced number of groundwater wells is not enough for an accurate conclusion and more monitoring groundwater wells should considered in the future.

Although presenting a lower specific aquifer capacity, the urban region of Montes Claros also shows a higher concentration of groundwater wells (70%). Besides an eventual depletion of the groundwater level, this well concentration could increase the negative water balance since the groundwater exploitation is higher than the local rainfall recharge.

As a future research, it is relevant to analyze a possible groundwater interference between groundwater wells spatial distribution and/or a possible groundwater overexploitation associated to the regional groundwater depletion, increasing the water stress. Otherwise, a watershed recharge added to possible external sources could be sufficient to a sustainably groundwater exploitation through wells.

On the total registered groundwater wells located in the Vieira River

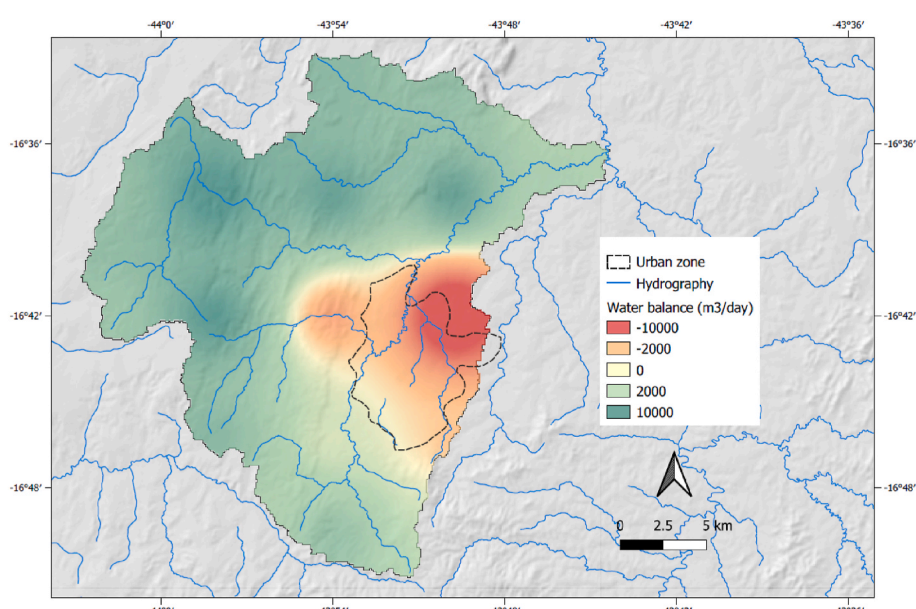

Fig. 7. Negative water balance in the urban zone of Montes Claros (adapted from ANA, 2018b). Datum: WGS 84.

watershed, the lithological sections on 150 groundwater wells will allow to the definition of a groundwater conceptual model on the region. However, this information also indicates a geological complexity for the effective definition of aquitards related to the metapelitic units of the Lagoa do Jacaré formation and specially to the Serra da Santa Helena formation. For a future hydrogeological advance on the Montes Claros area, it will be important to identify more characteristics and tools that will help on the aquifer system delimitation, ensuring that this contour condition will be satisfactory for groundwater flow modeling and to evaluate groundwater availability on the Montes Claros urban zone.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Authors would like to thank IGAM (Instituto Mineiro de Gestão de Águas, Brazil) for the data provided. This research was carried out under de ICT Centre programme, University of Minho (Portugal).

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