sociedade & natureza

DOI: 10.14393/SN-v32-2020-56221
Received: 21 July 2020 | Accepted: 26 August 2020

Combining natural and anthropic atributtes for aquifers contamination potential in southeast of Brazil

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Keywords:
Groundwater
GIS
Multicriteria analysis
Geo-environmental attributes

Abstract
The compromise of surface water resources' quantity and quality, as well as the extensive use of groundwater, exposes aquifers to contamination risks. Considering this, combine natural and manmade influences is a proper strategy for potential aquifer contamination evaluation. This article presents charts of aquifer contamination potential in Rio Claro watershed (251,91km², in Santa Rita do Passa Quatro, SP) at 1:50,000 scale, taking in account aquifer units, surface geology units, soil and steepness information; operated using multicriteria analysis. The classes “Very high” and “High potential” where the most representative classes of contamination potential in the watershed (performing 46.1% in 1994 and 48.6% in 2014). Obtained contamination potential expressed geological attributes influence in the area. Land use / land cover changes were determinant for higher potential maintenance with time. Adoption of land use / land cover control measures and improvements in tillage management are alternatives for the groundwater protection in this watershed.

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INTRODUCTION

Groundwater is the world's main source of fresh water supply (MACHIWAL et al., 2018). However, intensive and indiscriminate use has caused diversified impacts on its quality and quantity (FOSTER et al., 2013; RAVENGA, 2005; SCHEWE et al., 2014). On a global scale, it is estimated that 20% of aquifers are overexploited (MILLENNIUM ECOSYSTEM ASSESSMENT, 2005; WHO, 2008; WWAP, 2015).

The main sources of degradation are related to urbanization (ALLOUCHE et al., 2017) and the diversification of agricultural, industrial, chemical, oil and mining activities (BORCHARDT et al., 2003; JOHANSSON; HIRATA, 2004; MORAN et al., 2005; GANDY et al., 2007; OSENBRUCK et al., 2007; IRITANI et al., 2013; KHOSRAVI et al., 2018), which drive the discharge of contaminated effluents. According to Varnier and Hirata (2002) and Mahvi et al. (2005), Nitrate derived from agriculture and urbanized areas with sanitation infrastructure problems (POWELL et al., 2003), is the contaminant that negatively affects aquifers the most on a global scale.

Allied to this scenario, Tundisi et al. (2008) highlights the lack of management and governability of these resources and the impairment of native vegetation in a watershed (TUNDISI; MATSUMURA-TUNDISI, 2010), which significantly increases the costs of water treatment for public supply. According to Attanasio et al. (2013), Schilling and Jacobson (2014), Tanaka et al. (2016), Tromboni and Dodds (2017), Mello et al. (2018), Valera et al. (2019) and Guidotti et al. (2020), the lack and / or reduction of riparian vegetation represents more damage to the quality of water resources than the absence of vegetation in the rest of the watershed.

Thus, the investigation of the gorundwater contamination has a strong connection with agro-industrial and urban activities and is an appropriate tool for adopting technical measures of water management (FOSTER et al., 2013) and land use management (COSTA et al., 2019). Many compounds resulting from these activities are transformed into other materials and inserted in the hydrological cycle by natural and anthropic processes, modifying the hydrogeochemical characteristics of the system.

Assessing the vulnerability of groundwater has become very important in the field of geosciences (GORELICK; ZHENG, 2015; WACHNIEW et al., 2016). However, in Brazil, the understanding of this theme is recent and restricted, since the user of this resource, private or governmental, still does not know its importance and ignores the consequences of its contamination (LOURENCETTI et al., 2007).

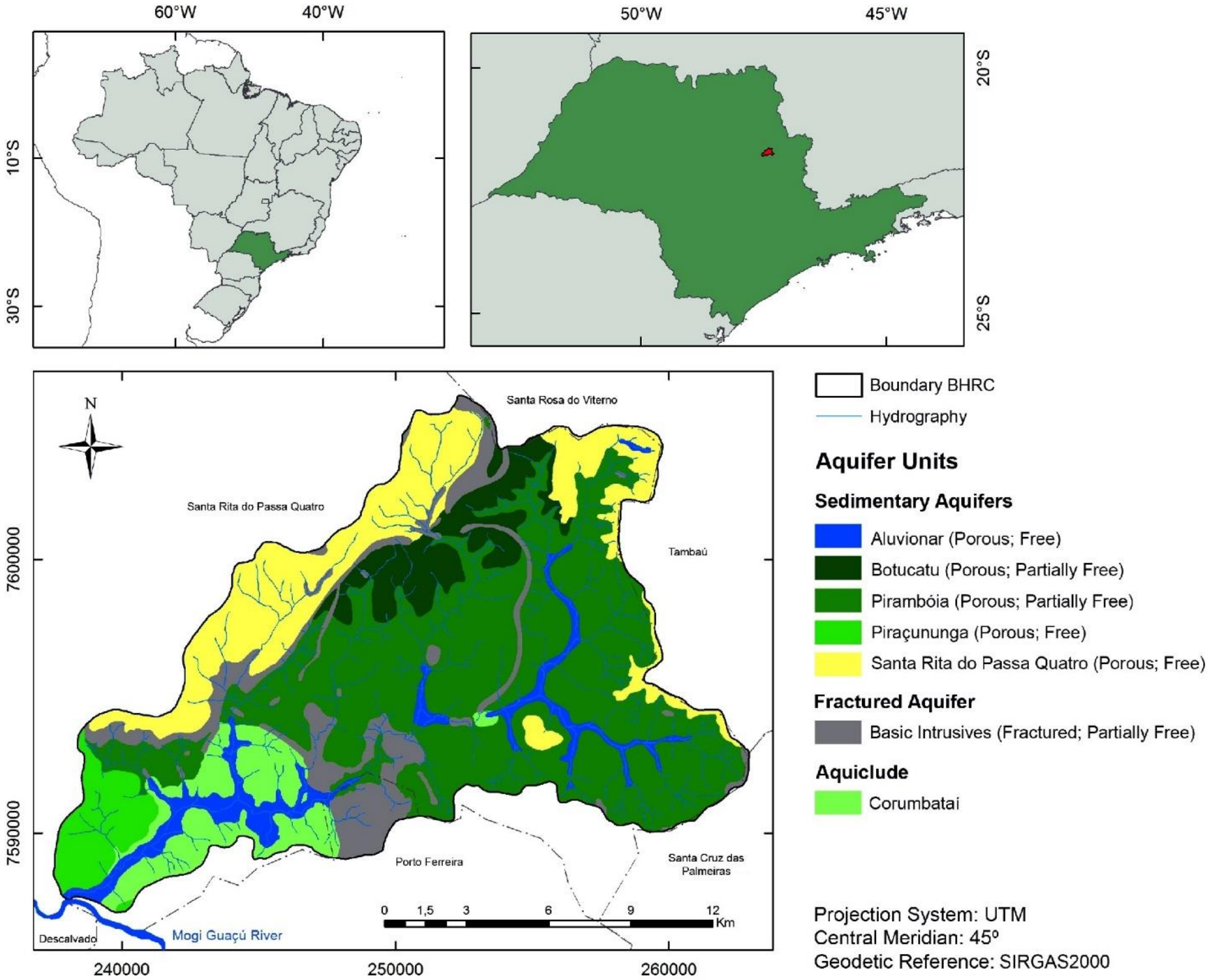
Then, there is a need to develop comprehensive environmental analysis models that seek to understand possible risks of underground water resources contamination by the contribution of waste from various human activities (CANÇADO et al., 2008; TAVANTI et al., 2009; MORAES et al., 2011; IRITANI et al., 2013; MENEZES et al., 2014; COSTA et al., 2015b). Globally, among the most used methods, drastic (ALLER et al., 1987) and GOD (FOSTER, 1987) stand out. In Brazil, the multicriteria analysis involving decision matrices and overlapping information plans in the GIS environment have achieved adequate and low-cost results (MARANGON et al., 2017; PIGA et al., 2017; COSTA et al., 2019).

Considering the human activities existing in the Rio Claro watershed (a significant portion of the urban areas of Santa Rita do Passa Quatro and Santa Cruz da Estrela; associated with sugarcane culture), sources of organic contamination are expected, especially domestic sewage effluents and agricultural and fertigation inputs (LORANDI; LOLLO, 2016). In this context, based on the combination of attributes of the physical, biotic and anthropic environment, as well preliminary investigations (LORANDI et al., 2014), the present study characterized the potential for aquifer contamination in the Claro River watershed.

Location and geoenvironmental characterization of the study area

The Mogi Guaçu river watershed, denominated Water Resources Management Unit 09 (UGRHI 09) in the State of São Paulo is inserted in the Rio Grande hydrographic watershed, northeastern region of the state. One of the sub-basins of this UGRHI is that of the Claro River, which is all inserted in the Middle compartment of the Upper Mogi.

Figure 1 - Geographical location and aquifer units of the Claro River watershed.



Source: IG (1981a, 1981b, 1984). Org.: The Author, 2020.

Based on maps, scale 1:2,500,000 (FEITOSA, 2008), this watershed is located in the Hydrogeological Province of the Paraná basin, characterized by presenting very high average hydrogeological favorability. In a more detailed version (scale 1:1,000,000), it is observed that the watershed is territorially involved by the Guarani (outcrop) and Serra Geral Intrusivas (DAEE-IG-IPT-CPRM, 2005). On a scale of 1:50,000, there are six aquifer units (LORANDI et al., 2014) (Figure 1).

According to the Instituto Geológio – IG (1981a, 1981b, 1984) and Melo (1995), the studied area presents the following geological formations (Table 1):

Table 1. Recognized lithostratigraphic units in the study area.

Unit	Era Period	Description
Alluvial Deposits	Cenozoic Holocene	They are represented by wide plains that occur along the bottom of the Rio Claro valley and main tributaries. They consist of alluvial and colluvial sediments with a sandy texture due to the contribution of adjacent lithologies.
Piraçununga Formation	Cenozoic Tertiary	It is composed of light brown sandy-clayey sediments without very poorly selected sedimentary structures. At the base, it usually presents a line of pebbles or gravel, with quartz and quartzite pebbles and fragments of limonite, overlapping discordantly over the Corumbataí Formation.
Santa Rita do Passa Quatro Formation	Cenozoic Tertiary	They consist of sands in a clayey matrix, without sedimentary structures with basal gravel pebbles predominantly of quartz. In the area, these sediments are brown in color, very friable and have quartz granules dispersed throughout the thickness, which varies from a few cm to a few meters with a wide horizontal distribution (MASSOLI, 1981).
Serra Geral Formation	Mesozoic Cretaceous	They are regionally constituted of sills and dikes of basic magmatites, of phaneritic texture and gray to black color, presenting intensely fractured and dense aspect. In aerial photographs, they have dark gray tones, steep slopes and preferential distribution along interfluves.
Botucatu Formation	Mesozoic Jura / Cretaceous	Consisting predominantly of aeolian sandstones attributed to deposits in a desert environment, with fine to medium grain, well rounded particles and essentially quartz composition (80%), the thickness varies between 20 and 280 meters. It has a large number of interconnected pores and a high capacity to store and supply water.
Pirambóia Formation	Mesozoic Triassic	Composed of whitish, yellowish and pinkish river sandstones, medium to fine, sometimes quite clayey, due to stratigraphic positioning. In aerial photographs, they present light gray to white shades, with a poorly developed drainage system, with dendritic pattern.
Corumbataí Formation	Paleozoic Permian	Regionally composed of variegated shales, being positioned between the Irati (lower) and Pirambóia (upper) formations. In aerial photographs, print dark gray tones and high drainage density with feather pattern.

Org.: The Author, 2020.

According to Lorandi and Lollo (2016), the units of soils identified in the watershed have their main geotechnical characteristics presented in Table 2.

Table 2 - Geotechnical characterization of soils.

Soils	Area (km^2)	Thickness (m)	Granulometry (%)*			Permeability coefficient (cm/s)
			Cl	S	Sa	
Quaternary	15.87	<2, 2-5	5	4	91	$6.1\ 10^{-3}$
Res. Santa Rita do P.	45.72	>5	14	8	78	$3.7\ 10^{-2}$
Res. Piraçununga	11.38	>5	28	7	65	$4.2\ 10^{-3}$
Res. Botucatu	17.65	<2, >5	20	5	75	$3.8\ 10^{-3}$
Res. Pirambóia	11.38	<2, >5	24	6	70	$7.1\ 10^{-3}$
Res. Magmatitos Básicos	26.48	<2, 2-5, >5	47	1	36	$4.9\ 10^{-4}$
Res. Corumbataí	19.65	<2	77	9	14	$4.1\ 10^{-4}$

* Cl = Clay, S = Silt, Sa. = Sand. Org.: The Author, 2020.

By the geomorphological division of the State of São Paulo (ROSS; MOROZ, 1997), the watershed is inserted in the Morphostructural Unit of the Paraná sedimentary basin, partially covering the Morphoscultural Unit Peripheral Depression of São Paulo, which is carved almost entirely in paleozoic and mesozoic sediments. At the lower taxonomic level, it is represented by the morphological unit called Mogi Guaçu Depression, which consists of hills with broad tabular tops, with valleys carved up to 20m, and interfluvial dimension between 1,750 and 3,750m. The predominant altimetric dimensions are between 500 and 650m and the predominant slopes between 5 and 10%.

According to the Köppen system (1948), the climate is classified as Cwa type, i.e. dry winter (dry season), in which the average temperature of the coldest month is bellow 18ºC and that of the hottest month exceeds 22ºC (rainy season). The forest cover is composed of the Atlantic Forest and the Cerrado, with a predominance of the Atlantic formation of the Semideciduous Seasonal Forest (SÃO PAULO, 2009).

MATERIALS AND METHOD

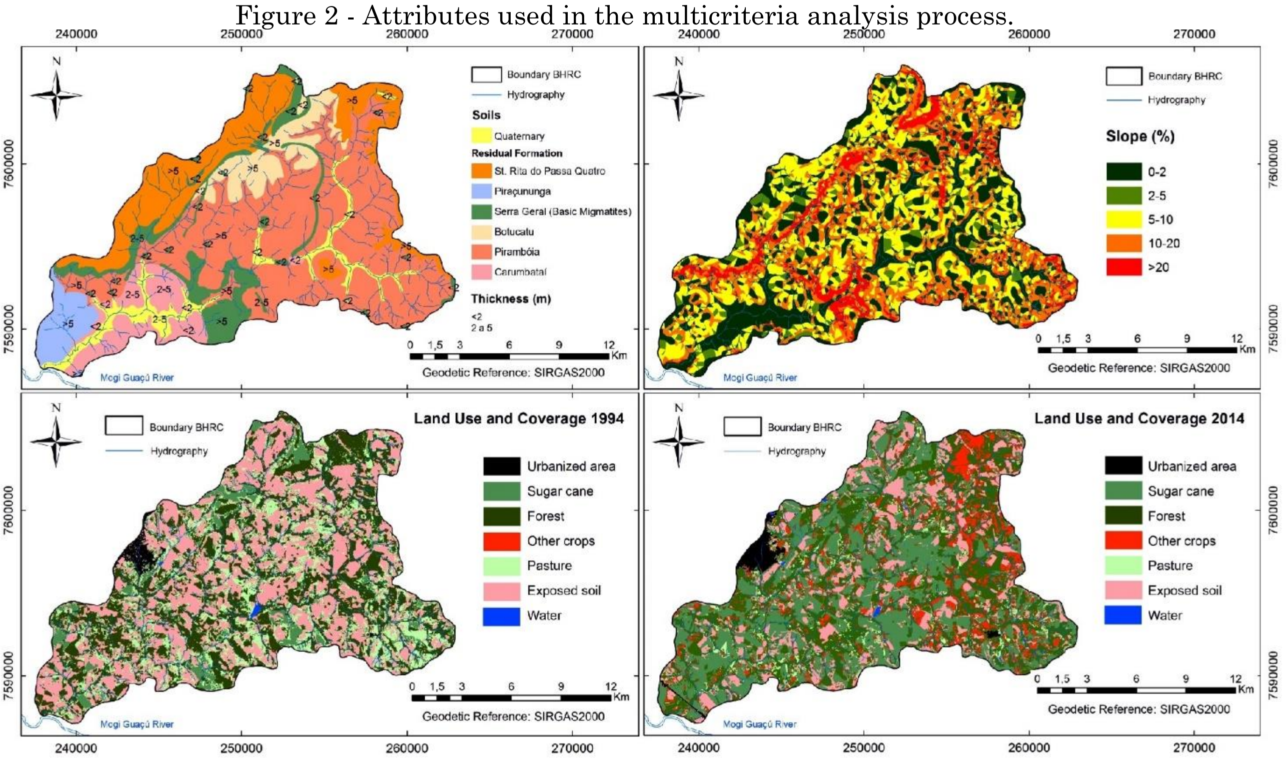
The delimitation of the Claro River watershed (limited by the extreme coordinates 47°17'35,13" W and 47°32'8.9" W; 21°37'46.7" S and 21°48'13" S), was performed from the digitization of topographic sheets (IBGE, 1972). The information plans were georeferenced in zone 23S, adopting the geodesic reference SIRGAS2000 (IBGE, 2005) and Universal Transverse Projection of Mercator (UTM). For the spatial treatment of the data, the software ArcGIS® 10.2 (ESRI, 2013) and Idrisi Selva were used.

To assemble the database with geographic information, the following cartographic documents were used, all in the scale 1:50,000: map of the surface geological formations (IG, 1981a, 1981b, 1984), the map of soils, letter of the classes of slope and the letter of aquifer units (LORANDI et al., 2014).

To elaborate land use and land cover maps, through supervised classification, images from landsat 5 satellite of 05/31/1994 (RGB color composition of bands 5, were used, 4 and 3), spatial resolution of 30 meters and LANDSAT images 8 of 22/05/2014 (RGB color composition of bands 6, 5 and 4), spatial resolution of 30 meters, with the fusion of the panchromatic band 8 of 15 meters (USGS, 2016) were used.

Figure 2 shows the spatial distribution of the following attributes: soils, slope and land use and cover (1994 and 2014).

Figure 2 - Attributes used in the multicriteria analysis process.



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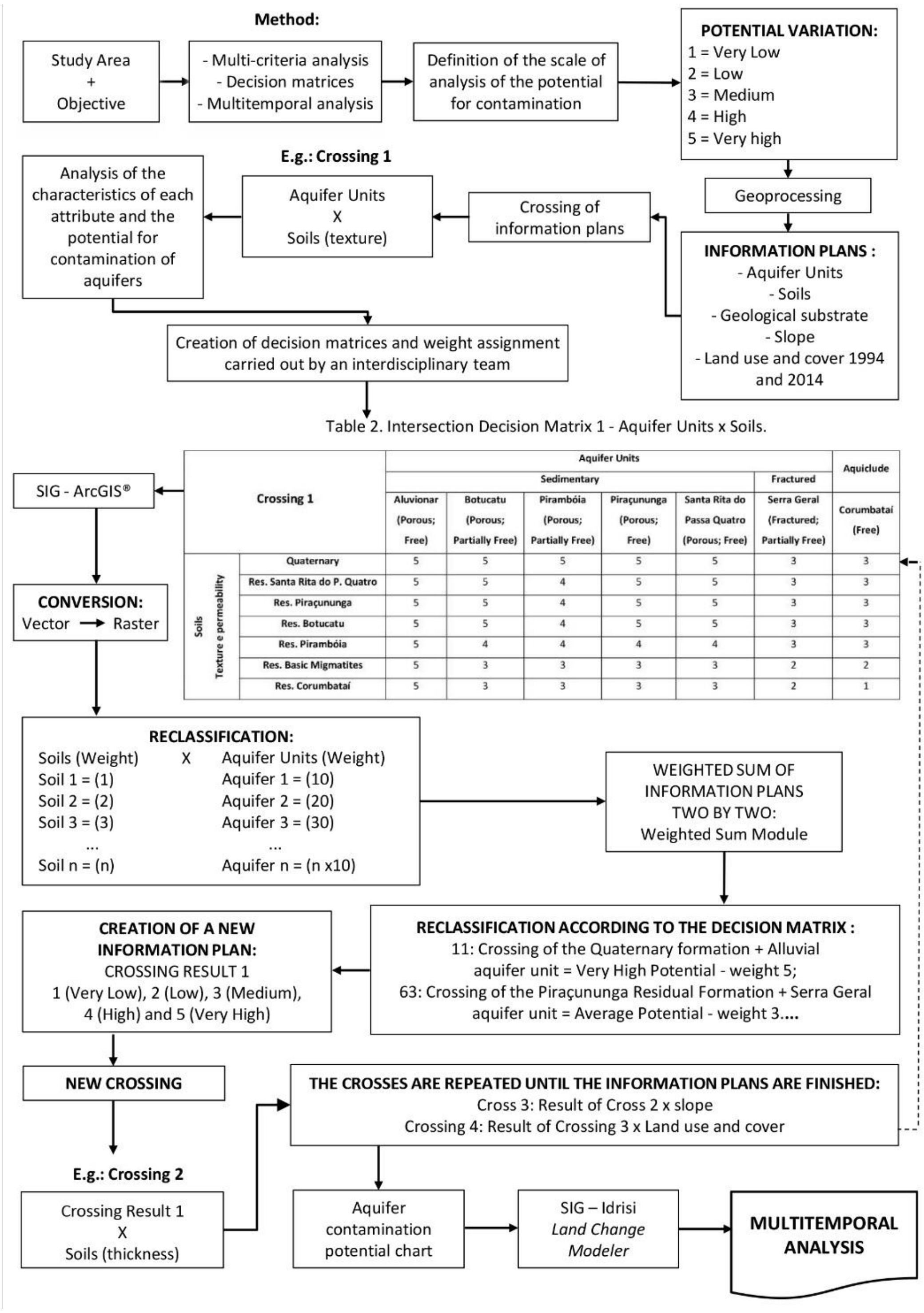
Multicriteria analysis was used, based on decision matrices and the evaluation of criteria by a multidisciplinary team. Multicriteria analysis is characterized by the logical overlap of attributes of the physical environment and anthropic in the GIS environment.

From this process, the analysis of the various criteria was obtained, which led to the verification of the contamination potential of aquifers during 20 years (1994 and 2014), and descriptive scenarios arising from changes in land use that occurred during this period. Figure 3 illustrates the method used, containing, as an example, the first overlap (Aquifer Units x soils – texture and permeability).

Figure 3 - Flowchart of the multicriteria analysis process.



Crossing 1		Aquifer Units						Aquiclude
		Sedimentary					Fractured	
		Aluvionar (Porous; Free)	Botucatu (Porous; Partially Free)	Pirambóia (Porous; Partially Free)	Piraçununga (Porous; Free)	Santa Rita do Passa Quatro (Porous; Free)	Serra Geral (Fractured; Partially Free)	Corumbataí (Free)
Soils – Texture e permeability	Quaternary	5	5	5	5	5	3	3
	Res. Santa Rita do P. Quatro	5	5	4	5	5	3	3
	Res. Piraçununga	5	5	4	5	5	3	3
	Res. Botucatu	5	5	4	5	5	3	3
	Res. Pirambóia	5	4	4	4	4	3	3
	Res. Basic Migmatites	5	3	3	3	3	2	2
	Res. Corumbataí	5	3	3	3	3	2	1

Org.: The Author, 2020.

The map algebra, related to the use of defined weights, was based on the methodology described by Costa et al. (2019), which consisted of the integration of information plans in a GIS environment, through decision matrices, using the Weighted Sum tool of the ArcGIS software® 10.2 (ESRI, 2013). The crossings of the geoenvironmental attributes were performed two by two, and the weights, with values ranging from 1 to 5 (Very Low and Very High), were established from the experience and expertise of researchers in the area of geosciences, from Tables 3 to 5.

Table 3 - Crossing decision matrix 2 - Result 1 x soils (thickness).

CROSSING 2		Soils (thickness)		
		(>5m)	(2 – 5m)	(<2m)
Result 1	Very Low - 1	1	2	3
	Low - 2	1	2	3
	Average - 3	2	3	4
	High - 4	3	4	5
	Very High - 5	4	5	5

Org.: The Author, 2020.

Table 4 - Crossing decision matrix 3 - Result 2 x Slopes.

CROSSING 3		Slopes				
		> 20%	10 - 20%	5 - 10%	2 - 5%	0 - 2%
Result 2	Very Low - 1	1	1	1	2	3
	Low - 2	1	1	2	3	4
	Average - 3	2	2	3	4	4
	High - 4	3	4	4	5	5
	Very High - 5	3	4	5	5	5

Org.: The Author, 2020.

Table 5 - Crossing decision matrix 4 - Result 3 x Land use and cover.

CROSSING 4		Land use and coverage						
		Sugarcane	Water	Other uses*	Pasture	Exposed soil	Native vegetation	Urbanized area
Result 3	Very Low - 1	2	3	2	1	2	1	2
	Low - 2	3	3	2	2	3	1	3
	Average - 3	4	4	3	3	4	2	4
	High - 4	5	5	4	4	5	2	5
	Very High - 5	5	5	5	5	5	3	5

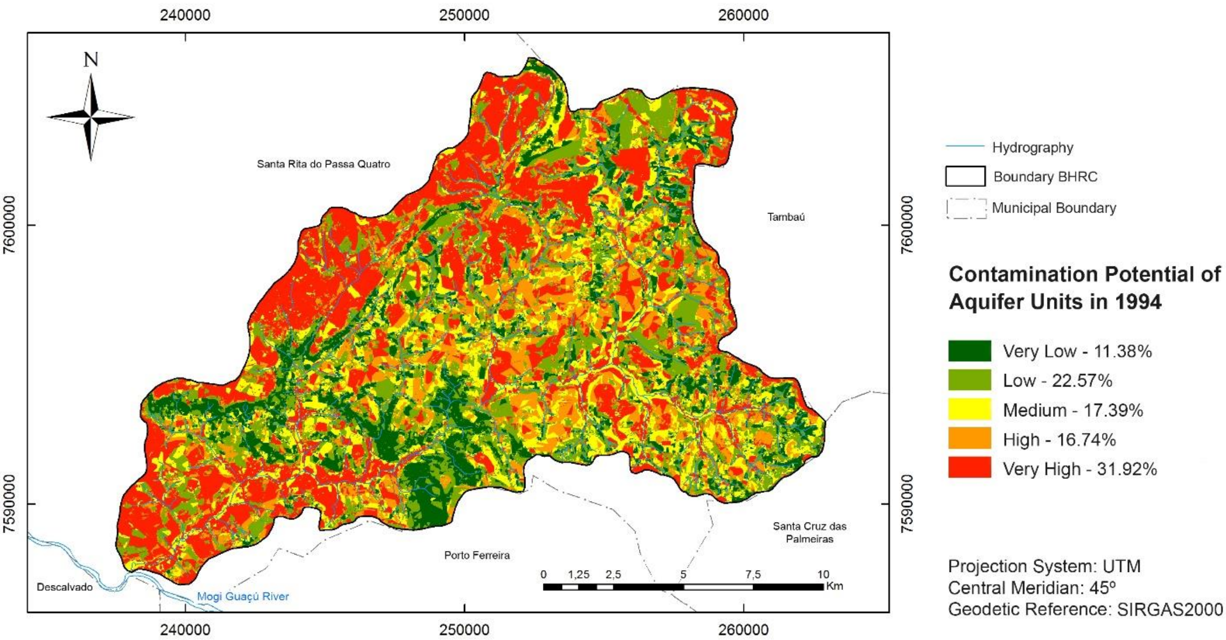
*Citrus, Coffe, eucalyptus. Org.: The authdo Autor, 2020.

Crossing decision matrix 4 - Result 3 x Land use and cover. In order to evaluate the changes in land use and land cover, was used the Land Change Modeler module (EASTMAN, 2012) of the Idrisi Selva software based on 1994 - 2014 classifications. The techniques used to create scenarios considering historical data were based on the works of Oñate-Valdivieso and Sendra (2010) and Huong and Pathirana (2013).

RESULTS AND DISCUSSIONS

The results with the five hierarchical levels of groundwater contamination potential, considering land use and cover in 1994, are shown in Figure 4.

Figure 4 - Potential contamination of aquifer units in 1994.



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The high and very high contamination potential classes represent 46.1% of the watershed area. The significant percentage of these high and very high potential classes is a reflection especially of the geological environment, which presents in most of its area porous aquiferous units, free and partially free, in lithostratigraphic units constituted by sandstones.

The most frequent class in spatial terms (30.7%) is that of very high potential of contamination, whose areas are concentrated in the NW and SW portions of the watershed.

In addition, the characteristics of the aquifer units had a great influence on the identification of high and very high potential classes because they are covered by soils of sandy texture, in areas of low slope of the land associated with land uses that favor infiltration (especially agricultural).

The high potential class represents 15.4% and is spread through the watershed. It results from bythe combination of sandy soils covering porous aquifers, partially free, in exposed soil areas and slopes below 10%.

The designated medium potential class (17.1%), which is also dispersedin the area, is mainly due to the combination of low slope with profiles of soils of small thickness and exposed soil, which makes even areas of occurrence of semi-confined aquifer units present medium potential.

The areas with low contamination potential represent the second most frequent class (24.0%), and their identification is associated with the areas of semi-confined aquifer units in high slope reliefs, alteration profiles with greater thicknesses and in areas generally occupied by forests.

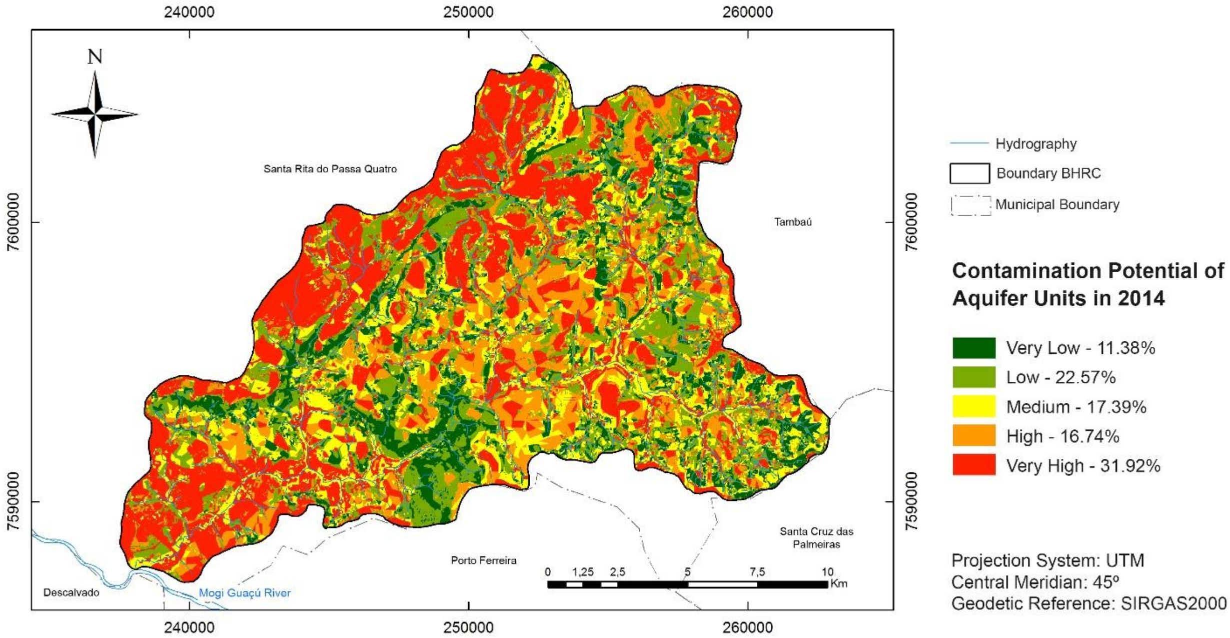
Finally, areas classified as very low potential (12.7%) were related to areas of greater slope and forests.

The classification of contamination potentials in 2014 illustrates how changes in land use and cover patterns that occurred in the area can influence the vulnerability of aquifer units (Figure 5).

In 2014, the very high contamination potential class represented the highest percentage of the area (31.9%) that along with the high potential class, represented 48.6% of the watershed area.

When compared to 1994, the areas classified as very high potential remained practically the same, occupying areas in the NW and SW regions, due to the same factors: porous and free aquifer units, covered by soils of sandy texture in areas of low slope and agricultural use, in the cultivation phase or preparation of the land for planting.

Figure 5 - Potential contamination of aquifer units in 2014.



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Similarly, the high potential class (16.7%) brought free and partially free aquifer units, with coverage of sandy soils with small to medium thickness and agricultural use. Its spatial distribution occured dispersedly throughout the hydrographic watershed, being higher in the central region.

Average contamination class (17.4%) occurs in a dispersed pattern in the area, despite its common occurrence in bottoms valleys, associated to alluvionar aquifer (porous and free).

The low and very low potentials (22.6 and 11.4%, respectively) were concentrated in the higher portions of the land, in an area with slopes greater than 10% in the aquifer units called Corumbataí and Basic Intrusives.

Influence of land use and cover changes

Lnad use / land cover changes ussually increase groundwater contamination potential. Thus, the spatialization of this dynamic has fundamental importance for a better understanding of how they directly affect ecosystem services, especially water supply for industrial and agricultural use.

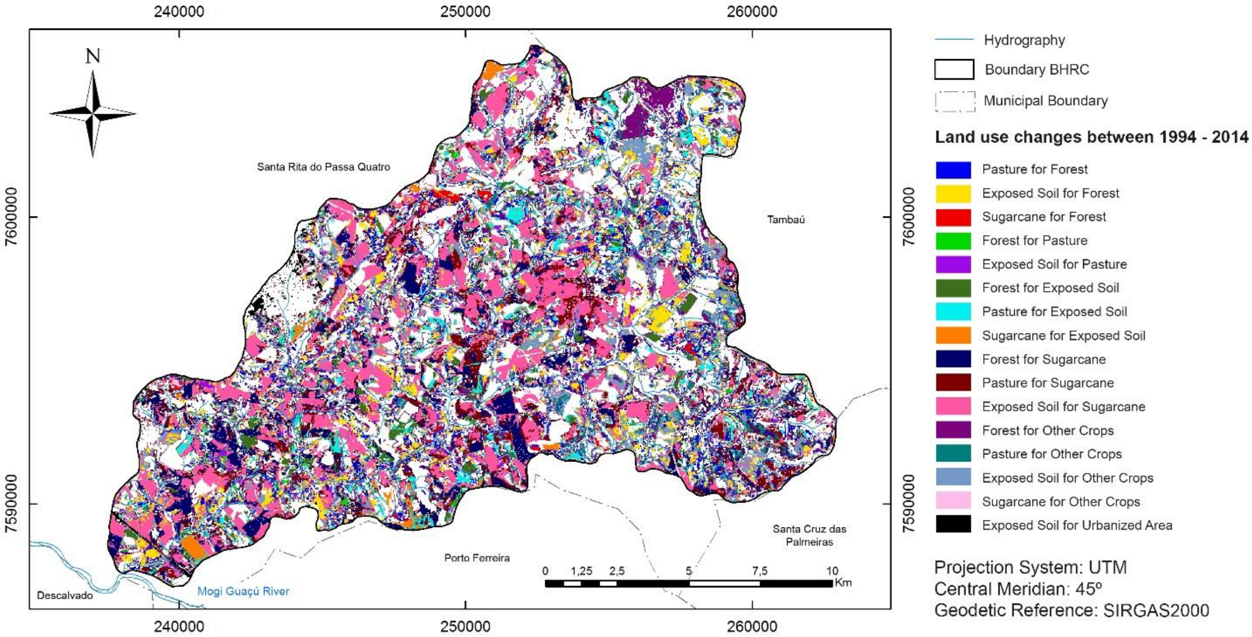
The land use and cover charts from 1994 and 2014 showed a scenario common to much of the interior of São Paulo, especially the replacement of rural pasture areas for annual crops, in particular sugarcane.

In 1994, urban areas represented 1% of the watershed, sugarcane 8%, exposed soil 38% and pastures 19%. The high percentage of exposed soil occured as a function of the preparation for cultivation and the pasture areas with low plant density, mainly in the dry season. The percentage of 33% covered by forests in 1994 reflects the typically pastoral use in the watershed with natural pastures, without the removal of tree vegetation cover.

In 2014, urban areas started to occupy 5% of the watershed, sugarcane 34%, exposed soil 13% and pastures 4%. It is important to highlight that even with the growth of the watershed portion occupied by sugarcane plantations, the percentage of forests did not present significant reduction, a fact related to the location of these tree coverings in areas with steeper slopes or in areas of litholic soils, not favorable for the sugarcane farming.

Considering that the physical attributes such as geology, soils and slope did not undergo significant changes in the period, the use of the Land Change Modeler allowed verifying the dynamics of changes in use and coverage in the area, which are intrinsically related to the changes in the potential for groundwater contamination for the years 1994 – 2014. In Figure 6, it is possible to identify important changes in the exposed soil and sugarcane classes.

Figure 6 - Changes in land use and land cover (1994-2014).



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Persistence (areas that had no changes in land use and land cover) for the same classes are presented in Figure 7. In this case, persistences in the forest, exposed soil, and sugarcane classes are evident.

Figure 7 - Persistence of land use and cover (1994-2014).

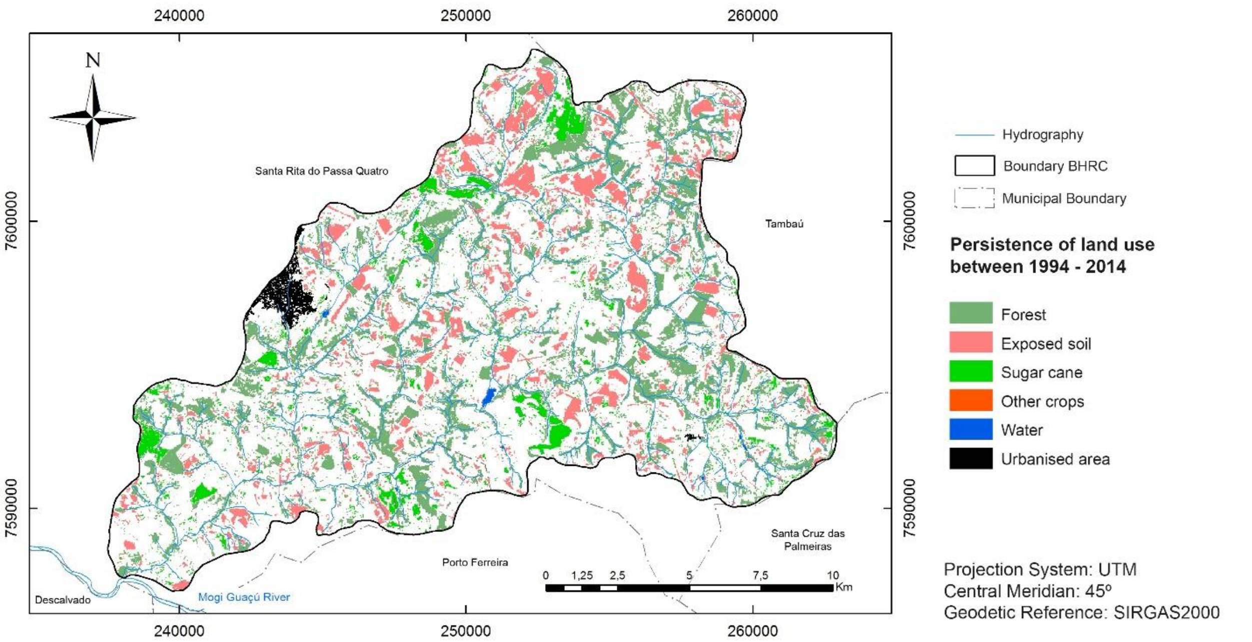

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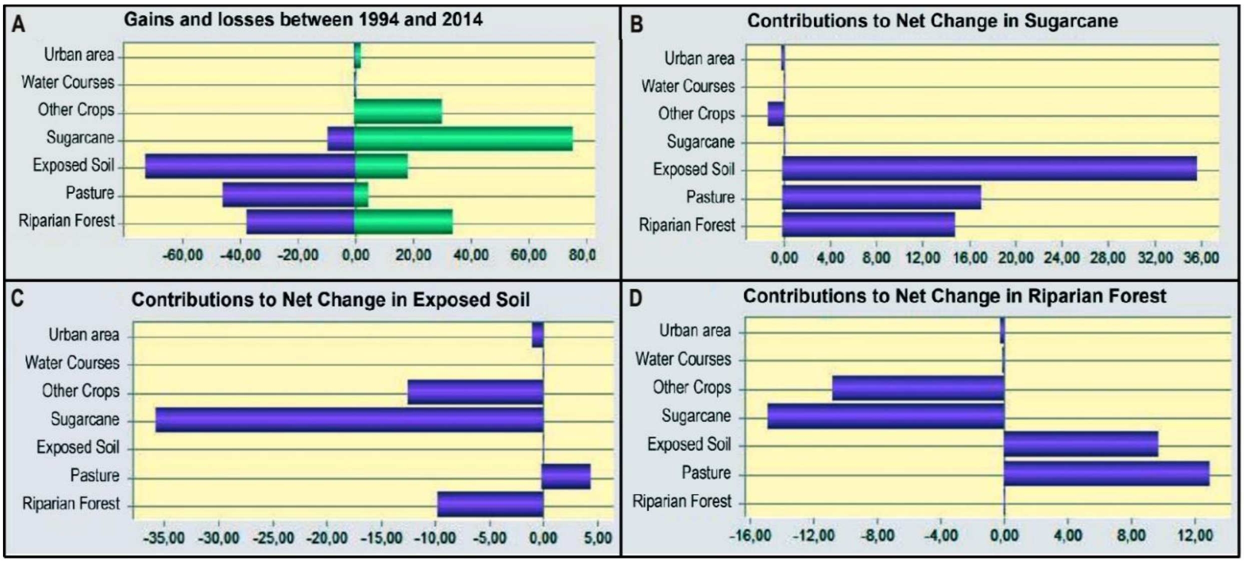
Figure 8 shows the gains and losses in land use and land cover changes between 1994 and 2014. The persistences in plots of the area classified as sugarcane are justified because they are properties that traditionally present such cultivation. On the other hand, the areas with persistence of the exposed soil class occured due to the constant preparation of the lands to receive the sugarcane in addition to areas with rarefied vegetation, especially in the dry season.

Figure 8 - Gains and losses on land use and coverage changes between 1994 and 2014 (A), changes in increasing the sugarcane (B), reduction of exposed soil class (C) and changes in the reduction of the riparian forest (D).



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The most notable changes (Figure 8a) have a direct correspondence with the significant growth of the sugarcane class and the emergence of the class other crops, with strong reductions in classes, exposed soil and pasture, and a small reduction in the forest class.

It is also verified that the increases in the sugarcane class occurred particularly at the expense of reductions in the exposed soil classes (35%), pasture (17%) and forest (14%) (Figure 8b); while the reduction in exposed soil class resulted from the expansion of sugarcane areas and other crops (Figure 8c).

Important portions of the forest class had their use changed for the sugarcane and exposed soil classes (Figure 8d). This indicates inefficient supervision and a lack of awareness, and this substitution must be prevented in every way. However, the new Forest Code of 2012 (BRASIL, 2012) made this protection more fragile, especially in the areas of permanent preservation of watercourses, which largely decreased from 30m to 5m. In the case of reservoirs, the difference in altitude between the maximum quota previously used (BRASIL, 1965) and the operational quota currently used generated significant losses of marginal vegetation, a good example is verified in the study by (ROCHA; FREITAS; CASQUIM, 2019). The hilltops practically ended up with the understanding that preservation should start from the "saddle point quota closest to the elevation". Here, it is worth pointing out that it was an unprecedented environmental setback. On the other hand, the Atlantic Forest Law (BRASIL, 2006) should be another way to prevent this negative trend, however, there is small effectiveness in compliance with the law.

Given the surveys carried out for the characterization of the attributes of the physical environment and changes in land use as well as cover identified in the watershed, it is possible to relate this set of information with the observed dynamics, considering also results obtained by other authors in contiguous watersheds that present the same geological and geomorphological context.

Based on regional terms, it is common to find researches (LOLLO, 1991; BROLLO, 1991; AGUIAR, 1995) that highlight the occurrence in the region of units of residual and reworked materials of sandy texture, with thick alteration profiles, and high porosities. Such alteration profiles, besides being very favorable to infiltration, occur more frequently on hilltops with low slopes (usually less than 5%), a geological context characteristic of recharge areas in this portion of the Peripheral Depression.

Considering the potential for aquifer contamination and its relationship with geoenvironmental units, Costa et al. (2015b) established the relationship between the aquifer units with clastic lithologies and sandy texture (Pirambóia, Botucatu and Tatuí) and the soils residual materials of sandy texture derived from them and high potentials of contamination, particularly when the conditions of use and land cover favor the appearance of sources of contamination. Analogous conjunction of factors is repeated in the Rio Claro Hydrographic watershed, in particular concerning the Pirambóia Aquifera Unit.

Territorial planning and groundwater protection strategies

In Brazil, there is no specific legislation directly aimed at the protection of aquifer recharge areas, with regional and continental importance.

In the State of São Paulo, Decree Num. 32,955/91 regulating Law Num. 6,134/91 provides that the recharge areas to be protected will be "established based on hydrogeological studies, after the municipalities and other interested bodies". This Decree also classifies as "Maximum Protection Area: comprising, in whole or in part, aquifer recharge areas that are highly vulnerable to pollution and constitute essential water deposits for public supply" (MORAES et al., 2016).

In the absence of a federal or state law defining the protection areas for recharge, the Master Plans of the municipalities located mainly in the outcrops of the Botucatu and Pirambóia Formations, which constitute the Guarani Aquifer, assume an important role and should complement such laws (COSTA et al., 2019).

However, as also verified by Moraes et al. (2016), the Master Plan of Santa Rita do Passa Quatro (SANTA RITA DO PASSA QUATRO, 2006) does not include a specific zoning for the highly vulnerable areas in relation to groundwater contamination (Botucatu and Pirambóia), which are also direct recharge of the Guarani Aquifer. For these areas, the definition of natural heritage protection units seems to be the most viable alternative for protecting groundwater..

Given the vast change in natural conditions identified in the Claro River Watershed and the lack of specific laws, it is up to the technicians in the area to propose territorial management strategies that reduce the negative impacts of human activities on underground water resources in the spring:

Laws on a more refined scale should be included in municipal legislation in order to plan land use specifically in the outcrops areas of the Aluvionar, Botucatu and Pirambóia aquifers. In these areas, the greatest potentials of contamination were found, concomitantly, is where the capacity of infiltration of rainwater is intensified.

Priority should be given to revegetation practices on the tops of hills, places that, when preserved with native vegetation, favor water infiltration and recharge (ROCHA, 2019).

Monitor in situ, the use of agrochemicals in sugarcane crops and citrus on porous and free aquifer units, as is the case of the Aluvionar Aquifer, Botucatu and Pirambóia.

Make mandatory the territorial protection of the areas of the Aquifer Alluvial, which are arranged in the bottom areas of valleys and, usually, have a connection with the saturated zone. The protection of native vegetation in these areas will serve as a natural filter intended to contain sediments and diffuse pollution carried along with surface runoff, especially when these alluvial plains are surrounded by sugarcane and citrus cultivation. Studies showing the importance of these 'buffering' zones were presented by Attanasio et al. (2013), Schilling and Jacobson (2014), Tanaka et al. (2016), Tromboni and Dodds (2017), Maello et al. (2018), Valera et al. (2019) Rocha et al. (2019) and Guidotti et al. (2020).

- In order to make municipal legislation more protective than Technical Standard P4.231 (CETESB, 2014), which allows the application of vinasse in free aquifers (more susceptible to contamination) with a depth of water level of at least 1.5m, the use of pesticides and fertigation in the domains of the Alluvial aquifer (porous and free) should be prevented, as they represent potential sources of chemical and organic contamination.

Form a single register of rural properties in order to subsidize, on a municipal scale, the monitoring of the areas of legal reserve of permanent preservation according to the legislation.

In order to intensify the protection of areas with higher contamination potentials, the Payment for Environmental Services (PSA) should be implemented to rural producers who conserve their springs covered by tree vegetation, along the lines of the "Conservative Water Program", implemented in the municipality of Extrema, MG (JARDIM; BURSZTYN, 2015).

FINAL CONSIDERATIONS

The Rio Claro hydrographic watershed presented a high rate of aquifer contamination potential for the analyzed period. In 1994, the high and very high contamination potential classes covered 46.1% of the watershed area, while in 2014, this percentage increased to 48.6%.

This representativeness in the watershed is notable for the hydrogeological characteristics of the area that dominantly presents porous, free and partially free aquifer units, in lithostratigraphic units constituted predominantly by sandstones from the Paraná Sedimentary basin. Concomitantly with this subsurface condition, the occurrence of soils with sandy texture, high permeability coefficients in areas of low slope of the land and land uses destined to agricultural activity, especially sugarcane, were determinant to increase the degree of potential contamination of groundwater.

When considering the impacts of the variation of land use and cover on the potential for contamination, it was found that the interleaving between sugarcane cultivation and exposed soil (prepared for cultivation) was fundamental to maintain the high potential for aquifer contamination. Thus, it is evident the need to adopt conservation practices in sugarcane cultivation, especially in the off-season, to minimize the negative environmental impacts of this crop.

ACKNOWLEDGMENTS

The authors acknowledge the São Paulo State Research Support Foundation (FAPESP) Process 2013/03699-5, the Brazilian National Research Council (CNPq) Process 443802/2014-9 and Coordination for the Improvement of Higher Education Personnel (CAPES) Funding Code 001 for the financial resources that made feasible the development of this work.

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