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Surface runoff associated with climate change and land use and land cover in southeast region of Brazil

Leticia Tondato Arantes[a], Ana Claudia Pereira Carvalho[b], Ana Paula Pereira Carvalho[b,*], Reinaldo Lorandi[b], Luiz Eduardo Moschini[b], José Augusto Di Lollo[a]

[a] Civil Engineering Department, São Paulo State University, Avenida Brasil, 56, CEP 15385-000, Ilha Solteira, SP, Brazil
[b] Department of Environmental Sciences, Federal University of São Carlos, Washington Luís Highway, km 235, SP-310, CEP 13565-905, São Carlos, SP, Brazil

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ABSTRACT

Changes in climate and in land use/cover can compromises water resources availability and quality, conditioning the planning and management of these essential resources. The objective of this research was to understand the environmental dynamics of the studied region considering this context and to develop instruments for the best management of water resources, based on Potential Runoff Charts generated from natural and anthropic environment attributes consideration in the years 2001 and 2017. The study area was the Rio Claro Watershed (RCW), which covers 251.91 km^2 and is located in the northwest region of São Paulo State, Brazil. Analytic Hierarchy Process (AHP) was used to define weights of the environmental attributes: steepness; total annual rainfall; land use/cover; soil; landforms; and aquifer units. The charts present the surface runoff in five classes (Very Low, Low, Medium, High, and Very High). The results showed significant changes in the period, due to climate changes, and, secondly, due to land use/cover changes. While in 2001 the Low and Medium Potential classes (59.3%) predominated, in 2017 the Medium and Very Low Potential classes (56.5% total) were the most common. High and Very High Potential classes showed small variations in the two years. Results derivate especially from lower rainfall in 2017 compared to 2001, showing that climate changes does not always mean an increase in rainfall on a regional scale and that water resources management instruments should consider such situations. The proposed measures aim to favor infiltration, reduce erosive processes, and favoring aquifers recharge.

1. Introduction

Freshwater resources are increasingly scarce, requiring effective water management tools (Anderson et al., 2012; Huntjens et al., 2012). A set of factors such as agricultural and urban uses, hydroelectric power generation and climate change has influenced this reality, requiring river basin management plans that allow the implementation of new environmental policies (Hering et al., 2015; Nkwonta et al., 2017).

According to Molina-Navarro et al. (2018), it requires interdisciplinary approach to understand the factors involved and their interactions, and contributes to water resources impact mitigation. Adequate land use planning is central in such approach (Neupane and Kumar, 2015). Long-term management of water resources also depends on understanding the effects of climate and land use/cover changes on watershed dynamics (Dixon and Earls, 2012; Zhou et al., 2015; Anache et al., 2018).

Anthropogenic activities modify land use and cover, contributing to the alteration of hydrological processes, and generating negative impacts on the environment (Dey and Mishra, 2017; Ahn and Merwade, 2017). As example, soil occupation is becoming increasingly evident as a relevant factor in hydrological processes at the regional and watershed levels. So, a better understanding of how changes in soil occupation interfere with hydrological systems is necessary for better management of water resources formulation. Several authors have presented studies considering how land use and land cover patterns and climate change can influence surface runoff (Zhang et al., 2015; Paule-Mercado et al., 2017; Guzha et al., 2018; Paule-Mercado et al., 2018; Zhang et al., 2020; Risal et al., 2020).

Le et al. (2018) emphasize the mutual dependence between water resources and human uses, the availability of water, enabling patterns of use, and this, in turn, affecting water supply and quality. The changes in soil use and cover influence processes of surface runoff, aquifer recharge,

* Corresponding author.
E-mail addresses: letondato@gmail.com (L.T. Arantes), anaclaudiaengamb@gmail.com (A.C.P. Carvalho), appc.engambiental@gmail.com (A.P.P. Carvalho), lorandir@gmail.com (R. Lorandi), lemoschini@ufscar.br (L.E. Moschini), jose.lollo@unesp.br (J.A. Di Lollo).

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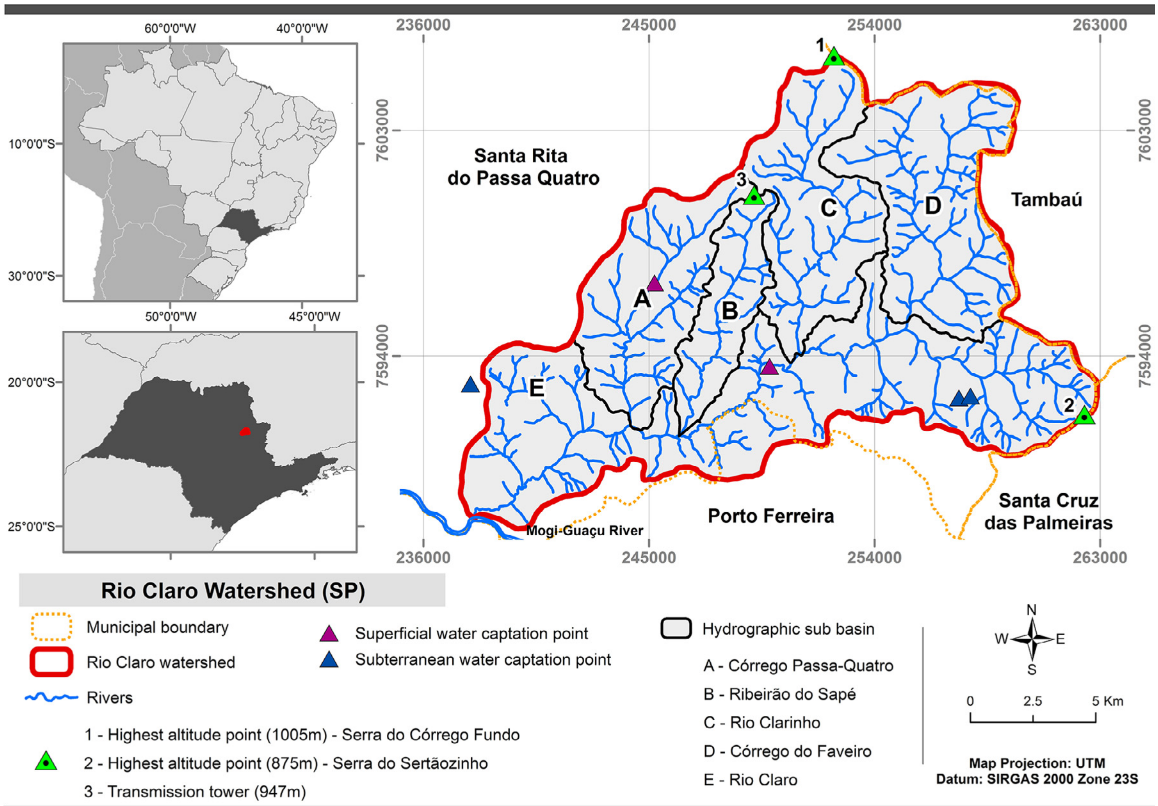

Fig. 1. Rio Claro watershed location.

infiltration, interception and evaporation, which affect water availability (Sajikumar and Remya, 2015) and water quality (Tong et al., 2012).

Serpa et al. (2015), Mohammad and Adam (2010), Mohamadi and Kavian (2015) highlight the influence of land use/cover changes in environmental degradation, mainly soil erosion and sediment transportation to water bodies (Abdelwahab et al., 2014; Mohamadi and Kavian, 2015). Thus, studies dealing with changes in land use and land cover based on patterns and dynamics play a major role in resource planning and management processes (Assis et al., 2014; Butt et al., 2015).

The knowledge of soil cover changes allows to identify its effects on the hydrological processes (Warburton et al., 2012), and to understand the influence of changes in use and coverage in order to predict its hydrological consequences (Woldesenbet et al., 2017; Korkanç, 2018).

Fang et al. (2014) highlight recent attention to environmental outspreads due to climate change, involving monitoring and modeling studies aimed at environmental management. Climate change can affect the availability of long-term and short-term water resources (Ye et al., 2013), and generate large-scale droughts and flood phenomena (Olmstead, 2014).

In this context, the integration of climate change and human interference with data from the natural environment allows understanding of the dynamics of the watersheds, allowing the proposition of instruments for local and regional management of water resources.

Given this, the main objective of the article was to elaborate the Surface Runoff Potential Chart for the Rio Claro watershed, based on the weighting of attributes of the natural and anthropic environment, using the map algebra technique based on the Analytic Hierarchy Process (AHP). The product had the purpose of identifying how these attributes interfere with the water behavior of the area. The study area was chosen because it presents records of environmental degradation (floods, changes in water courses and widespread occurrence of erosion processes), resulting in water resources quality problems.

2. Studied area

The Rio Claro Watershed (RCW) is part of the Water Resources Management Unit 09 of the State of São Paulo (FEHIDRO - Fundo Estadual de Recursos Hídricos, 2011), presents an area of 251.91 km^2 and has its location shown in Fig. 1, where they are also presented the hydrographic sub-basins referring to the Córrego Passa-Quatro, the Ribeirão do Sapé, the Rio Clarinho, the Córrego do Faveiro and the Rio Claro.

Mendonça and Danni-Oliveira (2007) describe the climate in the basin as Tropical Wet-dry (4a), with dry winter with 4 to 5 months, and concentrated rainfall in the summer, between October and April. Regarding the characteristics of the RCW geological units, these are briefly described in Table 1, with their respective geochronological units (Era and Period).

In 55.40% of the area, there are concave medium hills with slopes between 5% and 10%; medium hills cover 15.90% of the area in areas with slopes lower than 5%. The other forms of relief in the area are small convex hills (12.33%), scarps (7.50%), wide open valleys (7.29%), and small closed valleys occupying 1.39% of the area (Lorandi and Lollo, 2016).

According to (IF - Instituto Florestal do Estado de São Paulo 2010), the RCW conserves an important part of the remaining vegetation cover of the Atlantic Forest biome, with semideciduous forests, as well as floodplains and cerrado areas to a lesser extent. In addition to remnants of native vegetation, agricultural activities (sugarcane, coffee, citriculture, forestry), pasture, urbanization and mining were identified.

The soils in the basin have predominantly sandy texture, with the exception of the residual soils of Basic Magmatites and Corumbataí For-

Table 1
Litostratigraphic units on Rio Claro watershed.

Unity	Era & Period	Description
Alluvial Deposits	Cenozoic; Holocene	They occur in broad alluvial plains of the Rio Claro and its main tributaries. They are deposits of sandy texture originating from the erosion of adjacent lithologies.
Pirassununga Formation	Cenozoic; Tertiary	It is composed of light brown sandy-clayey sediments of massive structure, poorly selected, with a line of quartz pebbles, quartzite, and limonite fragments at the base, overlapping in a discordant manner on the Corumbataí Formation.
Santa Rita do Passa Quatro Formation	Cenozoic; Tertiary	It consists of sands in a clayey matrix, friable, without sedimentary structures, of brown color, with thickness of 5 to 15m, with basal gravel of predominantly quartz pebbles. In the area these sediments present dispersed quartz granules.
Intrusive Tabular	Mesozoic; Cretaceous	They are made up of sills and dikes of basic magmatites, of faneritic texture and coloration gray to black, intensely fractured.
Botucatu Formation	Mesozoic; Jura/ Cretaceous	It is composed of sandstones attributed to deposits in a desert environment, from fine to medium granulation, well rounded particles, quartz composition (80%), and thickness ranging from 20 to 280 m.
Pirambóia Formation	Mesozoic; Triassic	Composed of whitish, yellowish and rosy fluvial sandstones, medium to fine, sometimes quite clayey.
Corumbataí Formation	Paleozoic; Permian	Composed of variegated shales, being positioned between Irati (lower) and Pirambóia (upper) formations.

Table 2
Geotechnical characterization of soils (mean values).

Soils	Area (km^2)	Thickness (m)	Granulometry (%)*			K_{20} (cm/s)[b]	Mini MCV[c]
			Ag	S	Ar		
Quaternary	15.87	< 2, 2 - 5	5	4	91	$6.1\ 10^{-3}$	NA
Santa Rita do Passa Quatro	45.72	> 5	14	8	78	$3.7\ 10^{-2}$	NA'
Pirassununga	11.38	> 5	28	7	65	$4.2\ 10^{-3}$	NA'
Botucatu	17.65	< 2, > 5	20	5	75	$3.8\ 10^{-3}$	LA
Pirambóia	11.38	< 2, > 5	24	6	70	$7.1\ 10^{-3}$	LA
Magmatitos Basics	26.48	< 2, 2 - 5, > 5	47	17	36	$4.9\ 10^{-4}$	LG'
Corumbataí	19.65	< 2	77	9	14	$4.1\ 10^{-4}$	NG'

*Ag: Clay, S: Silt, Ar: Sand
[b] coefficient of permeability
[c] Moisture Condition Value

mation, according to mean values (area, thickness, granulometry, K_{20} and Mini Moisture Condition Value) presented in Table 2.

3. Materials and methods

The sequence of methodological procedures adopted in this study is shown in Fig. 2, and includes the choice of environmental attributes, the weighting of the classes of each environmental attribute using the AHP method, and the overlapping of attributes in the ArcGIS® software. Table 3 presents the sources of data and information used for the elaboration of the Surface Runoff Potential Chart.

The weights definitions for Surface Runoff Potential Charts production was based on AHP (Analytic Hierarchy Process) method of Saaty (1980), whose criteria of weight assignment are presented in Table 4. The relative priorities among attributes were based on available knowledge about the studied area. The attributes used in the analysis were: terrain steepness; landforms; soils; aquifer systems; land use/cover (2001 and 2017), and annual rainfall (2001 and 2017). These years were chosen because they represent the period of the history of RCW with significant changes in land use/cover, especially the expansion of sugar cane cultivation.

Rainfall data were obtained from the National Institute of Meteorology (INMET, 2018) and the Department of Water and Electrical Energy (DAEE, 2018) data, based on four climatic stations: São Carlos (x: 204616.7 and: 7568841.9); São Simão (x: 235773.8 and: 7622573.9); Luís Antonio (x: 199790.9 and: 7625702.7); and Vargem Grande do Sul (x: 303625.8; y: 7584409.3), coordinates in Datum SIRGAS 2000. Rainfall data were spatially generalized by estimation by ordinary kriging on software Surfer®, generating the rainfall maps for the years 2001 and 2017.

In the map algebra generation from AHP use, the weights of each class of the attributes in the analysis was defined by the AHP eigenvectors, using Reclassify tool of ArcGIS 10.5.1®. Subsequently, a consistency analysis of the weights adopted for the information plans was carried out, in this way, the Consistency Ratio (RC) and the Consistency Index (CI) were calculated, according to the equations in Table 5, proposed by Saaty (1980). The weights adopted can be considered coherent if the RC ≤ 0.10.

The weights adopted through the AHP method for each class of attributes are shown in Table 6. Based on the weighting of the information plans, the RCW ArcGIS the Surface Runoff Potential Charts software was developed. Figs. 3 and 4 show, respectively, the spatial distribution of the attributes of the natural environment in the area, and the distribution of land use/cover and precipitation for 2001 and 2017, with the quantification of the area of each class (in km^2 and %).

The map algebra was developed using Weighted Sum function, and the used weights corresponded to the values of the eigenvectors for each environmental attribute obtained from AHP, as shown in Table 7.

The weights of the environmental components were defined considering its importance on surface runoff in the watershed. The steepness was the component that received the highest weight since it is a determinant factor in the local surface runoff; rainfall was the second component in importance, since the regional climate is characterized by rainfall concentrated in short periods of the year (four months of summer).

The components soil, landforms, and aquifer systems resulted in lower weights depending on the preferences adopted. The reasons for

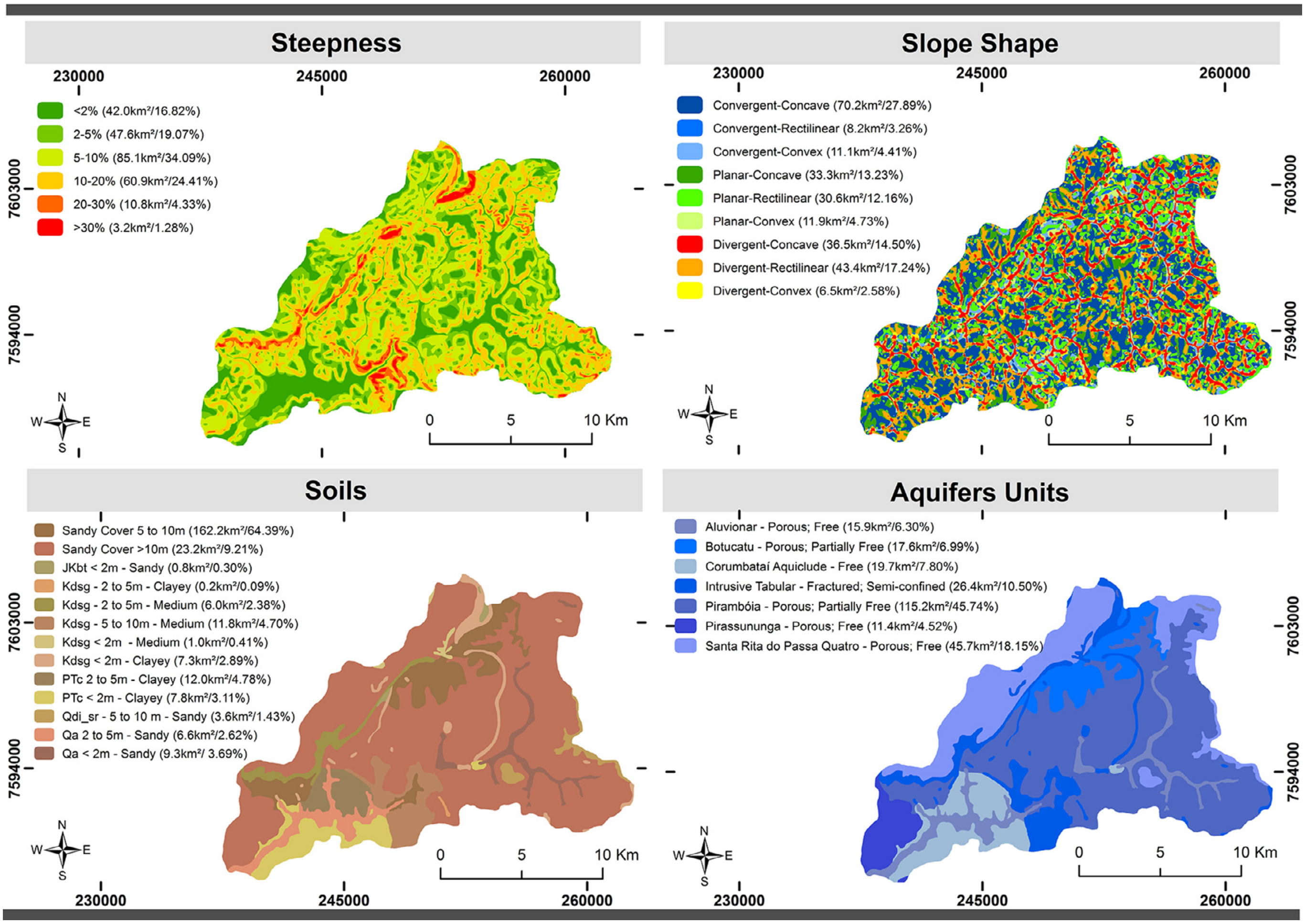

Fig. 3. Attributes of the natural environment used for Surface Runoff Potential Charts production in 2001 and 2017.

Table 3
Information of the environmental attributes used to elaborate the classes.

Data	Description	Source	Scale
Physiographic limits	Claro River Watershed and its sub basins limits	Developed by the authors through Global Mapper® software	1:50,000
Relief	Steepness	DataGEO (2018) - Environmental System Paulista	1:50,000
	Slope Shape	Topodata - (INPE - Instituto Nacional de Pesquisas Espaciais 2017)	1:50,000
Soils	Soils Class	Lorandi and Lollo (2016)	1:50,000
Rainfall	Total Annual Precipitation	INMET (2001 and 2017) DAEE (2001 and 2017)	-
Aquifer systems	Aquifers Units	Lorandi and Lollo (2016)	1:50,000
Land use and cover	Land Use and Cover Class	LandSat 7 (23/03/2001), R6G5B4 composition, 15m resolution. LandSat 8 (01/03/2017) R6G5B4 composition, 15m resolution.	1:50,000

Table 4
Scale of hierarchical values.

Scale of Hierarchical Values			
Values	Importance	Values	Importance
1/9	Extremely less importance	3	Moderate importance of one over another
1/7	Much less strongly importance	5	Essential or strong importance
1/5	Strongly less importance	7	Very strong importance
1/3	Moderately less importance	9	Extreme importance
1	Equal importance	2, 4, 6 and 8	Intermediate values

Source: Saaty (1980).

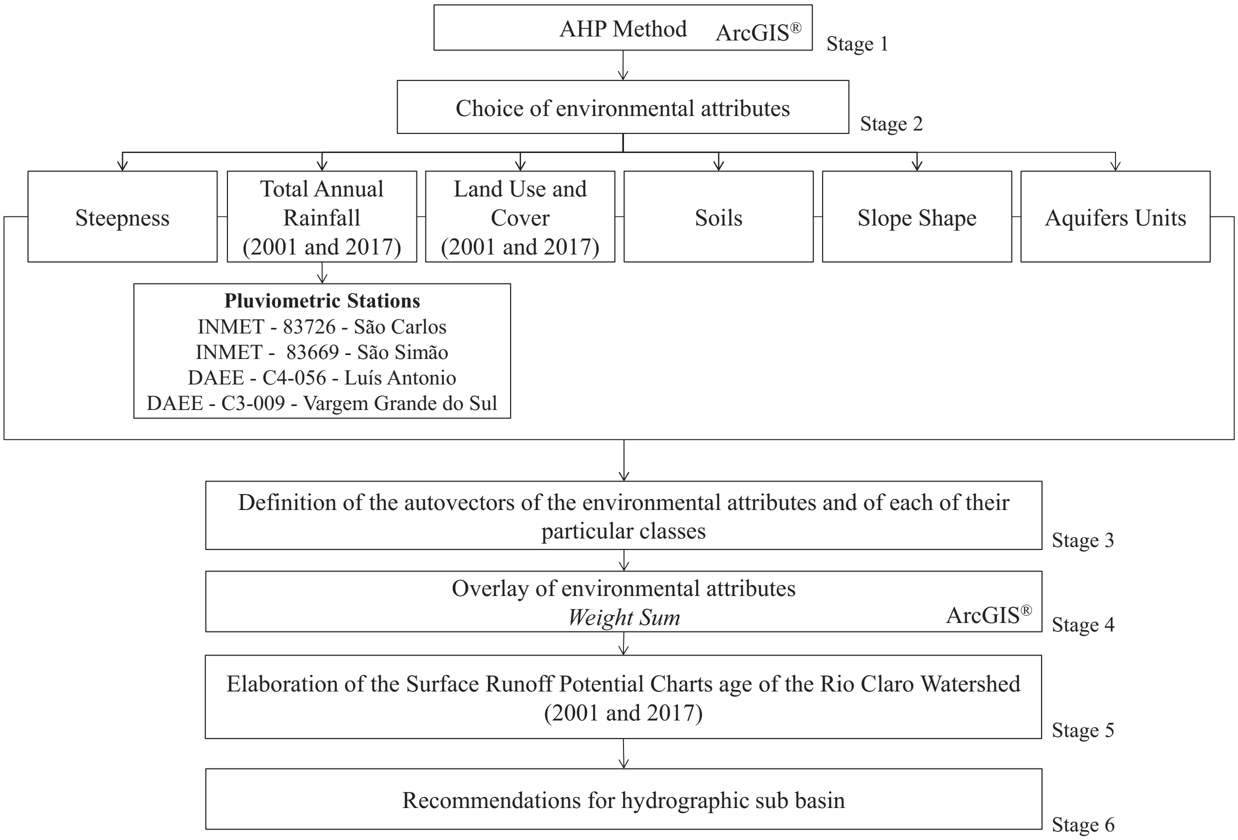

Fig. 2. Synthesis of the steps developed in Claro River Watershed analysis.

Table 5
Consistency analysis equations and random consistency index according matrix order.

Equations					Description of Equation Variables									
$RC = \frac{IC}{IR}$					RC = Consistency Ratio					$\lambda m\acute{a}x$ = Maximum Auto Value				
					IR = Random Consistency Index					T = Normalized Auto Vector				
					n = Number of the array order									
$IC = (\lambda m\acute{a}x - n) \div (n - 1)$					W = Sum of the columns of the array of compared for each attribute									
$\lambda m\acute{a}x = T \times W$														
(n)*	1	2	3	4	5	6	7	8	9	10	11	12	13	14
(IR)*	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57

Source: Saaty (1980). * n: Array Order; IR: Random Consistency Values.

such decisions were: in the case of the soil component, the predominance of sandy soils with thick profiles favours water infiltration instead runoff; the smooth wavy local relief implies low landforms influence in runoff; and the large thicknesses of soil profiles recovering the aquifer systems, result aquifer units lesser influence in runoff generation.

The Surface Runoff Potential Charts resultant from natural and natural/anthropic environments of the RCW (years 2001 and 2017) were presented considering five runoff classes (Very Low, Low, Medium, High and Very High). These classes were quantified for each of the five sub-basins of the RCW. The sub-basins were individually analyzed in order to verify the expected runoff conditions in these areas so that water management recommendations for each sub-basin could be elaborated. The sub-basins were automatically delimited in the Global Mapper® software, and their limits were obtained using the Generate Watershed tool, through the drainage network generated from the Digital Elevation Model obtained from the Topodata Project (Valeriano, 2008).

4. Results and discussions

The intermediate results used in Surface Runoff Potential Charts generation, i.e. land use/cover and annual precipitation charts, are showed in Fig. 4, referring to the years 2001 and 2017.

Regarding land use/cover, results show sugarcane cultivation and native vegetation as the predominant classes, corresponding to 72.53% (182.70 km^2) of the area. Exposed soil in 2001 includes fallow areas, which in the year 2017 were occupied by sugar cane cultivation, citriculture, forestry and pasture, which resulted in a reduction of 77.64% in this class. The urbanized areas of the RCW increased by 48.94% considering the studied period, generating a significant increase in the waterproofed areas in the basin.

Regarding the total annual precipitation, the RCW in 2001 presented values ranging from 1307.89 to 1343.26 mm, however, in 2017 there was a reduction of these levels to 1175.97–1218.45 mm (10% reduction in precipitation). The eastern portion of the RCW presents higher levels

Table 6
Weights of each of the classes of environmental attributes.

Environmental Attributes

Steepness	<2%	2–5%	5–10%	10–20%	20–30%	>30%
Weight	0.03	0.05	0.08	0.15	0.25	0.44

Rainfall (2001)	1307.89–1314.97 mm	1314.97–1322.04 mm	1322.04–1329.11 mm	1329.11–1336.18 mm	1336.18–1343.26 mm
Weight	0.04	0.08	0.14	0.26	0.47

Rainfall (2017)	1175.97–1190.13 mm	1190.13–1204.29 mm	1204.29–1218.45 mm
Weight	0.07	0.22	0.71

Land use and cover (2001 and 2017)	Artificial reservoir	Forestry/ silviculture	Exposed soil	Pasture	Citrus/ Coffee/ Sugar Cane	Mining	Urbanised area
Weight	0.02	0.04	0.07	0.09	0.16	0.23	0.39

Soils	Qdi_sr > 10 m - Sandy Qdi_p > 10 m - Sandy PTp > 10 m - Sandy Qa < 2 m - Sandy Qa < 2 m - Medium	Qa 2 to 5 m - Sandy PTp - 5 to 10 m - Sandy Qdi_sr - 5 to 10 m - Sandy JKbt - 5 to 10 m - Sandy	Kdsg - 2 to 5 m - Medium JKbt < 2 m - Sandy Kdsg - 5 to 10 m - Medium	Kdsg < 2 m - Medium Kdsg - 2 to 5 m - Clayey	Kdsg < 2 m - Clayey PTc < 2 m - Clayey PTc 2 to 5 m - Clayey
Weight	0.04	0.08	0.15	0.26	0.47

Slope Shape	Convergent-Concave	Convergent-Rectilinear	Convergent-Convex	Planar-Concave	Planar-Rectilinear	Planar-Convex	Divergent-Concave	Divergent-Rectilinear	Divergent-Convex
Weight	0.02	0.03	0.04	0.05	0.08	0.11	0.15	0.22	0.31

Aquifer Systems	Aluvionar - Porous; Free	Santa Rita do Passa Quatro - Porous; Free	Pirassununga - Porous; Free	Botucatu - Porous; Partially Free	Pirambóia - Porous; Partially Free	Intrusive Tabular - Fractured; Semi-confined	Corumbataí - Free
Weight	0.03	0.05	0.07	0.10	0.16	0.22	0.37

Source: Authors.

Table 7
Weights of each environmental attribute used.

Environmental attribute type	Weights
Steepness	0.40
Rainfall	0.27
Land Use and Cover	0.15
Soils	0.09
Slope Shape	0.06
Aquifer Systems	0.03

of precipitation, unlike the central-west region towards the mouth of Rio Claro, which present lower levels in both years.

In Fig. 5 the Surface Runoff Potential Charts considering natural environment attributes and natural/anthropic environments attributes in 2001 and 2017. Table 8 presents the quantitative data of the respective charts considering RCW sub-basins. The charts exhibit significant changes in runoff classes distribution for the period 2001–2017, with the main cause being the total annual precipitation, and, secondly, the changes in land use and cover.

The charts of potential runoff that did not consider the annual total precipitation show few differences for the two years analyzed. However, the charts that consider precipitation for the years 2001 and 2017 show significant changes resulting from precipitation levels in the two years of analysis. The results obtained for each sub-basin of the Rio Claro basin are discussed in the sequence. The choice to present the results by sub-basins was due to the differences in results between them and the fact that environmental management strategies could be more effective.

Córrego Passa-Quatro sub-basin (A)

In this sub-basin, "Very Low" and "Low" classes of surface runoff predominates in both years, and rainfall was the determining factor conditioning this classification, due to its lower levels of precipitation when compared to other regions of the RCW. Increases in rainfall in this area, can induces runoff increase and soil erosion (Anache et al., 2018).

The lower surface runoff favor the infiltration, contributing to the recharge of the Santa Rita do Passa Quatro and Pirambóia aquifers, with greater territorial extension in the sub-basin, both porous aquifers, which are sooty to soils with sandy texture and thicknesses greater than 10 m, occupied mainly by sugarcane and pasture, in both years considered.

In 2001, "Medium" class was mainly located in the urban area, associated with sandy soils, increasing soil erosion potential in extraurban areas. In 2017, this area was classified as "Low Potential Runoff", due to lower precipitation values, confirming the relationship of rainfall and surface runoff in this are. According to Griebeler et al. (2001), surface runoff only begins when precipitation occurs over a longer time interval than the rate of infiltration of water into the soil or also when the surface has exceeded its water retention capacity.

The "High and Very High" classes in this basin are associated to larger slopes (> 20%) and medium-textured and less thick soils. According to Fernandes et al. (2013), what favors the process of surface runoff is not only the factors that come from human interventions, but the factors related to geology, such as soil type, as well as climate-related factors, such as the quantity and intensity of precipitation.

Ribeirão do Sapé sub-basin (B)

The greater variation in the potential for surface runoff in this sub-basin between 2001 and 2017 was observed in the "Medium" class, with a reduction of 85.31%, with strong "Low Potential" growth (43.45%). The class occurs in areas of sugarcane cultivation and the presence of native vegetation, with vegetation cover reducing the surface runoff and increasing infiltration (Mohammad and Adam, 2010).

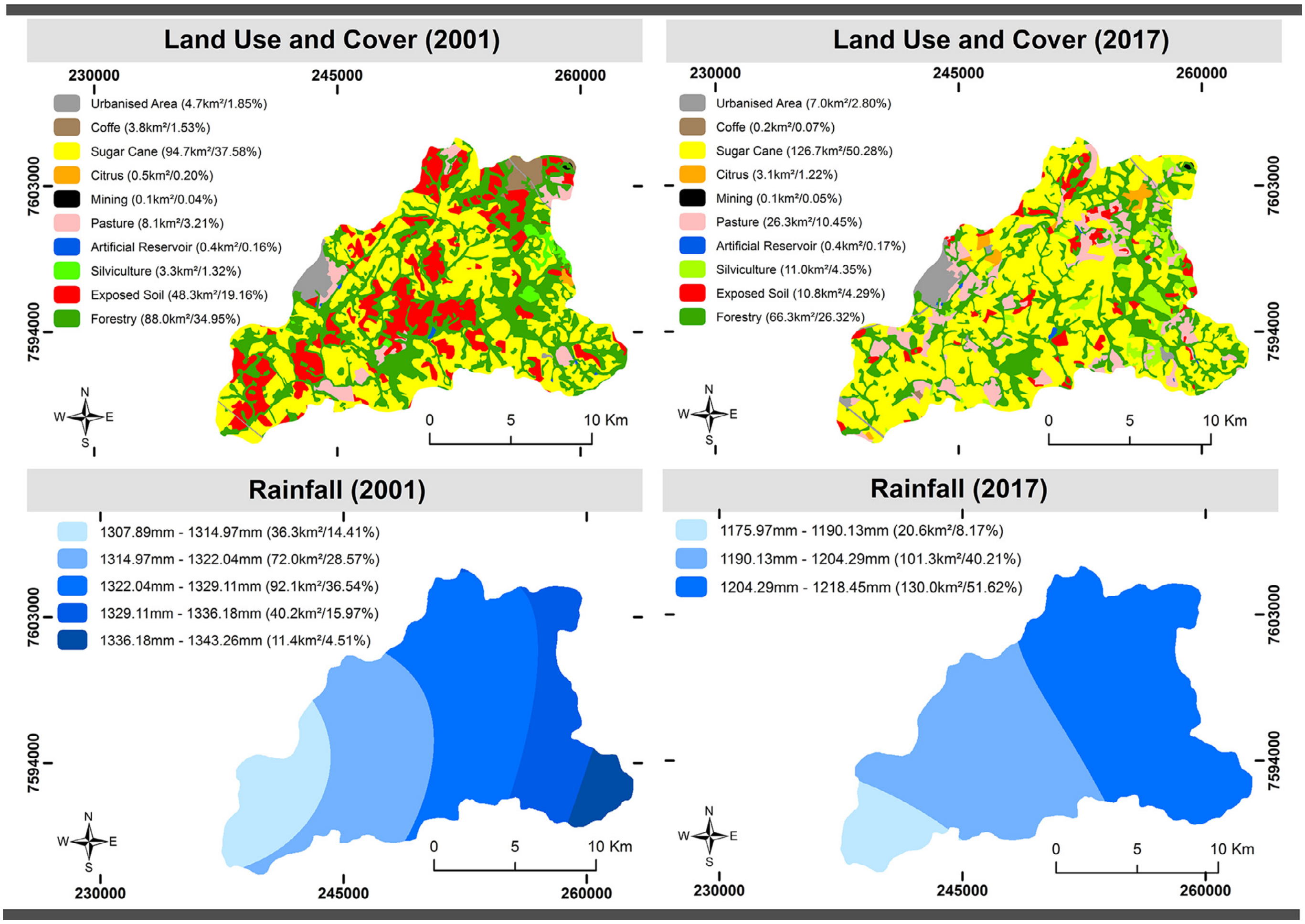

Fig. 4. Land use and cover and Rainfall for the years 2001 and 2017 that were used for the elaboration of the surface runoff potential charts.

In 2001, the occurrence of "High and Very High Potential" classes were associated with sandy texture soils in the northern portion and medium texture in the southern portion, both with depth ranging area, associated with highest precipitation taxes.

In 2017, "High" and "Very High Potential Flow" classes were identified in regions with high slopes (> 30%), directing flow to areas with softer slopes with sandy soils and profiles thicker than 10 m. The combination of attributes in this region of flat relief favors the recharge of the aquifer unit (Pirambóia).

Rio Clarinho sub-basin (C)

This area shows strong variation from "Very Low" and "Low" to "Medium" and "High" classes, mainly due to changes in total annual precipitation and in land use and cover changes. In 2001, total annual rainfall varied from 1314.97 mm to 1322.04 mm in the southwest portion, and between 1322.04 mm and 1329.11 mm in the rest of the sub-basin, while in 2017 the variations were between 1190.13 mm and 1204, 29 mm in the southwest portion, and 1204.29 mm at 1218.45 mm in the rest of the area.

Considering land use and cover, there is a decrease of exposed soil, and increases sugarcane cultivation. Another notable change was the change of sugarcane for pasture in the northern and central portions of the sub-basin. Between 2001 and 2017 there was a native vegetation loss of 30.1%, which also influenced the alteration of the surface runoff classes.

In addition, a small-scale increase of areas with citrus and silviculture in the center and south of the sub-basin in 2017, being the first class influencing the reduction of flow velocity due to planting in corridors (Molina et al., 2007). In places where the soil is covered by different types of crops, the flow process is not homogeneously distributed (Korkanç, 2018).

Runoff is conditioned by slope (10–30%) in the northern portion, associated with fine texture soils with thickness of less than 2 m. In the rest of the sub-basin, the soils have a sandy texture, favoring aquifer units' recharge.

Córrego do Faveiro sub-basin (D)

This was the only sub-basins that did not present the "Very Low" and "Low Potential" classes in 2017. In 2001, these classes occurred mainly in the western portion of the sub-basin, and in 2017 classified as "Medium" and "High" potential to the outflow.

This change was due mainly from land use and cover changes, such as the reduction of native vegetation as a result of increased agricultural activities (sugarcane, citrus, silviculture, and pasture) and mining. According to Santos and Lollo (2016), surface runoff is directly related to the physical and climatic characteristics of the area.

In the year 2001, the occurrence of "Medium Potential" class in the eastern portion (soil with sandy texture and depth above 10 m), contributes to Pirambóia Aquifer recharge. Annual rain fall shows increases from 2001 to 2017 in this area. In both, 2001 and 2017 years, Córrego do Faveiro sub-basin presented a higher percentage of the "Medium Potential" class, in areas with coarser soil texture.

The "High" and "Very High" classes were concentrated in the north-eastern and north-western portions in 2001, regions with gradients up

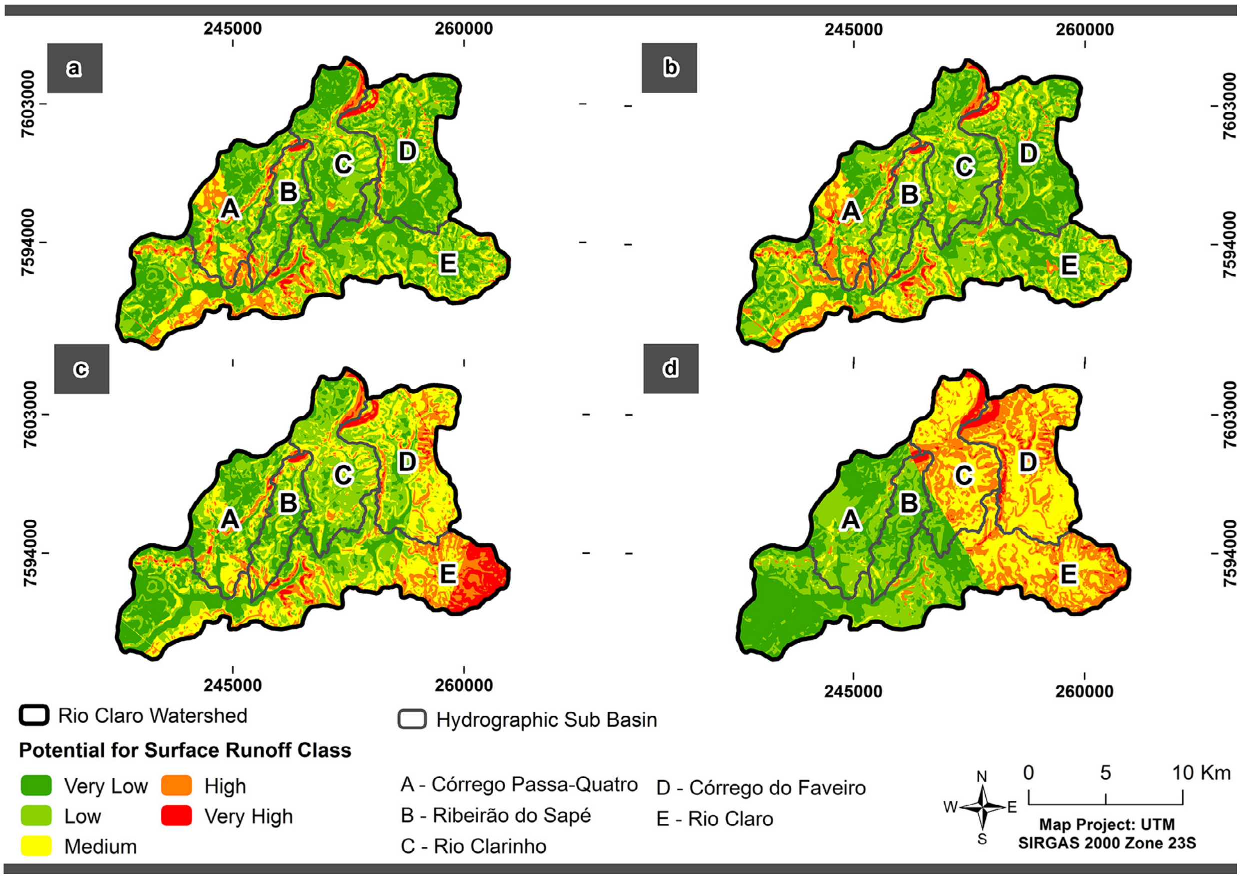

Fig. 5. Surface runoff potential charts. non considering total annual rainfall (a-2001; b-2017); considering total annual rainfall (c-2001; d-2017).

Table 8
Areas (km^2 and %) of each runoff potential class in Claro River Sub-basin (2001 and 2017).

Class	Potential for surface runoff (2001)		Potential for surface runoff (2017)		Variation (%)
	km^2	%	km^2	%	
Córrego Passa-Quatro Sub-basin (A) - 36.17 km^2					
Very Low	12.93	35.75	15.86	43.86	22.66
Low	10.76	29.75	18.00	49.76	67.29
Medium	9.02	24.94	1.68	4.64	−81.37
High	3.06	8.46	0.49	1.35	−83.99
Very High	0.40	1.10	0.14	0.39	−65.00
Ribeirão do Sapé Sub-basin (B) - 18.63 km^2					
Very Low	6.34	34.03	8.51	45.68	34.23
Low	5.80	31.13	8.32	44.66	43.45
Medium	4.63	24.85	0.68	3.65	−85.31
High	1.38	7.41	0.65	3.49	−52.90
Very High	0.48	2.58	0.47	2.52	−2.08
Rio Clarinho Sub-basin (C) - 40.46 km^2					
Very Low	7.20	17.80	3.20	7.91	−55.56
Low	21.28	52.60	1.40	3.46	−93.42
Medium	8.78	21.70	21.00	51.90	139.18
High	2.56	6.33	12.77	31.56	398.83
Very High	0.64	1.57	2.09	5.17	226.56
Córrego do Faveiro Sub-basin (D) - 49.31 km^2					
Very Low	3.90	7.91	0.00	0.00	−100.00
Low	12.85	26.06	0.00	0.00	−100.00
Medium	22.68	45.99	28.96	58.73	27.69
High	8.12	16.47	16.81	34.09	107.02
Very High	1.76	3.57	3.54	7.18	101.14
Rio Claro Sub-basin (E) - 104.95 km^2					
Very Low	26.46	25.22	36.71	34.98	38.74
Low	23.95	22.82	23.49	22.38	−1.92
Medium	28.24	26.91	24.22	23.08	−14.24
High	17.15	16.34	18.99	18.10	10.73
Very High	9.14	8.71	1.53	1.46	−83.26

to 30%, sandy soils with thicknesses ranging from 5 to 10 m, or greater than 10 m in areas with forms of relief (planar rectilinear and planar convex) that favor surface runoff. In these conditions, low influence of the uncontaminated materials on the potential flow, and strong control of the relief, the precipitation indices, and the types of soil use and cover are observed (Barros et al., 2014).

Rio Claro sub-basin (E)

Rio Claro sub-basin presents greater diversity among the environmental attributes. The area shows significant changes in soil cover in the period 2001–2017, influencing surface runoff, such as increased sugar cane cultivation and pasture, in the entire sub-basin; and decrease of exposed soil areas.

In 2001, total annual rainfall increases from west to east strongly than 2017. This was one of the factors that led to the decrease between the years 2001 and 2017 of 83.26% of the "Very High" class potential for surface runoff and the "Very Low" class increase in the order of 38.74% . The effects caused by precipitation types in the runoff process, as well as in soil loss are directly related to the duration and intensity of precipitation (Mohamadi and Kavian, 2015).

The areas with the higher slope (greater than 20%) are located in the eastern, central, and western portions of the sub-basin, moderately interfering with potential runoff. Soil texture varies from sandy to clayey texture, with a thickness ranging from less than 2 m up to over 10 m. From the western portion to the center of the sub-basin there are also scattered spots of clayey soils whose thickness does not exceed 5 m, regions with greater potential flow, influenced by the characteristics of the soils.

Considering this general scenario in RCW, and focusing in minimizing impacts from surface runoff, these set of recommendations were proposed.

“Very Low” and “Low” classes’ areas favor infiltration and recharging aquifers, needing cares related to farming conservative techniques and water resources protection. Some soil physical attributes can be modified by soil management and conservation practices are adopted, and the rate of infiltration of soil water can be modified, more favoring infiltration process.

In “Medium” class areas the above strategies needs to be associated with vegetation cover protection, mainly in areas of higher slope values, since the suppression of the vegetation can contribute to the reduction of the infiltration capacity and generate an increase in the surface runoff and the erosive processes resulting from it (Guerra, 2012).

Inadequate management and poor soil conservation practices have been considered as the main factors influencing surface runoff, resulting in changes in water infiltration conditions in soils and an increase in surface runoff, which may link erosion processes (Abdelwahab et al., 2014). To ensure the conservation of the soil and to minimize the degradation of these areas, it is possible to adopt some conservationist practices of edaphic, mechanical and vegetative character (Lepsch, 2010).

In “High” and “Very High” Potential areas, measures should be applied in agricultural areas with annual crops that can reduce runoff, such as terracing to reduce water loss and soil retention of streams when precipitation extrapolates the soil infiltration capacity. Another interesting alternative to reduce runoff is vertical infiltration furrow, which can provide increased water volume in the slopes, allowing perennial drainage channels (Carvalho, 2009).

It is important to preserve forest areas and Permanent Preservation Areas (APP) in accordance with the Forest Code (Law no. 12.651/2012) (BRASIL, 2012), as the absence of vegetation cover increases the probability of soil, either by detachment of particles or by removal of the surface layer from the soil. Secondly, such a measure has the benefit of decreasing the likelihood of sedimentation of water bodies. Calijuri et al. (2010) also point out that the presence of vegetation around the drainage channels is essential for retaining and purifying pollutants from agricultural and urban activities carried by surface runoff.

In the case of high-slope slopes, the reduction of the flow velocity obtained by the installation of energy sinks can be a tool to reduce the increase in surface runoff (Calil et al., 2012; Batista and Boldrin, 2018).

Although the Surface Runoff Potential Charts does not highlight the urban areas of the basin, it is essential to consider that urban growth tends to increase the waterproofed area, increasing the flow velocity. Thus, some specific measures can be adopted in urban areas, creating legal instruments that guarantee permeability rates between 20% and 30% of the total land area when it exceeds 300 m^2 of area; to build temporary rainwater storage tanks; deploy gardens along sidewalks; to implant sidewalks and gutters with drainage floors (Carvalho et al., 2015).

In urban areas, measures such as the green roof (Costa et al., 2012) can be incorporated, and other devices such as permeable and semi-permeable pavement; holding and holding tanks; trench and infiltration trench; and, basin, in order to reduce runoff and increase rainfall infiltration rates (Poleto, 2011).

5. Conclusions

In general, surface runoff potential charts produced for RCW show significant influence of total annual rainfall in both considered years, evidencing the importance of climate change, either globally or regionally. Rio Claro Basin, considering natural or manmade attributes, occurs in vast areas of the southeastern region of Brazil, which is why the conclusions observed here can be extrapolated to a large area of the Paraná Basin.

Considering local variations (sub-basins), we observe a strong control from soil texture and thickness and land use land cover in potential runoff. This situation indicates the need of large scale environmental management strategies, without neglecting local actions.

Surface Runoff Potential Chart enables the identification of specific areas that require constant monitoring to prevent and/or minimize negative impacts resulting from anthropic interventions, as leaching of fertilizers and pesticides that contaminate the soil and, consequently, the underground water resources from infiltration, and also the surface, with the flow of these components to the water courses changing their physical and chemical properties, often causing the eutrophication of water courses.

The proposed measures aim to favor infiltration, reducing the possibility of erosive processes in the soil and favoring the recharge of aquifer units. The results of this study can assist environmental managers and planners in their decision-making, aiming at a sustainable balance between socio-economic development and the rational use of water resources.

Declaration of Competing Interest

The authors declare no conflict of interest.

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