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ORIGINAL ARTICLE

Accelerated erosion in a watershed in the southeastern region of Brazil

Mariana Dorici[1] · Carlos Wilmer Costa[1] · Mayra Cristina Prado de Moraes[1] ·
Fabiola Geovanna Piga[1] · Reinaldo Lorandi[2] · José Augusto de Lollo[3] ·
Luiz Eduardo Moschini[1]

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Abstract An understanding of erosive processes and the washing away of sediments to watersheds is an essential tool for decision makers planning water resource use. This study assessed the potential for surface runoff due to natural attributes together with land use/land cover to highlight the potential for accelerated erosion in the Araras River Watershed (352.77 km^2) at a 1:50,000 scale. The analytic hierarchy process was used with the data provided to combine geoenvironmental attributes (soil, rock, water, relief and land use/land cover) that trigger erosive processes. Just over 51 % of the basin area presented an average potential for surface runoff, while 76.5 % presented a low to average potential for accelerated erosion. Despite this, upstream areas used for water collection for Araras city show a medium to high potential for surface runoff and accelerated erosion, reducing water infiltration and recharge, and resulting in the silting of reservoirs and water quality damage.

Keywords Geoprocessing · Soil · Water · Degradation · Brazil

Introduction

By prioritizing economic logic to the detriment of environmental issues, human action transforms the earth's surface, affecting ecosystems in a broad, significant and increasing way (Vitousek et al. 1997; Folley et al. 2005).

Global environmental degradation is dangerously approaching the threshold of an ecosystem collapse (Millennium Ecosystem Assessment 2005), which, combined with the deterioration of land and water resources, threatens soil quality, biodiversity and water resources (FAO 2011; WWAP 2015).

According to Palm et al. (2007), there were 2 billion hectares of degraded land worldwide in 1991. Recently, FAO (2011) noted that 25 % of the world's land is highly degraded, 8 % is moderately degraded and 36 % slightly degraded. It is estimated that, if no adequate soil preservation actions are taken, the increasing demand for resources, in particular for food production, will accelerate soil and water losses due to erosion, resulting in considerable impacts on society (Tundisi and Matsumura-Tundisi 2010; da Silva et al. 2011; Ziadat and Taimeh 2013).

✉ Mariana Dorici
marianadorici@gmail.com

Carlos Wilmer Costa
carloswilmercosta@gmail.com

Mayra Cristina Prado de Moraes
na_moraesrp@hotmail.com

Fabiola Geovanna Piga
fabipiga@gmail.com

Reinaldo Lorandi
dvlorandir@ufscar.br

José Augusto de Lollo
ja_lollo@yahoo.com

Luiz Eduardo Moschini
lemoschini@ufscar.br

[1] Environmental Sciences Department, Federal University of São Carlos - Campus São Carlos, Rodovia Washington Luís, km 235 - SP-310, São Carlos, SP CEP 13565-905, Brazil

[2] Civil Engineering Department, Federal University of São Carlos - Campus São Carlos, Rodovia Washington Luís, km 235 - SP-310, São Carlos, SP CEP 13565-905, Brazil

[3] Civil Engineering Department, Universidade Estadual Paulista "Júlio de Mesquita Filho" - Campus Ilha Solteira, Avenida Brasil, 56, Centro, Ilha Solteira, SP CEP 15385-000, Brazil

There are many factors that can interfere in soil erosion processes such as: climate, physical–chemical properties of soil, the length, shape and steepness of slopes, rocky substratum, vegetal cover and soil use (Lenhart et al. 2010; Santos et al. 2013; Gabarrón-Galeote et al. 2013; Zhou et al. 2016). Abiding by such factors, erosive processes vary due to erosion triggering mechanisms and specific predisposing conditions (Lollo and Sena 2013).

Despite being a worldwide problem, soil erosion occurs more intensively in countries with tropical climates such as Brazil where extensive areas are affected by erosive processes. According to Bertoni and Lombardi Neto (1999), the country loses approximately 500 million tons of soil annually—the state of Sao Paulo represents 25 % of this amount. Therefore, rainwater plays an important role in this scenario by facilitating the surface runoff accountable for most of the washing away of soils (Pejon 1992; Chen et al. 2006; Lima et al. 2013; Merten et al. 2015). The erosive power of raindrops and stream velocity over surfaces result in degradation and the washing away of materials according to soil erodibility, causing different erosion conditions (Libardi 2005; Blodgett and Hoopes 2010; Gross et al. 2010; Shi et al. 2012).

Aside from hydrodynamic power, the removal of soil particles is also connected with the shape, size, roughness of and contact with other particles (Bigarella and Mazuchowski 1985; São Paulo et al. 1990; Coulthard et al. 2012). Such factors, related to land use for agribusiness activities, may increase erosive processes, resulting in accelerated erosion (Guerra et al. 2014; Saad et al. 2013; Leh et al. 2011). This occurs due to inadequate human-made interventions that affect the shape and intensity of natural erosive processes, interfering with their characteristics (Morgan et al. 1998; Raposo et al. 2010).

Accelerated soil erosion leads to the formation of grooves, ravines and gullies, resulting in the loss of soil and the washing away of nutrients, thus affecting food production and safety, causing widespread pollution and the silting of watercourses and reducing the useful life of reservoirs (Hrissanthou 2005; da Silva et al. 2013; Vente et al. 2013; Zhao et al. 2013).

However, as noted by Zhang et al. (1996), Merritt et al. (2003), Aksoy and Kavvas (2005), Vente and Poesen (2005) and Vente et al. (2013), most models are aimed at the anticipation of laminar erosion of small areas in the watershed, and there is a lack of models regarding processes involved in linear erosion generation and permanence (Rocha et al. 2014). Considering this scenario, studies based on the occurrence and magnitudes of accelerated erosive processes are needed in support of territorial planning, mostly at water basin scales.

Most of southeastern Brazilian is covered with residual soils from sedimentary rocks from the Paraná Basin, and its local relief conditions and land use/land cover trigger significant erosion processes. This study assessed the potential for surface runoff and accelerated erosion potential considering geoenvironmental attributes that enable methodological advances and support measures for land management in the Araras River Watershed (ARW), as well as other areas in Paraná Basin with analogous environmental conditions.

Studied area characterization

The ARW is entirely located in the Araras (SP) municipality between 47°29′2, 4″W; 22°13′52, 7″S and 47°12′32, 4″W; 22°26′42″S. The Araras River presents an average- to high-density dendritic drainage pattern (Christofoletti 1974) and can be classified as a fifth-order watershed according to Strahler (1952). Its main course is a tributary of the Mogi-Guaçu River in the Paraná River Basin, and it drains part of the south of Brazil, near 16°S latitude. Araras, with a population of 118,843, is 155 km from the city of Sao Paulo, the main economic and most populated center of South America. Its intensive use of soil is due to agribusiness activities (Fig. 1).

In a continental geological scale, the area is within the Phanerozoic domain (the sub-Andean foreland, inclusive) in the tectonic provinces of Paraná (Hasui 2012). The basin geology is described (Table 1) based on Brollo (1991), Lollo (1991) and Aguiar (1995).

Residual soils and sediment units result from sandstones, argillites, siltstones, basalt and diabase weathering, with differentiated geotechnical characteristics such as thickness, texture, mineral composition and permeability. Units were defined and mapped by Brollo (1991), Lollo (1991) and Aguiar (1995) (Table 2).

According to the Institute of Technological Research (IPT) (1981), the ARW is located in the dissected plateau of the peripheral depression of the Mogi-Guaçu River zone, with the following shapes of relief: hilly relief (with a predominance of low declivities, up to 15 %, and local amplitude lower than 100 m) and hillock relief (with a predominance of middle and high declivities, over 15 %, and local amplitude lower than 100 m).

In the hilly relief, we can highlight the subclass wide hills with interfluve areas over 4 Km^2; extensive and flattened summits; straight to convex slopes; low drainage density and sub-dendritic drainage patterns; open valleys, alluvial lowlands and the presence of perennial or intermittent lagoons. The

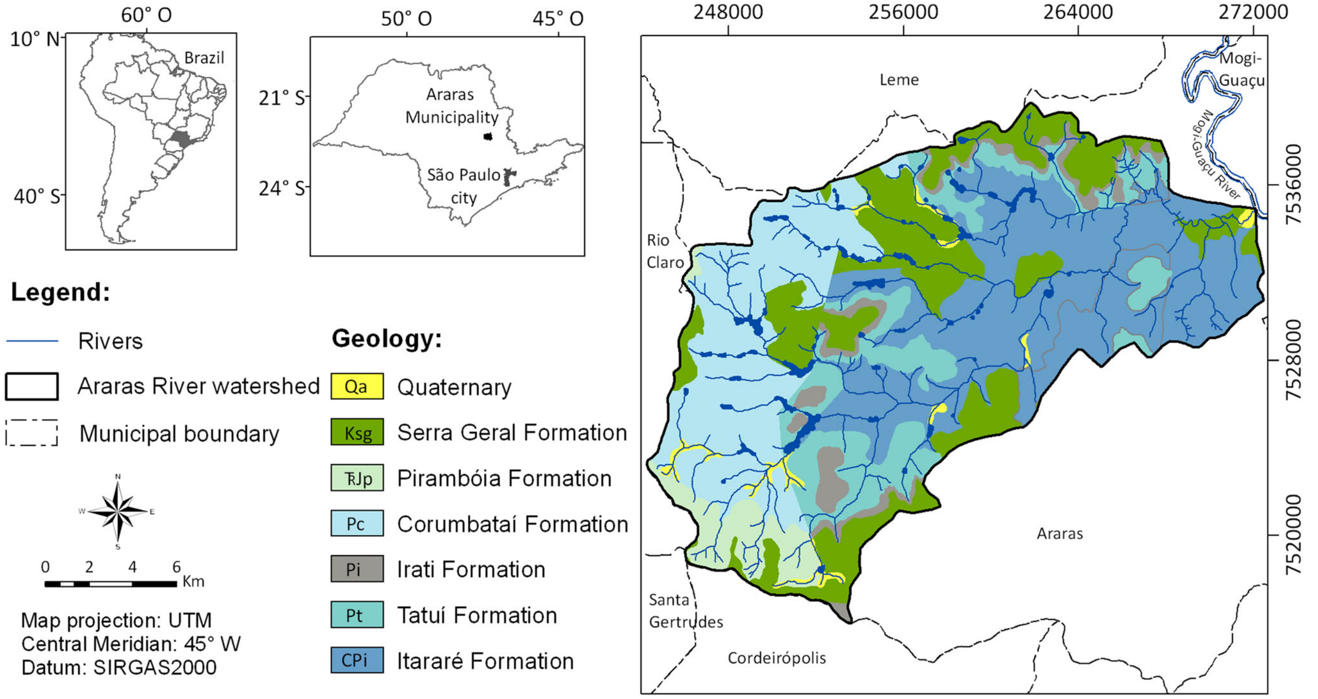

Fig. 1 Location and geological map of the study area

Table 1 Geological units in Araras River Watershed

Geological units	Area (km^2)	Characterization
Quaternary (1,8 My)	6.26	Distributed along valley bottoms in the north and southwestern region of the basin, they are formed by silt and clayey sands, clayey sandstone, clayey alluvium and sandstone mudslide
Serra Geral Formation	74.58	Distributed all over the basin, the south and north regions of the Serra Geral Formation are the most relevant Basaltic rocks tholeiites and diabase dikes associated
Pirambóia Formation	16.73	Starting southwest the basin, in this formation we can find water sources of Furnas, which gives rise to Araras River. Argillite, sandstone shale, siltstone and siltstone–argillite are predominant
Corumbataí Formation	73.10	Argillite, siltstone–argillite, clayey siltstone, sandy siltstone and fine to very fine grained sandstones
Irati Formation	16.16	Argillites, siltstones, clayey siltstones, argillite–siltstones, with silicified limestone and dolomitic limestone in its upper portion
Tatuí Formation	46.50	Sandy siltstones, clayey siltstones, siltstone-sandstone, argillite and siltstone–argillite
Itararé Formation	119.44	Complex lithological association consisting of siltstones, clayey siltstones, argillite, siltstone–argillite, fine to very fine grained sandstones, micaceous sandstones and migmatite

subclass elongated hillock and crests is predominant in the hillock relief area; the interfluves have no preferential orientation, angular summits, straight gullies and closed valleys.

In the Mendonça and Danni-Oliveira (2007) classification, the regional climate is classified as Central Brazil tropical climate without droughts. Rain is more frequent in the summer (from October to March), but the area has wet weather all year long and an average annual rainfall of 1450 mm. The ARW exhibits two global hot spots forest formations: Atlantic Rainforest and *Cerrado*, with the Atlantic formation being predominant (São Paulo 2009).

Materials and methods

This study was based on a methodological proposal developed by Pejon (1992) to assess the potential for surface runoff and accelerated erosion at the watershed scale. The methodology, aside from its explanatory purpose, is adapted to Brazilian conditions and therefore has a more realistic representation of regional processes. The slope shapes and the soil use and cover were included in the analysis as they are essential attributes for modeling approaches involving accelerated erosive processes.

Table 2 Geotechnical characterization of soil types

Soils	Area (km^2)	Thickness (m)	Average granulometry (%)^{a}				Coefficient of permeability (cm/s)
			C	S	FS	MS	
Sandy alluvial	15.85	<2 to >5	22	17.5	57.5	3	1.19×10^{-3}
Clayey alluvial	10.84	<2 to >5	60	29	12.5	1.5	7.42×10^{-6}
Clayey sand I	76.11	<2 to >5	35	21	42	4.5	3.19×10^{-2}
Clayey sand II	50.07	<2 to >5	21	15.5	62.5	3	3.71×10^{-3}
Silty sand	6.57	2 to 5	21.5	28.5	48	2	1.96×10^{-3}
Sandy clay I	125.62	<2 to >5	42.5	25.5	28	2.5	7.07×10^{-5}
Sandy clay II	27.16	<2 to >5	57	19	22.5	2.5	5.1×10^{-7}
Silty clay I	8.27	<2 to >5	41	36	20.5	1.5	1.34×10^{-4}
Silty clay II	12.44	2–5 and >5	54	31.5	15	1.5	5.5×10^{-6}

[a] *C* Clay, *S* silt, *FS* fine sand, *MS* medium sand

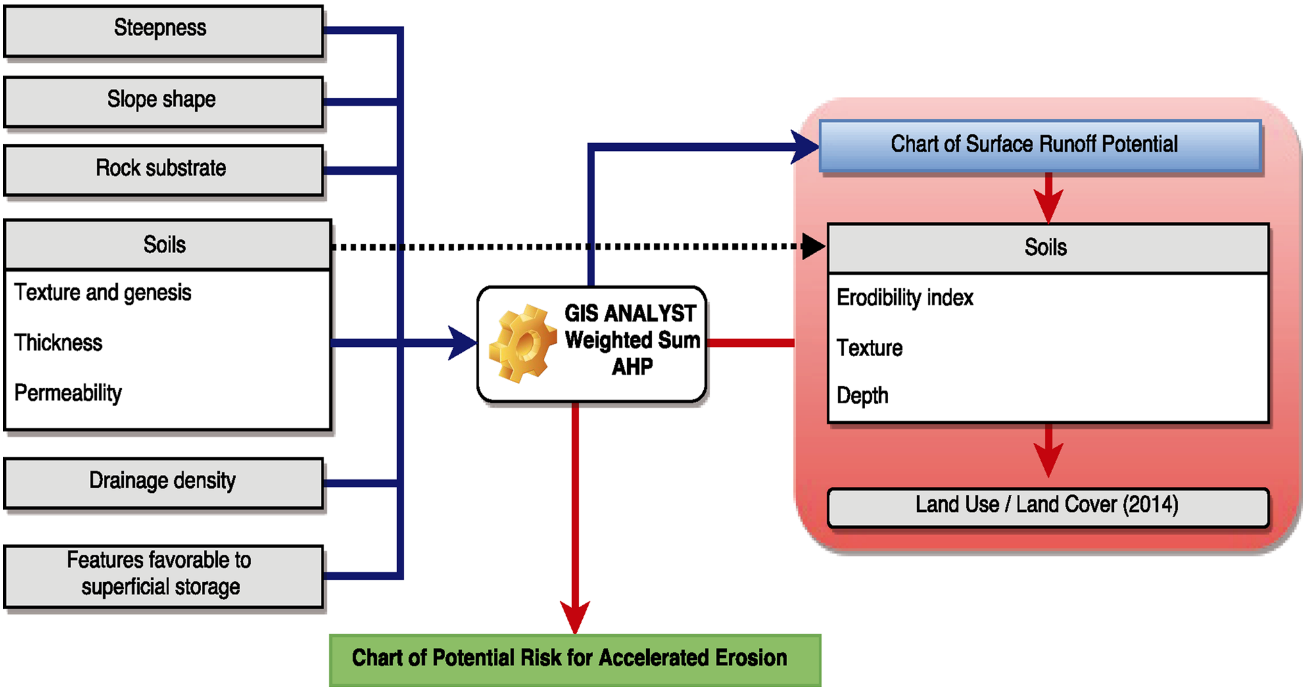

Fig. 2 Flowchart of the method used

The methodology consists of assigning attributions and ranking several factors that affect erosive processes including geoenvironmental variables, such as rocks, soils, relief, hydrography and soil use and cover, involving preliminarily and potential surface runoff chart production (Fig. 2).

Attributes considered for this study were heterogeneity, consolidation degree and lithological type; texture, genesis, thickness and permeability of soils; slope shapes and steepness of terrains; favorable conditions for surface water storage; density of the drainage network; and human interference due to different types of land use.

The data special treatment was performed with ArcGIS® 10.2 (ESRI 2013) using the SIRGAS2000 (IBGE 2005) geodetic reference and the Universal Transverse Mercator (UTM) projection at 23S Zone (Table 3; Fig. 3).

The analytic hierarchy process (AHP) was used for data processing based on specialist knowledge and the discussion of weight definition. The AHP method consists of determining relevance and priorities of the chosen geoenvironmental attribute from the attribution of numerical values. The attribute forms a hierarchical arrangement evidencing its degree of pertinence to the final analysis (Pourghasemi et al. 2012).

Table 3 Geoenvironmental attributes

Data	Description	Source	Scale
Hydrography	Rivers	Topography charts (IBGE 1971)	1:50,000
		LandSat 8 image of 2014	
Relief	Steepness	Topography charts (IBGE 1971)	
		Araras—SF-23-Y-A-II-3	
		Conchal—SF-23-Y-A-II-4	
		Leme—SF-23-Y-A-II-1	
	Slope shape	Topodata—INPE	
		Valeriano (2008)	
Geological formations	Rock substrate maps	Araras chart—Brollo (1991)	
		Leme chart—Lollo (1991)	
		Conchal chart—Aguiar (1995)	
Soils	Cover materials		
Land use and cover—2014	Classes of land use	LandSat 8, path/row	–
		220/75 from 16/12/2014	
		Colorful composition—: 6, 5 and 4 bands with panchromatic fusion (15 m pixel)	

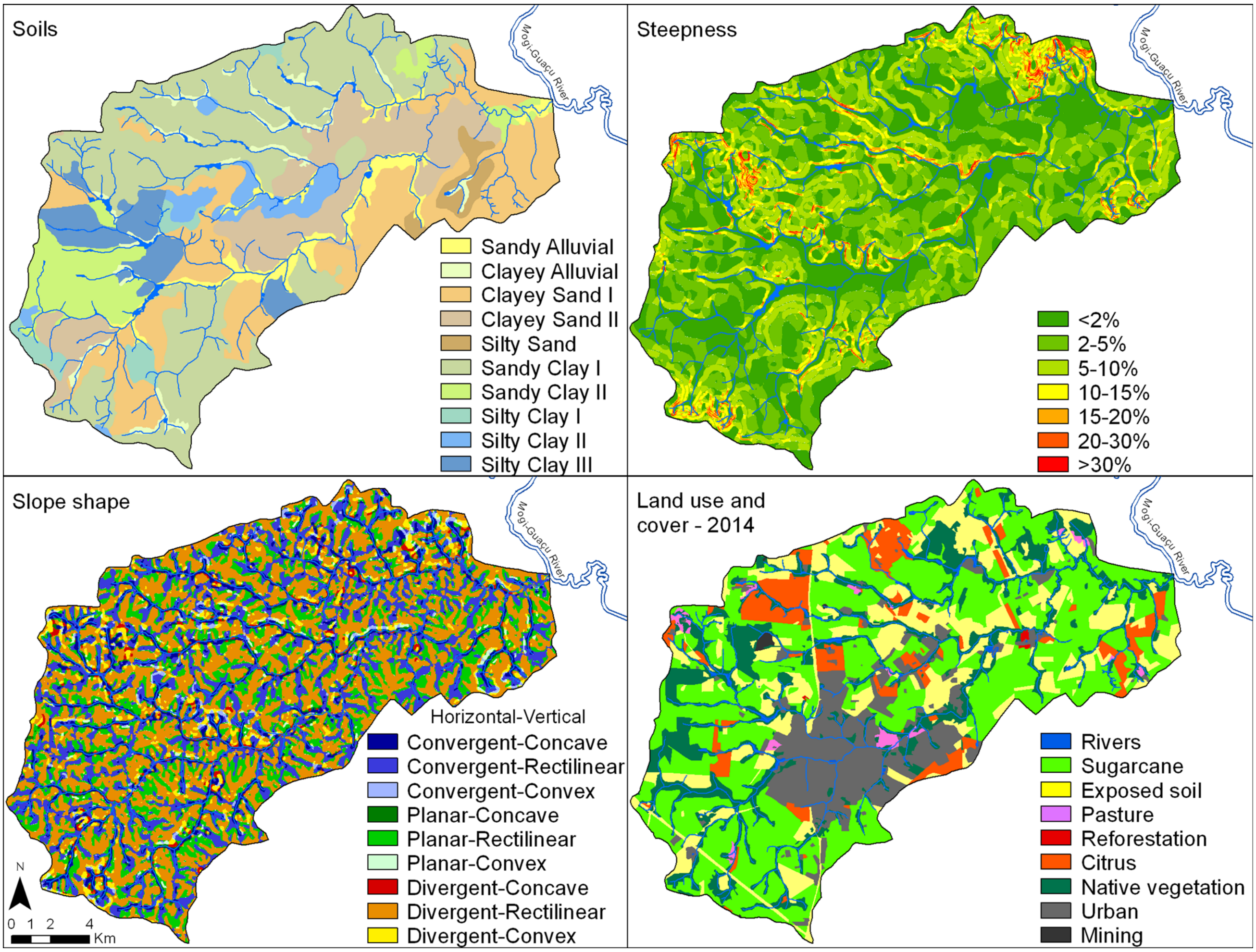

Fig. 3 Relief, soil and land use/land cover distribution in the area

Potential surface runoff and potential risk for accelerated erosion charts were performed according to the weight ranking presented in Tables 4 and 5. The sum of the attributes was conducted with the support of map algebra in ArcGIS® (ESRI 2013).

Results and discussion

Surface runoff Potential

According to Pejon (1992), runoff and sediment transportation may be strengthened due to lithological structure; relief characteristics such as the terrain unit's shape and steepness; conditions favoring water storage (i.e., lakes, lagoons and depressions); soils and sediments properties such as genesis, texture, thickness and permeability; and the relationship of land use and management practices. The results show that land use/land cover is the main trigger of erosive processes in the studied region.

Considering the ten classes of potential runoff considered, the ARW shows the predominance of classes 4 and 5, representing 51.18 % of the area (Fig. 4). We identified that surface runoff potential classes vary in outcrop areas of the same lithology due to differences of other attributes.

In areas of the Serra Geral Formation (sills and diabase dikes) and the Irati Formation (clay/siltstone), we identified variable classes of surface runoff potential, from very low to high (classes 2–10). Areas with high to very high surface runoff potential and limiting conditions of infiltration presented less developed soil profiles, thin profiles (thickness <2 m), clayey soil texture (>50 % clay) and middle to low permeability coefficients, varying from 10^{-5} to 10^{-7} cm/s (Table 1). Classes of steepness above 10 % and divergent slopes (concave, straight and convex) that do not favor percolation are predominant in these areas.

The areas with low-permeability rocks, such as the Corumbataí Formation (argillite, clayey and sandy siltstone, banks and lenses of fine to very fine sandstones), on the west/northwestern regions of the basin present limited percolation capacity, resulting in medium to very high classes of potential runoff (classes 5–9) that can be explained by the soil's small thickness profiles (<2 and from 2 to 5 m), fine texture, clay grains >50 % and average to low percolation coefficients (10^{-5}–10^{-7} cm/s).

The very low to medium classes of surface runoff potential (classes 1–6) are distributed in the center-northeast axis of the ARW, on the Itararé Formation with sandy texture (high intergranular porosity). The main characteristics of its soil profiles are sandy texture (>50 % fine sand), medium to high soil thickness (from 2 to 5 and >5 m), high permeability coefficients (10^{-3}–10^{-2} cm/s), and low steepness (<2 % and from 2 to 5 %), a condition that favors water infiltration thus recharging local water bodies. However, surface runoff potential increases where the Itararé Formation is constituted by diamictites with a silty and/or clayey matrix in the eastern and northwest areas of the basin.

The Pirambóia Formation (pure to arcosean and clayey sandstones) comprises high porosity sandstones combined with sandy soils, with thicknesses over 5 m, a high coefficient of permeability (10^{-2} cm/s) and a steepness of up to 10 %, resulting in lower surface runoff potential (classes 2–4). In the ARW, these attribute associations favor infiltration and help recharge surface and underground water bodies responsible for urban water supply.

In opposition to this scenario, in surface runoff units in these areas where the soil presents a clayey texture, with varying steepness classes, a profile thickness over 5 m and a medium permeability coefficient (10^{-5} cm/s), higher potential runoff units (classes 5–7) result.

The region of the Tatuí Formation (sandy and clayey siltstone, fine to very fine sandstone banks and clayey lenses) exhibited a variety of surface runoff indexes (classes 2–8). Such conditions reflect areas favorable for percolation in the central portion of the basin where steepness classes are lower than 10 %, soils range from 2 to 5 m thick, coefficients of permeability are high (10^{-3}–10^{-2} cm/s) and there is a substantial percentage of fine sand (>50 %).

Notwithstanding, in the northwest region the surface runoff potential is higher resulting from the reduced thickness of soils settled (<2 m), clay texture, silty texture and an average coefficient of permeability (10^{-5} cm/s). This result was also conditioned by the shape of divergent slopes (convex and straight) and straight flats, combined with a steeper relief that would not favor surface water storage. In these areas, steepness reached classes over 30 % with dense drainage networks.

The quaternary undifferentiated cover is constituted by alluvial deposits overlaid to varied lithology in deep valleys along the main drainage, constituting floodplains. In these areas, low declivities (<2 %) and round slope shapes (convergent-concave and straight) are predominant, contributing to water accumulation. Due to washed away materials, these areas present clayey and sandstone textures influenced by the parent rock matrix. Due to such features, we observed that most of the alluvial areas presented a low potential for surface runoff (classes 1–5).

Potential for accelerated erosion

The ARW displayed low to average potential for accelerated erosion, evidenced by large areas with classes 4, 5 and 6, which make up 76.5 % of the basin. Classes 9 and 10 do not occur in the study area (Fig. 5).

Table 4 Surface runoff potential

		Runoff potential							
	–	→							+
Runoff classes	1	2	3	4	5	6	7	8	9	10
Attributes	50–69	70–89	90–109	110–129	130–149	150–169	170–189	190–209	210–229	230–245
Steepness	<2 % (6)		2–5 % (10)	5–10 % (14)	10–15 % (18)	15–20 % (24)		20–30 % (30)	>30 % (36)	
Slope shape	CC (3)	CR (6)	CX (12)	PC (16)	PR (20)	PX (28)	DC (36)	DR (42)	DX (54)	
Geological formations	Quaternary (indiscriminate texture) (4)		Pirambóia (pure sandstones to arcosean and sandstone clay) and Itararé (sandy) (10)	Tatuí (siltstones sandy and clay, fine sandstone banks to very fine and mudstone lenses) (16)	Itararé (diamictites with clayey and/or silty matrix) (20)		Serra Geral and associated intrusives (dikes and sill of the diabase) (30)		Corumbataí (mudstones, clay and sandy siltstones, bank and lenses of the fine to very fine sandstone) and Irati (mudstones/ siltstones) (40)	
Soils										
Texture and genesis	Sandy alluvial (2)	Clayey alluvial (5)	Clayey sand II (fine sand >50 %) (8)	Silty sand (fine sand prevalence) (10)	Clayey sand I (fine sand <50 %) (14)	Sandy clay I (clay <50 %) (18)	Silty clay I (clay <5 %) (20)	Sandy clay II (clay $\geq$50 %) (28)	Silty clay II (clay between 50 and 60 %) (30)	Silty clay III (clay >60 %) (40)
Thickness (m)	>5 (10)			2–5 (16)		0.5–2 (20)		<0.5 (30)		
Permeability	$>10^{-3}$ (5)		10^{-3} to 10^{-4} (6)		10^{-4} to 10^{-5} (7)		10^{-5} to 10^{-7} (8)		$<10^{-7}$ (12)	
Drainage density (watercourse/ km^2)	Less than 2 (10)				5–2 (20)				More than 5 (3)	
Features favorable to superficial storage	Lagoon, small depressions (large quantity) (10)				Lagoon, small depressions (small quantity) (20)				Not present (30)	

Table 5 Potential risk for accelerated erosion

		Potential erosion risk								
	–	→								+
Potential erosion risk classes	1	2	3	4	5	6	7	8	9	10
Total points of each class	20–32	33–45	46–57	58–70	71–83	84–96	97–109	110–122	123–135	136–150
Runoff potential	1 (5)	2 (8)	3 (10)	4 (13)	5 (15)	6 (20)	7 (25)	8 (30)	9 (35)	10 (40)
Soils										
Erodibility	Non-erodible (5)					Erodible (20)				
Texture	Silty clay (5)			Clayey silt (10)		Sandy <30 % fine (20)		Sandy <20 % fine (30)		
Depth (m)	<0.5 (5)			0.5–2 (10)		2–5 (20)		>5 (30)		
Land use and land cover	Urban and rivers (0)		Native vegetation (1)	Reforestation (3)	Pasture (5)	Sugarcane and other plantations (10)		Citrus (15)	Exposed soil mining (30)	

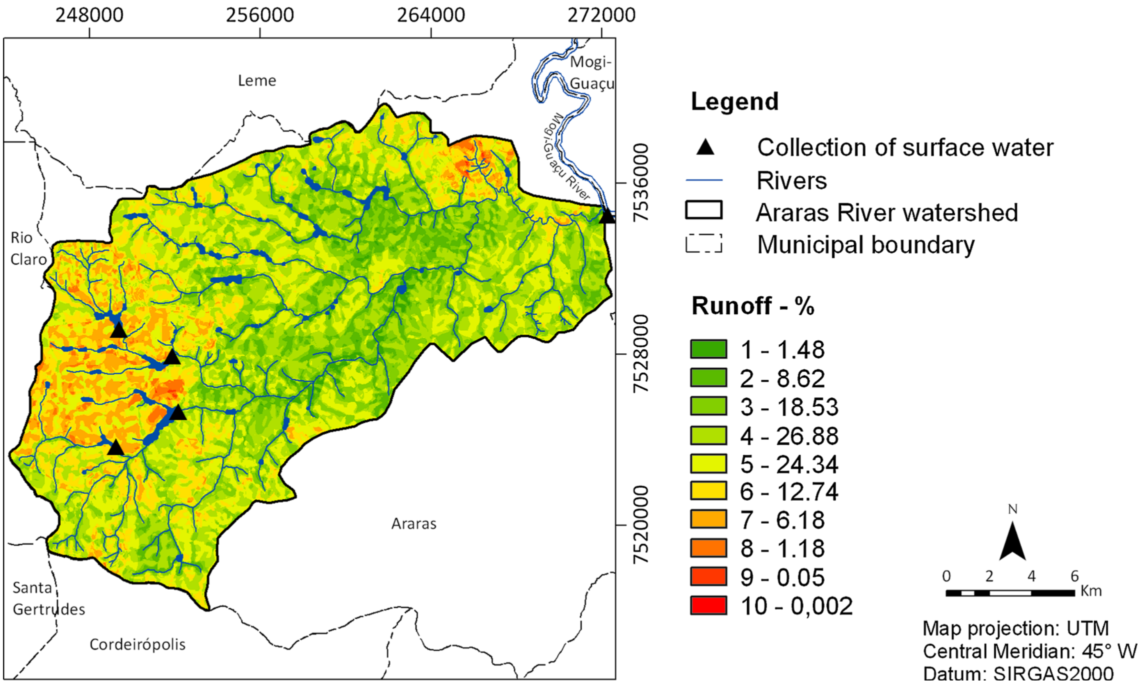

Fig. 4 Chart of surface runoff potential of the ARW

Triggering factors for accelerated erosion are conditioned by interrelations between natural attributes (soils, rocks and relief) and man-made factors (soil use and cover), which have a great influence on the intensity and recurrence of erosion processes.

Classes with lower to medium potential for erosion (1–5) can be found throughout the basin, particularly in areas with native vegetation, along water courses and in the bottom of valleys. These areas feature low surface runoff potential and are connected to convergent-concave slope shapes. Such slopes, due to their geometry, favor stream velocity reduction from the top to the bottom of the hill.

The areas with higher potential for accelerated erosive processes (classes 6–8) were identified in the central, eastern and southeastern regions. These areas, conditioned by sandy soils (>30 % fine sand) arising from the Itararé and Pirambóia Formations, represent a high potential for erodibility and depths varying from 2 to 5 m and over 5 m.

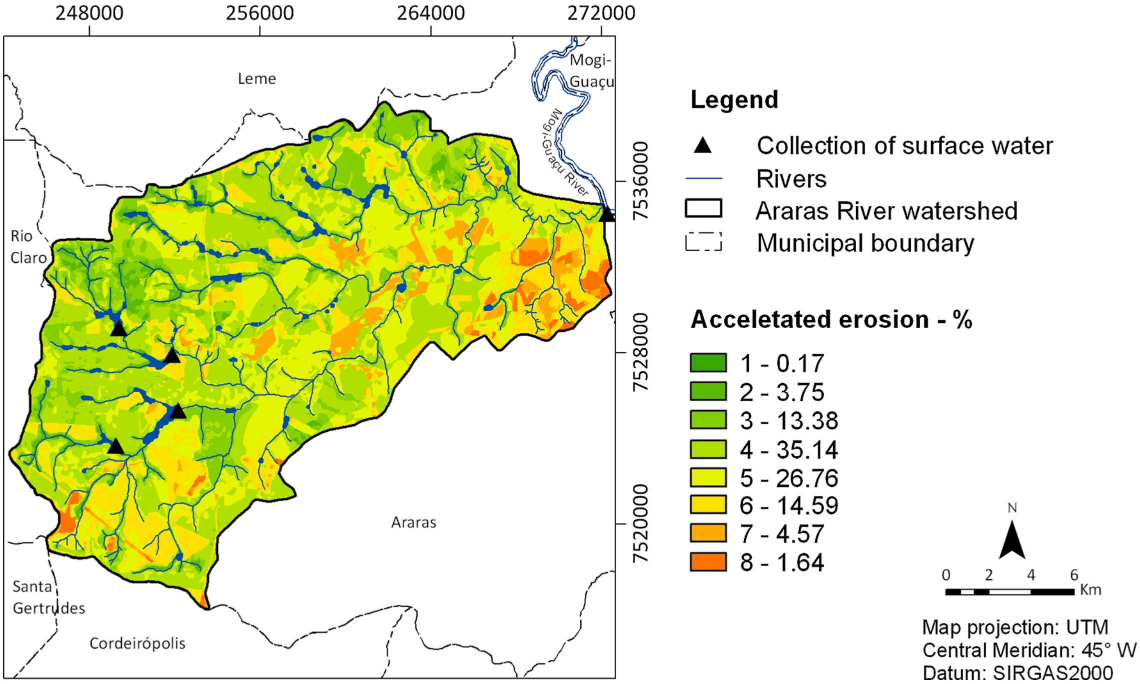

Fig. 5 Chart of potential risk for accelerated erosion of the ARW

Low-compactness sandy soils are extremely fragile in terms of erosion resistance once some granulometric fractions are more easily removed.

The uses of soil related to classes with potential for accelerated erosion consist predominantly of exposed topsoil in citrus and sugar cane cultivation areas. Once the image used for land use/land cover classification was from December, a period of more intense rainfall on exposed topsoil being prepared for the cultivation of sugar cane is a driving force that triggers accelerated erosive processes.

When deprived of its natural vegetation, the soil, exposed to a series of factors, tends to be impoverished (Bertoni and Lombardi Neto 1999; Lepsch 2010). Even in low-steepness terrain, this type of soil use increases the potential for erosion.

Concerning agricultural practices, some types of crops are more detrimental to the soil than others. Sugar cane farming in the ARW makes soil more susceptible to erosion than perennial farming (Jinno et al. 2009; Lepsch 2010). Sugar cane farming, when combined with inadequate soil management practices, may affect the form and the intensity of natural erosive processes and accelerate the development of grooves, ravines and gullies (Salgado and Magalhães Júnior 2006; Assunção and Cunha 2009).

By analyzing the relation between the chart of surface runoff and accelerated erosion, one can observe that in places with higher altitudes where lithology and clay/siltstone soil predominate, the potential for surface runoff is higher. In such cases, the continuous increase of the slope length will result in the accumulation of water sufficient to channel the flow, which may strengthen mechanical degradation and wash away particles of soil in situ, triggering the formation of gullies.

The reduction in upstream water retention time and the consequent increase in river flow may result in the intensification of marginal erosive processes in the Araras River, where runoff drains on low-resistance sandstone soils and where increased indexes of potential for accelerated erosion were observed. Nevertheless, in regions close to the basin estuary, a reduction in stream velocity is common, once water percolation occurs in sandstone soils, increasing accelerated erosion processes and soil losses.

Considering water collection points for supplying Araras city (shown in Figs. 4, 5), we observe that these areas are in average to high potential for surface runoff and accelerated erosion regions. Therefore, the natural rainwater percolation and underground recharge process may be reduced when considering the impact of anthropogenic uses and the physical characteristics of the basin.

In the case of areas intended for sugar cane farming, this is worsened due to the extensive use of agricultural machines and the stillage for fertirrigation, leading to soil compaction (Severiano et al. 2010) and the clogging up of soil pores, thus reducing permeability and recharge (Alves 2007). Studies by Zuquette et al. (2006) in neighboring river basins with the same physical characteristics showed that instead of having homogeneous soils, percolation and surface runoff rates depend on soil use and management practices.

According to Costa et al. (2015), in 2014 the city of Araras (SP) underwent an unusual scenario with the emptying of the main surface water collection sources and a loss of resilience after a period of drought. Such conditions were also felt in all southeast regions of the country, with conditions so severe in the state of São Paulo that decision makers were forced to adopt extreme measures such as compulsory water rationing.

Conclusions

Runoff potential and accelerated erosion potentials in the ARW imply some unique consequences: large volumes of water do not infiltrate in downstream supply areas due to the combination of lithology and sediment of fine soil; the greatest potential for surface runoff resulted in the lixiviation of sediments due to erosion by surface water bodies, resulting in the silting of water reservoirs; allied with natural factors, the water deficit foreseen by city administration is worsened by an increase in demand, a reduction in native vegetation areas and intensification of sugar cane farming, considerably reducing soil permeability coefficients.

Measures should be taken so that the agricultural matrix, marked by the widespread presence of sugar cane, is managed with sustainable practices and technically planned extensions of agricultural activities instead of being defined on the grounds of economic criteria alone. Low-potential areas also need more attention so that suitable land management allows them to remain within such classes.

The charts of potential for surface runoff and accelerated erosion, once reflecting natural and man-made influences in environmental conditions, must be considered in watershed planning to identify local techniques for soil and water conservation to preserve important ecosystem services.

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