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Estimating the surface runoff from natural environment data

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Abstract

Purpose – The purpose of this paper is to estimate quick and low-cost processes for surface runoff potential on the basis of natural environmental attributes.

Design/methodology/approach – An approach based on the natural environmental attributes and on the Cook's method was used for maximal peak flows of surface runoff, as well as for assigning weights to the considered attributes. Used attributes are as follow: steepness, bedrock (lithology), soil (texture, genesis, thickness, and permeability coefficient), drainage density, and favorable features to surface storage.

Findings – Using natural environmental attributes from previous available studies, adapted from different scales, the authors obtain a low-cost potential surface runoff chart, which can be useful for planning, impact and hazard analysis, and decision purposes in an area without large financial resources, like small communities in developing countries. Despite the common scarcity of data in these communities, often regional basic studies of soil and bedrock are available, making this kind of analysis possible.

Originality/value – The highlights are quick and low-cost procedures in characterizing the natural environment for planning activities, providing the basis for further detailing, which focus on solving local problems. This approach to runoff estimation allows for the definition of the criteria, considering the potential geodynamic processes. Thus, this kind of study may be very useful for land use planning in developing countries.

Keywords Caçula stream, Ilha Solteira, Natural environment attributes, Superficial runoff, Surface geodynamic processes, Watershed

Paper type Research paper

1. Introduction

Information on runoff conditions constitutes a fundamental base for understanding dynamic processes and life support requirement (Bonetti and Miranda, 1997; Griebeler *et al.*, 2001).

Watershed natural environment identification controls the location and quantification of water flows, governing the terrain changes that give important contribution to environmental degradation such as erosion and mass movements (Guerra and Cunha, 2000; Santana, 2003).

Erosion was highlighted as a major environmental problem due to its social and economic impacts and it is influenced by soil erodibility, as well as human activity (Pejon and Silveira, 2007; Conoscenti *et al.*, 2008).

According to Soares *et al.* (2012), infiltration and runoff portray watersheds as dynamic reservoirs, and are related to underground storage as well as rivers.

Surface runoff is primarily related to climate and natural attributes of the area (Pruski *et al.*, 2001). Properties of rock influence terrain permeability, depending on its genesis, texture, and thickness. Soil properties control how water infiltration occurs and relief characteristics have strong influence in runoff/infiltration balance (Mota, 1981; Griffiths and Stokes, 2008; Camarinha, 2011).

Drainage density (number of drainage channels per linear kilometer) determines the rate of infiltration, resulting in rapid development of surface runoff, whereas according to

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Mendonça and Lorandi (2006) areas with low-drainage density present a high rate of infiltration and widespread laminar runoff channels.

Contributing areas of infiltration-excess overland flow are determined by the interaction between rainfall intensity and soil permeability. The least-permeable soils in a basin are the most likely contributors to infiltration-excess overland flow. As rainfall intensity increases, areas with more moderate permeability may also contribute to the overland flow (Juracek, 2001). Inconsideration of natural attributes and related land use can be the origin of several environmental problems (Tang, 2005; Grindlay *et al.*, 2011; Fidelis and Roebeling, 2014).

Thus, land-use changes generate infiltration changes which can lead to various degradation processes such as erosion (Neris *et al.*, 2012). Meeuwig (1970) emphasizes the importance of vegetative cover in maintaining the infiltration capacity and soil stability.

Runoff processes are expected to affect water quality in streams, although possibly in different ways due to different flow paths. The identification of potential runoff-contributing areas in a basin can provide guidance for targeting the best planning practices (Juracek, 1999).

Changes in land use, particularly urbanization, affect hydrological processes and result in erosion and water resources impairment (Du *et al.*, 2012; Suriya and Mudga, 2012). According to planning policies for environment protection and conservation, establishing a proper relationship between land uses and watersheds management allows integrated management of water resources (surface and groundwater) (Martín-Duque *et al.*, 2003; Rufino *et al.*, 2009; Mendes and Lorandi, 2010; Gyawali *et al.*, 2013).

According to Juracek (2000), potential runoff-contributing areas with high percentages of cropland and/or urban land uses would be expected to have a higher potential for runoff compared with areas with similar relief and soils with high percentages of grassland and/or woodland. Moreover, areas classified as non-contributing, on the basis of the relief and soil characteristics, may contribute to runoff if the land use is mostly cropland and/or urban.

Thus, watershed territorial planning, based on its natural environmental conditions, can be an option in solving this problem (Mota, 1995; Guerra and Cunha, 2000; Dibieso, 2007).

Brazil National Water Resources Policy established watershed as a territorial unit for analysis and decision making (Mota, 1995; Brasil, 1997; Bottino, 2008; Sullivan, 2014). Although, most of the Brazilian watersheds lack basic data (Porto and Porto, 2008), thereby, resulting in the adoption of Hydrographic Basin Committees as a way of data survey and technical studies. Based on its principle and large territorial dimensions, São Paulo State was divided into 22 units of water resources management (named UGRHI's), as shown in Figure 1.

The estimation of the potential runoff from hydrological models has some limitations, despite its apparent simplicity regarding the parameters used, facility of manipulation of equations, and fastness in obtaining results. According to Tucci (1998), the models require proper training of users in understanding the chosen template, in order to avoid tendentiousness in their use.

Cook's method enables us to estimate peak flows resulting from river basin runoff considering four categories of sum of numerical values and weights of attributes: terrain, infiltration, vegetation cover, and storage conditions.

On the basis of Cook's method, Pejon and Zuquette (1993) proposed a method for surface runoff chart production by combining the intervals of weights and values. Barreto-Neto and Souza Filho (2003) and Zuquette and Gandolfi (2004) stated that this method can provide more realistic runoff coefficients and help in the planning and management of watershed with poor hydrological data and subjected to constant land use changes.

Natural environment attributes include steepness, lithology, soils (texture, genesis, thickness, and permeability), drainage density, and surface storage features. The weights for each attribute class are related to runoff potential influence.

Source: Integrated Water Resources Management

Figure 1. Units of water resources management – SP

2. Material and methods

2.1 Studied area

This study is aimed at estimating the surface runoff potential of the watershed of Caçula Stream, Ilha Solteira (Brazil), based on natural environmental attributes analysis, in order to provide subsidies to urban planning, using agile and low-cost processes.

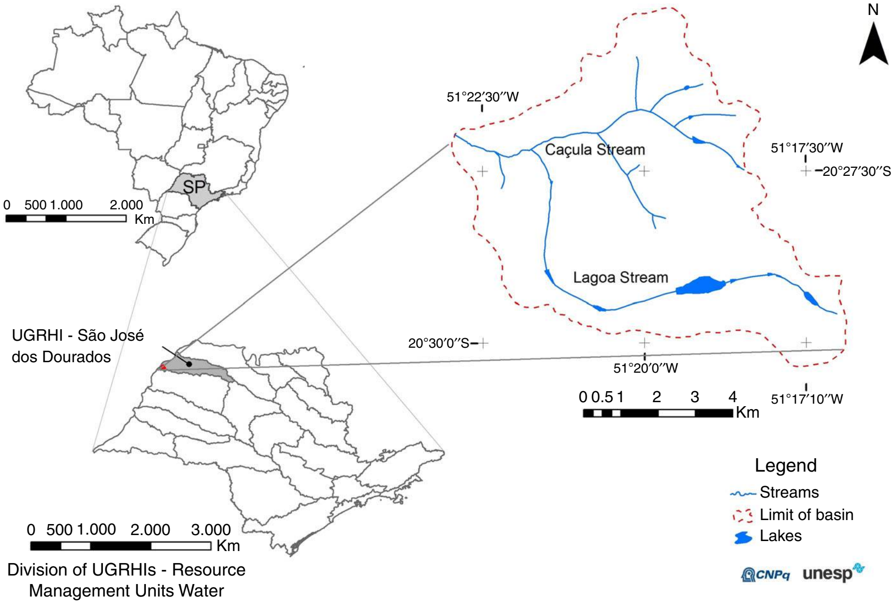
Caçula Stream Watershed (56.3 km²) is located in northwest of São Paulo State (Figure 2), belonging to São José dos Dourados Unit of Water Resources Management (UGRHI 18), which comprises several small river basin watercourses flowing to Ilha Solteira Hydroelectric Power Plant reservoir (Sistema Integrado de Gerenciamento de Recursos Hídricos de São Paulo, 2013).

Ilha Solteira town is located between meridians 51°00’ and 51°30’W and the parallels between 20°15' and 20°45’S, comprising an area of 656.22 km², and having a population of 25,064 inhabitants, 23,520 of those live in urban areas (Instituto Brasileiro de Geografia e Estatística, 2012).

Caçula Stream Watershed location comprises urban and extra urban areas of Ilha Solteira, resulting in conflicts due to urban areas going toward extra urban portions (Figure 3). The watershed presented several flooding events in the past ten years, and public works done to reduce these events were unsuccessful, because they are destitute of efficient environmental attributes.

The population growth and urban expansion in the area are partially replacing livestock activities, removing riparian vegetation, and disregarding environmental conditioning, which result in soil degradation processes (Tavares, 2008; Santos and Hernandez, 2013).

According to Gonzaga *et al.* (2010), the combination of those events with domestic sewage, illegal connections and urban surface runoff and flows in Sem Nome Stream (Caçula Stream affluent) result in water quality problems in watershed.



Source: SRTM/2003 Projection: WGS (1984)

Figure 2.
Location of the study area

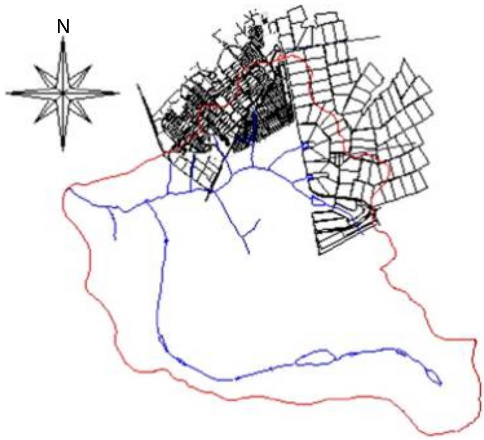


Figure 3.
Location of the Caçula basin related in relation to the urban area of Ilha Solteira

Ilha Solteira City Hall presented initiatives aiming at improving the environmental quality of this watershed, such as project of fluvial water catchment and municipal erosion control, and adhesion to govern programs involving projects of gully control in Caçula watershed (Prefeitura Municipal de Ilha Solteira – Ilha Solteira, 2004).

Still, most of these projects have no results in the expected control degradation processes (erosion, in particular) simply because they have disregarded natural environment attributes.

The expansion of urban areas of Ilha Solteira toward this watershed is resulting in environmental degradation (river valley erosion, channel silting, and flooding). Urban land use in the watershed exposes part of the population located next to water courses, thereby, jeopardizing the quality and quantity of water resources.

2.2 Potential runoff estimation

Surface runoff potential chart was produced for areas with degrees of higher to lower runoff potential areas using Pejon and Zuquette's (1993) proposal. Potential runoff was obtained by combining natural environmental attributes from relief (steepness), bedrock (lithology), soils (texture, genesis, thickness, and permeability), and hydrology (drainage density and surface water storage favorable features).

Considering Caçula watershed's conditions and history, we used data from previous surveys overlaying the area, being the feasible alternative for a low-cost data survey, due to its lack of detailed data and information survey.

The adopted strategy was used to adapt previous information (relief, rock, and soil) from different scales (Instituto Geográfico e Cartográfico do Estado de São Paulo, 1965, 1967; Instituto de Pesquisas Tecnologicas do Estado de São Paulo, 1981a, b; Consórcio Intermunicipal para o Desenvolvimento da Irrigação na Região de Urubupungá – CINDIRU, 1995; Lollo, 1998), and then combines this information with digital data from Topodata Project (Valeriano, 2008; Valeriano and Albuquerque, 2010). Topodata Project provides free geomorphometric data derived from Shuttle Radar Topographic Mission (SRTM) raw data.

Table I shows the weights proposed by Pejon and Zuquette (1993), whereas Table II shows the weights adopted for the Caçula Stream Watershed's geological, geomorphological, and pedological contexts, representing used attributes and their respective classes.

In Table II, the weights and classes of environmental components and attributes were defined considering the sequence proposed by Pejon and Zuquette (1993): analyze the variation of each attribute in the study area; establish classes with similar expected behavior, regarding the runoff for each attribute; dispose classes in ascending order of potential runoff, with each attribute individually; assign a rating to each class, putting the area's natural environmental context into consideration; establish the number of attribute's classes from the attribute which presents the highest number of classes; determine the relative importance of each set of attributes relative to the set which expresses the highest significance in runoff as a whole; establish minimum and maximum ratings for each attribute and the limits for intermediate classes, based on its influence on runoff.

Weights of each environmental component (expressed by basic maps) represent runoff potential in terms of values in the interval [1 to 10], wherein 1 represents lower potential runoff and 10 is the highest potential. Assignment of runoff for each component and weights for each class of attributes can be visualized in Table III. The chart was obtained from Map Algebra using Rater Calculator from ArcGIS 10.0™.

3. Results

3.1 Steepness

The map of steepness (Figure 4) was prepared from the radar image SRTM/2003 available online, which is in the website of the Topodata Project, and reclassified on the Software ArcGis 10.0. Considering relief local conditions (flat surfaces) and the maximum values obtained (highest values smaller than 30 percent), steepness was classified into six classes (0-2, 2-5, 5-10, 10-15, 15-20, and 20-30 percent).

If steepness of greater than 30 percent does not occur in the watershed, the highest weights (more than 66 percent) proposed in Pejon and Zuquette (1993) were not used. Thus, the lesser influence of steepness in runoff calculation properly express Caçula watershed environment.

Table I. Rating of the attributes of the natural environment for the development map of runoff potential according to Pejon and Zuquette (1993)

	Runoff potential increases									
Runoff classes	10	9	8	7	6	5	4	3	2	1
Attributes	272-250	249-230	229-210	209-190	189-170	169-150	149-130	129-110	109-90	89-70
Unconsolidated materials										
Declivity	> 45%		30-45%	20-30%	15-20%	10-15%	5-10%	2-5%		0-2%
	90	75	66	60	45	36		24		15
Lithology	Argillites, siltstones, and shales	Argillites, siltstones, and basic migmatites		Fine sandstones, siltstones, and diamictites		Fine to medium sandstones with clay				Fine to medium sandstones
	40	30		20		16				10
Texture and genesis	Residual silty-clayed	Residual clayed-silty		Reworked porous clayey		Sandy (< 30% fines) residual and reworked				Sandy (< 20% fines) residual and reworked
	40	30		20		14				10
Thickness (m)	< 0.5	0.5 a 3.0				3.0 a 5.0				> 5.0
	30	20				16				10
Permeability (m/s)	< 10-7	10-7		10-6		10-5				> 10-4
	12	8		7		6				5
Drainage density (channels/km)	More than 5	Between 5 and 2				< 2				
	3	20				10				
Favorable features to the surface storage	Do not present	Lagoons, small hollows (small amount)				Lagoons, small hollows (high amount)				
	30	20				10				

Table II. Rating of natural environment attributes for the development of the surface runoff potential map adapted to the study area

	Runoff potential increases									
Runoff classes	10	9	8	7	6	5	4	3	2	1
Attributes	197-202	184-196	171-183	158-170	145-157	132-144	119-131	106-118	93-105	80-92
Unconsolidated materials										
Declivity	> 45% 90		30-45% 75	20-30% 66	15-20% 60	10-15% 45	5-10% 36	2-5% 24		0-2% 15
Lithology		Basalt 40					Sandstone 30			
Texture and genesis		Red Oxisol 40					Red-Yellow Argisol 20			
Thickness (m)	< 0.5 30			0.5 a 3.0 20			3.0 a 5.0 16		> 5.0 10	
Permeability coefficient (m/s)	< 10-7 12		10-7 8		10-6 7		10-5 – LV 6		> 10-4 – PVA 5	
Drainage density (channels/km)	More than 5 3			Between 5 and 2 – Basalt 20				< 2 – Sandstone 10		
Favorable features to the surface storage	Do not present 30			Lagoons, small hollows (small amount) 20				Lagoons, small hollows (high amount) 10		

Table III. Assignment of the runoff potential for the attributes and classes

Attributes	Weight of attributes	Runoff value for each class					
Steepness	0.32	0-2% 1	2-5% 3	5-10% 4	10-15% 5	15-20% 6	20-30% 7
Lithology	0.20	Sandstone 6	Basalt 10				
Texture and genesis	0.20	Red-Yellow Argisol 6	Red-Yellow Oxisol 10				
Thickness (m)	0.15	> 0.5 2	3-5 4	0.5-3 8	< 0.5 10		
Permeability (m/s)	0.03	> 10-4 2	> 10-5 4				
Density drainage (channels/km)	0.10	< 2 4	2-5 8				

More frequent steepness classes in the watershed were between 2-5 percent (hill tops and slopes superior part), and 5-10 percent (encountered mainly in water courses margins). Steepness class of 0-2 percent is used in the study.

Classes representing bigger steepness values of 10-15, 15-20, and 20-30 percent are located very close to the watercourses, mainly in the northern part of the basin, being less expressive in the watershed. Despite it, these classes represent Caçula watershed terrains where most expressive erosion processes were observed.

3.2 Lithology

Bedrock in Caçula watershed resulted in Serra Geral Formation (basalts) and Santo Anastácio Formation (sandstones), as represented in the lithological map (Figure 5). Sandstone bedrocks are found at top and slope of hills, while basalt are found at the bottom of the valley.

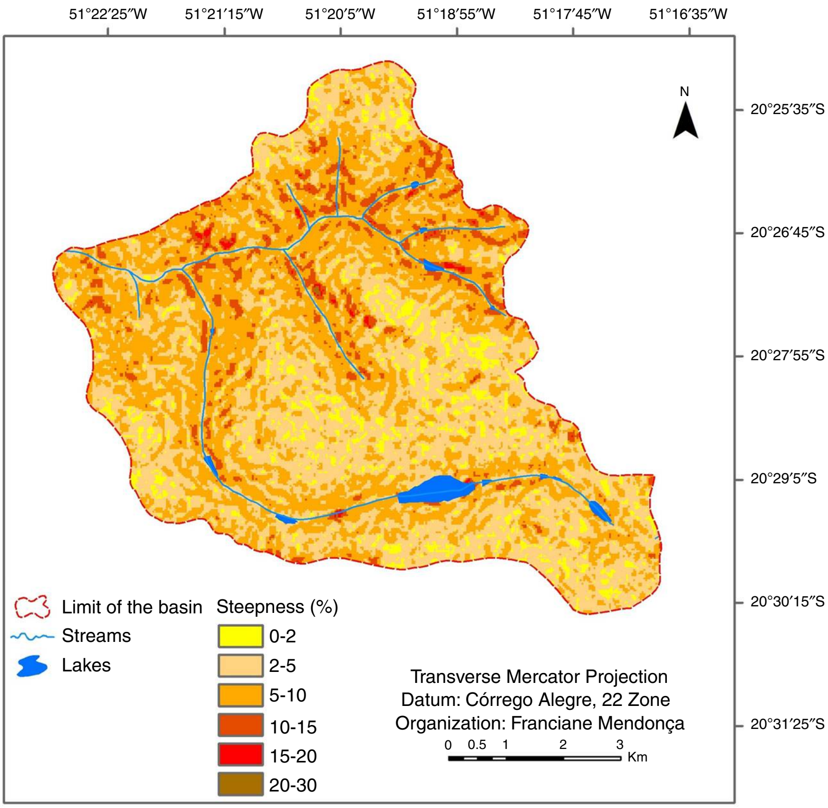


Figure 4.
Steepness map

According to its characteristics, these units were classified into the highest classes of weights for lithology. Basalts from Serra Geral Formation in this area are compact, have low permeability, and receives the weight 40, whereas for Santo Anastácio Sandstones, we adopt weight 30 due to their clayey cementation and siltstones lenses presence.

3.3 Soils

In terms of soils textures and genesis, the study area comprises Red-Yellow Oxisols (RYO) and Red-Yellow Argissol (RYA or Argissol), according to Consórcio Intermunicipal para o Desenvolvimento da Irrigação na Região de Urubupungá – CINDIRU (1995) pedological survey.

RYO soils present sandy texture, stable and well-developed profiles, usually deep, homogeneous, as well as present good drainage and low fertility (Empresa Brasileira de Pesquisa Agropecuária, 2006). Considering Pejon and Zuquette (1993) proposal, in terms of genesis, we adopted weight 40 for this class.

RYA soils are well drained and one of their main features is an increase in clay in the surface horizon A to the subsurface horizon B. The depth of this kind of soil may vary from shallow (lesser than 1 m) to deep. In terms of Pejon and Zuquette (1993) classes, this soil receives weight 20.

In the map of texture and genesis of soils, presented in Figure 6, it is possible to observe the presence of RYO soils in the northern part of the basin. In contrast, RYA soils are found in the southern part, having a small area in the northeast.

The map of thickness of soil classes (Figure 7) presents four classes of thickness, divided into: <1, 1-3, 3-5, and >5 m, respectively, according to Lollo's (1998) data. The class of

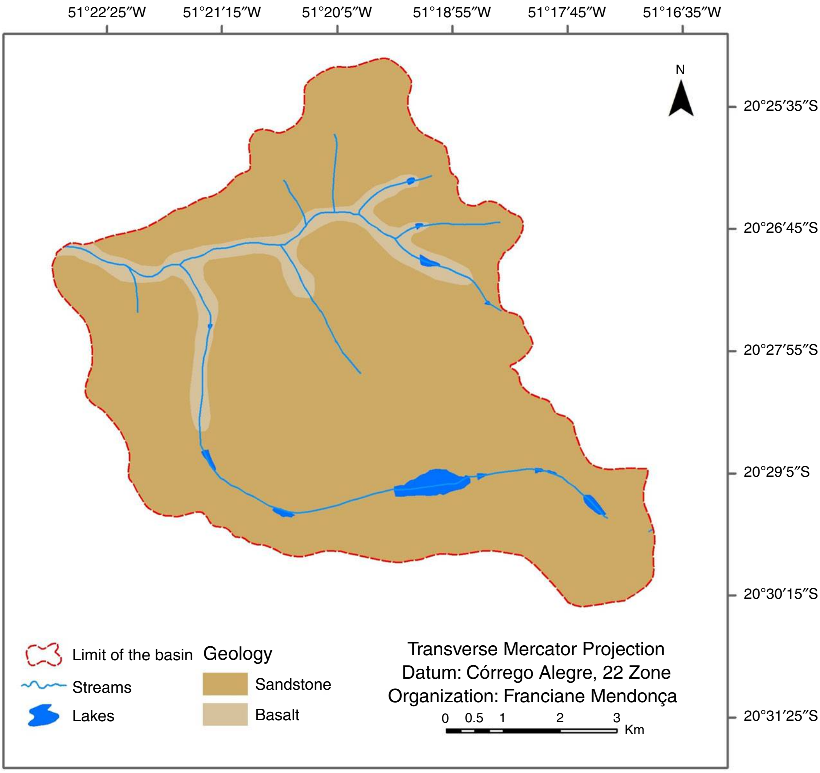


Figure 5.
Lithology map

thickness with less than 1 m represents a small portion located on the Caçula Stream, close to the estuary of the basin.

The intermediate classes of soil thickness (1-3 m thick) usually present higher runoff potentials, and are present in bottom valleys and third inferior portion of hills, with concave slopes.

Soil classes with 3-5 m thickness have higher tendency for infiltration. In Caçula stream, these occurrences were located in the intermediate part of hills, showing rectilinear to convex slope profiles.

The areas presenting soils with more than 5 m thickness are the most favorable for infiltration and they occupy the most significant part of Caçula watershed, mainly in hill top and hill superior convex slopes.

The map of soil permeability of Caçula Stream Watershed (Figure 8) was obtained using data from Lollo (1998), and it is divided into two classes. One of which shows a permeability coefficient of 10^{-5} m/s, and represents a more expressive class in territorial terms, related to RYO, whereas the other soil class shows permeability coefficient of 10^{-4} m/s or greater in the area of RYA.

3.4 Drainage density

The map of drainage density (Figure 9) is divided into two classes. The most expressive class of the area is that presents less than 2 channels/km², whereas the class presenting 3-4 channels/km² represents a less expressive class, occurring in the bottom of the valley near the estuary of the river basin.

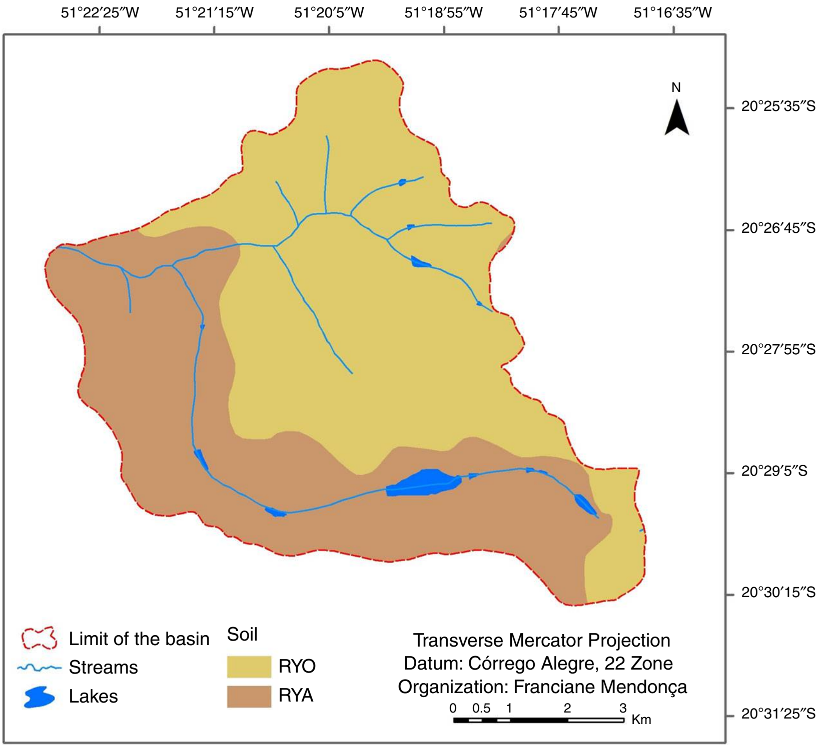


Figure 6.
Map of soil

This is an expected result for this watershed, once in major part of Paraná Basin where soil profiles are thick (like this area) and drainage density is controlled by soil profiles, which commonly shows high permeability coefficients (e.g. greater than 10^{-5} m/s).

3.5 Feature favorable to surface storage

All the Caçula watershed area presents the same class for this attribute, not presenting features favorable to water surface storage, which is not considered in this analysis. It occurs mainly due to higher soils permeability, as cited above.

3.6 Surface runoff potential

The surface runoff values were classified into three classes: low, medium and high, once bigger values foreseen in adopted method was not present in Caçula watershed. Potential Runoff Chart can be observed in Figure 10.

Low surface runoff values were calculated mainly in south and central portion of the watershed, which represent areas with lesser steepness (more flat relief) of the Caçula watershed. High runoff potential values occur in river valleys of Caçula watershed, and medium runoff values occur in transitions areas between low and high values.

4. Discussion

Runoff potential chart produced for Caçula watershed clearly expresses natural environment conditions and some of used attributes had more influence on results, since Pejon and Zuquette (1993) method strongly depends on these attributes.

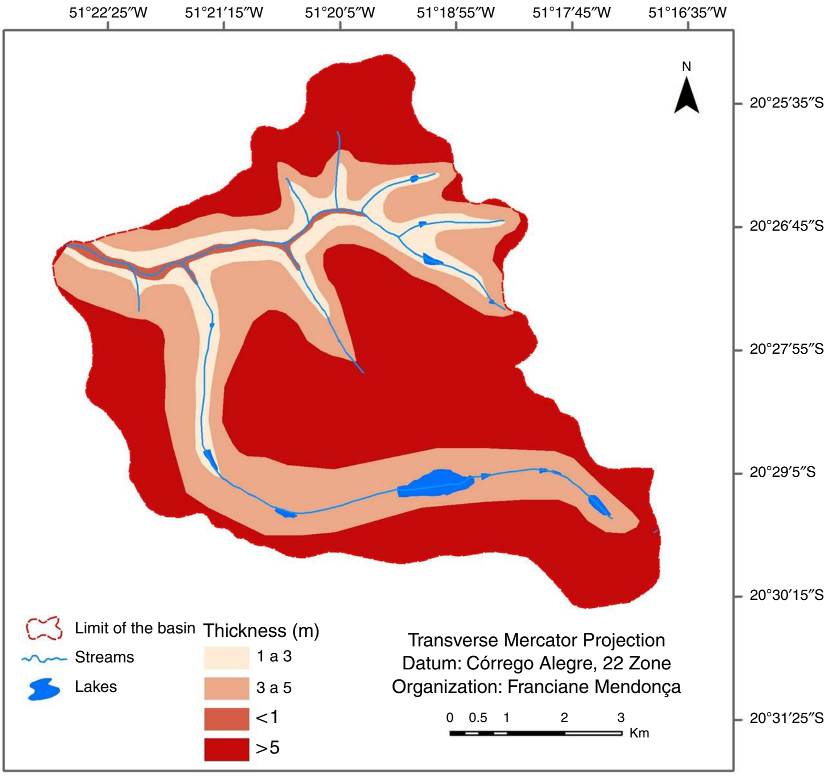


Figure 7.
Map of thickness

Steepness influence in runoff values is related to relief influence in runoff process, expressed in terms of its relationship with erosion and flood potentials (De Biasi, 1992); Guerra and Cunha, 2000; Zuquette and Gandolfi, 2004). Steepness values form 0-2 percent class are related to higher flood potential in fluvial plains, whereas steepness greater than 10 percent represents the areas with moderate to high susceptibility to erosion.

In Caçula watershed, steepness over 10 percent is associated with high erosion susceptibility, due to soil profiles characteristics in the area, whereas smaller steepness values (0-2 percent) usually are associated with flood events and water resources degradation (Gonzaga *et al.*, 2010; Manoel, 2013; Santos and Hernandez, 2013; Sistema Integrado de Gerenciamento de Recursos Hídricos de São Paulo, 2013; Vivanco, 2013).

In terms of bedrock, the basalt contributes more significantly to bigger potential runoff, due to its compact structure and smaller porosity. Sandstones, despite their clayey cement, present better infiltration potential, resulting in smaller potential runoff.

Bedrock watershed conditions contribute to final runoff potential results, although the weights adopted for this attribute had smaller influence, as basalt occurrence in bedrock is associated with greater steepness and less thick soil profiles. Considering that, Pejon and Zuquette's (1993) proposal is correct in considering bedrock as a significant attribute, despite the occurrence of more thick soil profiles in Paraná Basin.

In terms of soil texture and genesis, RYO present problems related to restricted permeability (high cohesion of aggregates, and extremely hard conditions when dry), with slow water infiltration. They also present high erodibility when used for plantations or pasture. RYA soils can induce runoff due to increase in their clay content when presenting shallow profiles.

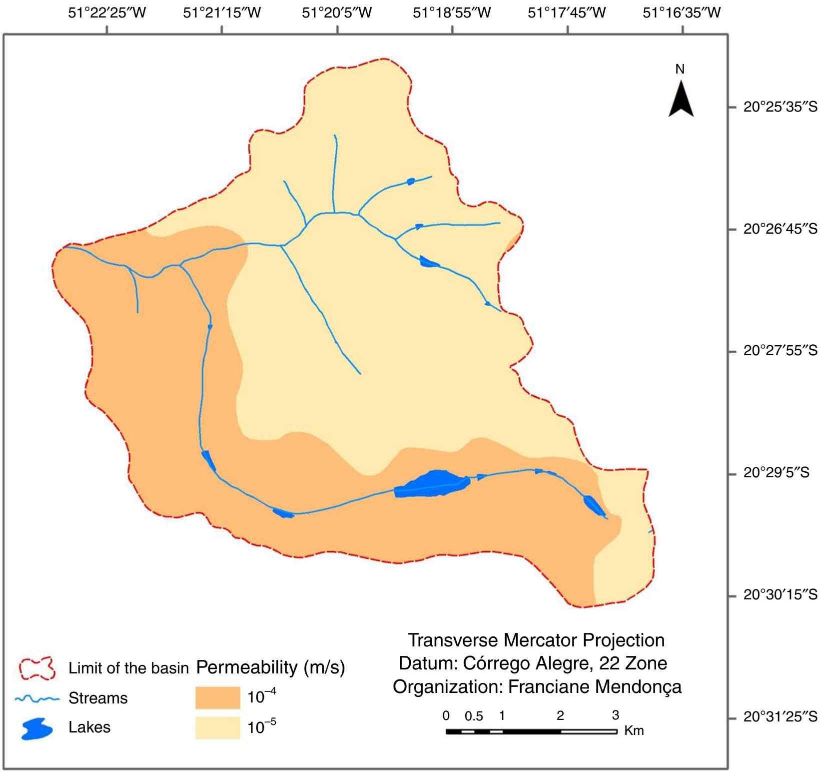


Figure 8.
Map of permeability

Despite the strong difference in weights values for soil texture and genesis occurring in Caçula watershed, runoff final results show small influence of these attribute.

Areas with soil thickness less than 1 m are the most favorable for the surface runoff, as this potential runoff is controlled by bedrock. For 1-3 m thickness, the soil profiles potential runoff is usually high, but presents some control due to soil genesis and texture.

Despite its significant potential runoff, 3-5 m soil thickness classes present influence of soil texture controlling runoff. For soil thickness > 5 m (majority of watershed area), soil even shows low runoff potential. This thickness class is often associated with top of hills and porous soils, thereby, increasing water infiltration potential.

Soil thickness chart presents influence in runoff potentials final results mainly in streams valleys and its vicinity. This situation results from lesser soil thickness association with higher steepness and basalt bedrock occurrence.

Permeability coefficient does not exhibit expressive variation in controlling runoff in Caçula watershed. The majority of area (located in central and north portions) shows less permeable soils conditioning, more significant potential runoff, whereas south portion of the area presents smaller permeability coefficients and, as a consequence, bigger potential runoff.

Furthermore, smaller permeability coefficient areas match with smaller steepness areas next to watershed body waters, areas which naturally exhibits bigger infiltration potentials.

Due to Caçula watershed characteristics, the overvaluation of these steepness and bedrock from Pejon and Zuquette (1993) exacerbated the importance of these attributes, but it is clearly coherent for this area.

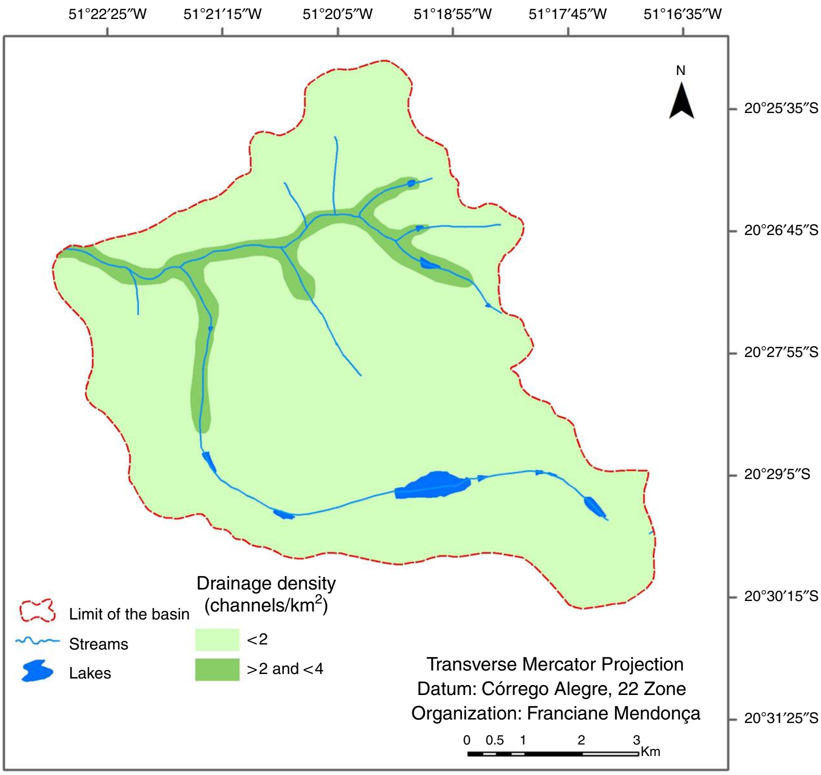


Figure 9.
Drainage density

On the other hand, the significant influence of soil attributes in the obtained results demonstrates an expected scenario in Brazilian southeast environments, since climate in this region allows deeper, more porous, and less compact soil profiles. Of course, this situation reveals different expression when soil profiles are thin.

It is worth highlighting that the methodology of Pejon and Zuquette (1993) was not developed for application in urban and urban expansion areas. This is the main reason why land use attributes were not considered by the authors in their analysis, as can be observed in Table I.

This peculiarity of Caçula watershed, considering urban and urban expansion uses can be considered to increase other methods, like Soil Conservation Service (USDA, SCS, 1972).

On the map, the areas with high surface runoff potential are located mainly at the bottom of the valley and expressively in the northern portion of the basin. This occurs due to the influence of the variables: drainage density (between 2 and 4/km^2 channels), lithology (basalt), permeability (10^{-5} m/s), texture and genesis (RYO soil – Oxisol).

Bottom valley land unit present high surface runoff potential due to geologic conditions (basalt) associated with thin soil profiles. The RYO soil – Oxisol presents low permeability (high cohesion and extremely hard when dry), resulting in slow water infiltration when used for crops or pastures with high erodibility. High surface runoff potential areas are also present in the northern part of the watershed, which has the urbanized area.

Areas with less potential for surface runoff are significantly located in the southern part of the basin, being representative of the weighting values attributed to the algebra maps of the variables: drainage density (< 2 /km^2 channels), lithology (sandstone), permeability (10^{-4} m/s) as well as texture and genesis (RYA soil).

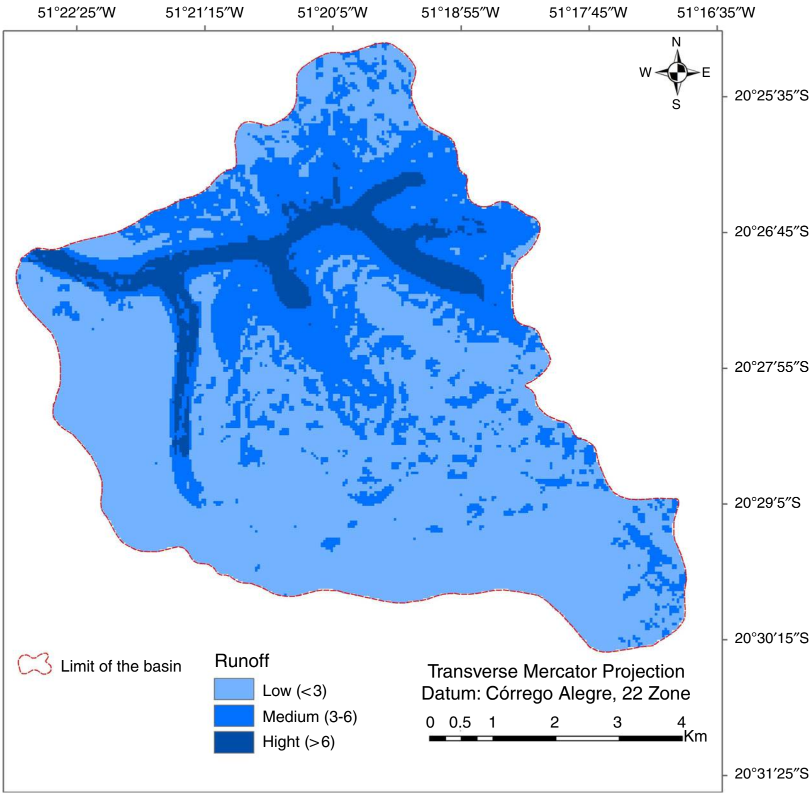


Figure 10.
Map of surface runoff potential

The areas classified with less potential for surface runoff are mainly concentrated in the southern region of the watershed due to soil type (RYA soil) presenting deep or very deep profile, well drained, medium texture and high to very high porosity. These areas also have large sections covered with perennial and temporary agriculture and forests and natural vegetation, which favor the infiltration process.

5. Conclusions

The used methodology results in surface runoff potential that express Caçula watershed natural environment and allows understanding erosion and flood previous occurred process.

The overvaluation in assigning weights of soil texture and genesis and permeability attributes from original method, which can compromise the quality of the results, were solved adopting weights suitable for Caçula watershed natural environmental conditions.

In Caçula Stream Watershed, low declivities and bedrock's low heterogeneity are the most important factors controlling runoff.

Thus, this work's approach and weights attribution discussion can be applied to many watersheds in large areas of the Brazilian territory, and also in regions of other countries with similar climatic conditions.

The study was applied in a watershed located in a third-world country (Brazil) with weak detailed data, using previous small-scale data adjusted and checked by field works and demonstrate that this approach may serve as an alternative in similar conditions.

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