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Papers

Runoff, Identification of Sensitive Zones in the Capivari Watershed – BA

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Abstract
The watershed is an active environment, defined as an area of land surface drained by a primary river and its tributaries, which are bounded by water dividers. Among the processes that affect water movement in a watershed, the surface runoff stands out, responsible for the transport of soil particles (nutrients and pollutants) to the lower parts of the landscape. The objective of this study was to demonstrate the influence of land use and cover on surface runoff dynamics in the Capivari Basin in Bahia, Brazil. To reach that objective, the Curve Number method (SCS-CN) was employed, with the ALOS/PALSAR RTC Digital Elevation Model; IBGE soil data; data from government weather stations and local agribusiness; land use and land cover from the LC08_L1TP_216069_20170619 landsat8 OLI sensor, through the classifier Bhattacharya. The processing was carried out on a GIS platform, using SPRING and QGIS software. Highest levels of precipitation, the soil features and the higher slope affected the greatest vulnerability to runoff at the mouth, based on the proposed model, however, the most conserved Permanent Preservation Area (PPA) have been effective in maintaining the Capivari River in these areas. The areas considered most critical in terms of the risk of water erosion for the year 2017 were those in the middle of Capivari, because they presented high precipitation in some months, but do not present PPA in riparian forest areas or in hill tops, this increases the vulnerability of these regions to erosion. The proposed model was successful in identifying areas most vulnerable to runoff in the Capivari Basin.

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INTRODUCTION

The hydrographic basin, or watershed, is a dynamic environment, with a chain of interdependence between its compartments (atmosphere, precipitation, vegetation cover, relief, soil and water), being defined as an area of the land surface drained by a main river and its tributaries, being delimited by the water dividers, or edges (BOTELHO, 2012), or even, as an area of natural capture of precipitation water that converges the flow to a single exit point, its outlet (SAHA et al., 2022).

In the current scenario, of scarcity of water resources both in quantity and quality (FERREIRA et al., 2020; KUMAR et al., 2021), it is essential to understand the processes that occur in a hydrographic basin, in addition to the environmental elements involved, considering that a developing society causes changes that influence the physical structure, affecting the contribution of sediment, the composition of biota, the hydraulic regime and the flow of substance and energy in these areas (FINOTTI et al., 2011).

During a precipitation event, rainfall that reaches the land surface can undergo two main processes: infiltration or runoff (KUMAR et al., 2020; WANG et al., 2019). Surface runoff, in a watershed, is responsible for carrying soil particles (nutrients and pollutants) to the lower parts of the landscape, which tends to intensify as a result of inadequate land use and occupation (MINELLA et al., 2010), intensive agricultural practices and lack of adequate management in cultivated areas (COSTA et al., 2016).

The transported sediments are usually deposited in streams, reducing their drainage canal. It leads to flooding, affecting riparian areas and urban centers (BENDA et al, 2007; ARAGÃO E GOMES, 2019), resulting in impacts felt both inside and outside the watershed. (FERNANDES et al., 2014; OLIVEIRA et al., 2015; APARECIDO et al., 2016; VEIGA et al., 2019; WANG et al, 2022).

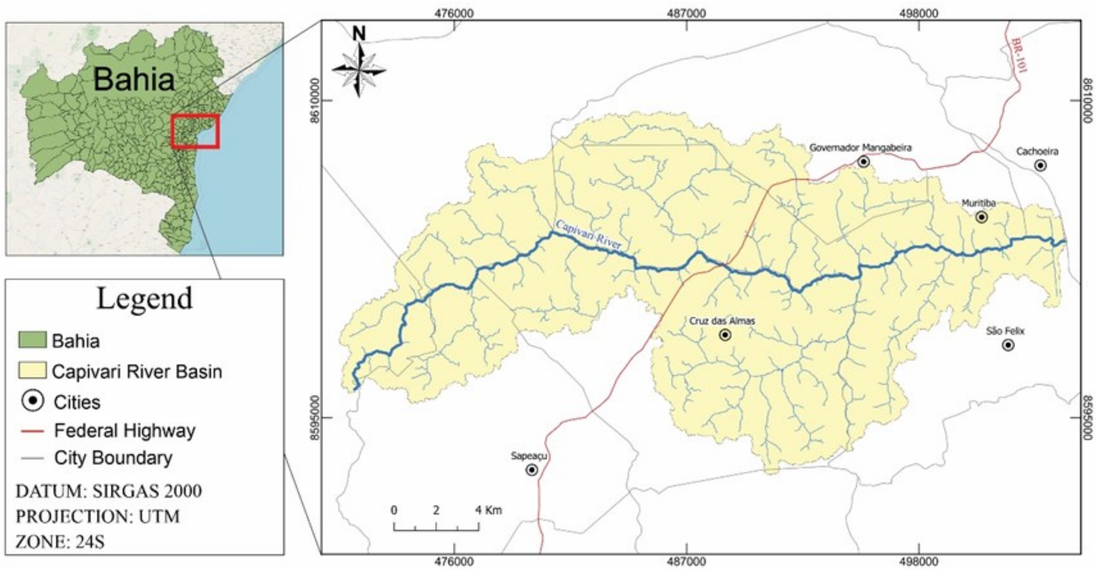
Consequently, it is essential to carry out surveys that help to find the factors that exert greater pressure on a watershed, providing managers with information on environmental quality and guiding decision-making for the effective management of the area (FELIPPE et al., 2016). Thus, the present study aimed to indicate the influence of land use and cover on the dynamics of runoff in the Capivari basin.

METHODOLOGY

Characterization of the study area

The Capivari River runs in the Recôncavo of Bahia (Figure 1), its source is in Castro Alves and its outlet in São Felix. The drainage basin covers around 318 km² and a total of seven municipalities, namely: Castro Alves, Sapeaçu, Cabaceiras do Paraguaçu, Cruz das Almas, Governador Mangabeira, Muritiba and São Félix.

Figure 1 - Location of the study area.



Source: The authors (2021).

Climate and Vegetation

The climate of the basin is quite diverse, ranging from semi-arid to humid, with a predominance of sub-humid climate (Table 1) and this characteristic directly influences the distribution of precipitation and vegetation within the basin area.

Table 1 - Climatic classification of cities in the Capivari Basin

City	Climate
Castro Alves	Semi-arid, Wet-dry
Cabaceiras dos Paraguaçu	Semiarid
Sapeaçu	Wet-dry
Cruz das Almas, Mangabeira e Muritiba	Subhumid
São Felix	Humid

Source: Organized based from Bahia (2012)

The average annual precipitation in this basin varies widely, ranging from 770 mm in the semiarid region (Castro Alves) to 1300 mm in the humid region (São Felix), with a concentration of rainfall in autumn and winter. Most of the basin is covered by the Atlantic Forest, specifically Dense and Seasonal Semi-deciduous Forest (BAHIA, 2012), presenting some remnants with secondary species from this biome. In the semi-arid part of the basin, the dominant biome is the Caatinga.

Soil

The classification adopted in this research is that of Santos et al. (2018), where 4 (four) soil domains for the basin are described: *Argissolo Vermelho-Amarelo* Distrófico (Dystrophic Yellowish red Acrisols), *Chernossolo Argilúvico* (Molisols), *Latossolo Amarelo Distrófico* (Dystrophic yellow Ferralsols) e *Planossolo Háplicos* (Planosols).

The Acrisols are soils constituted by mineral material with low activity clay (SANTANA et al., 2002), they usually present medium or sandy texture, varying, in their majority, from deep to very deep (SARTORI et al., 2005).

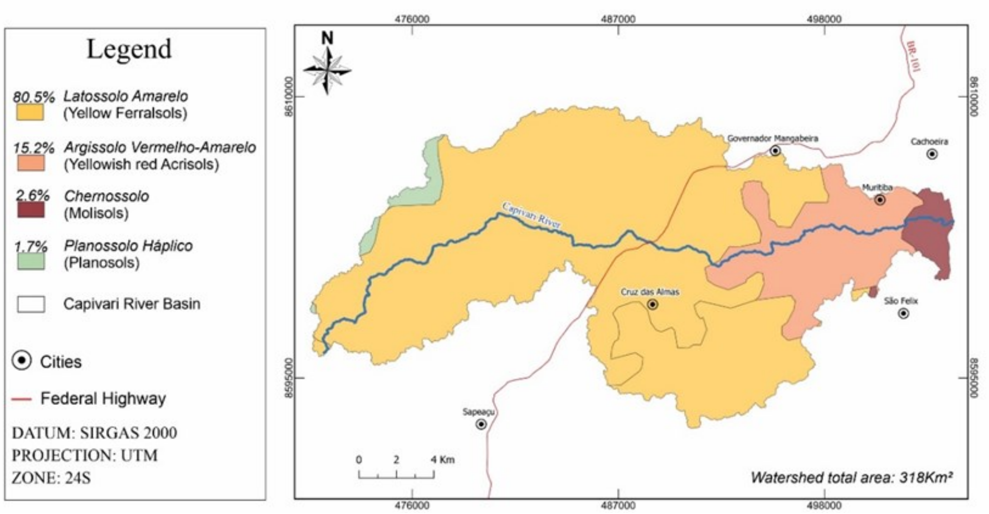
The Yellowish red Acrisol has an arenic or thickened character, (SARTORI et al., 2005). They occur in conditions of relief from relatively smooth to wavier, have a high susceptibility to erosion and have predominantly low chemical fertility (MARQUES et al., 2014).

The Molisols are rich in bases and with high activity clay, with a superficial horizon enriched with dark-colored organic matter, being developed from basic rocks, rich in iron-magnesium and/or limestone minerals (MARQUES et al., 2014). They are moderately permeable on the surface horizon and slowly on the B horizon, making this soil highly vulnerable to erosive processes (JARDIM, 2020; MARQUES et al., 2014). They have good natural fertility (OLIVEIRA et al., 2007) with high basic saturation, high plasticity and high adherence. They still have drainage restrictions, difficult to a very hard consistency, difficulties in manipulating soil with agricultural machinery and tools (MARQUES et al., 2014).

Ferralsols are generally well-developed, deep and well-drained soils with a Ferralsol B horizon, with morphological, physical, chemical and mineralogical characteristics, uniform in profile. They almost always have cohesive horizons in their profile (BA and top of B) – with a hard or very hard dry consistency (MARQUES et al., 2014; SANTOS et al., 2018). They generally occupy areas of flat to soft undulating terrain (RODRIGUES et al., 2009; MARQUES et al., 2014), usually situated in coastal areas (MOREAU et al., 2006).

In the study area, the soil with the largest distribution is the Yellow Ferralsols, which is reported by Rodrigues et al. (2009). They occupy areas where major farms are concentrated and have high levels of sand at horizon A, leading to greater vulnerability to erosion (Figure 2).

Figure 2 - Soils present in the Capivari Basin



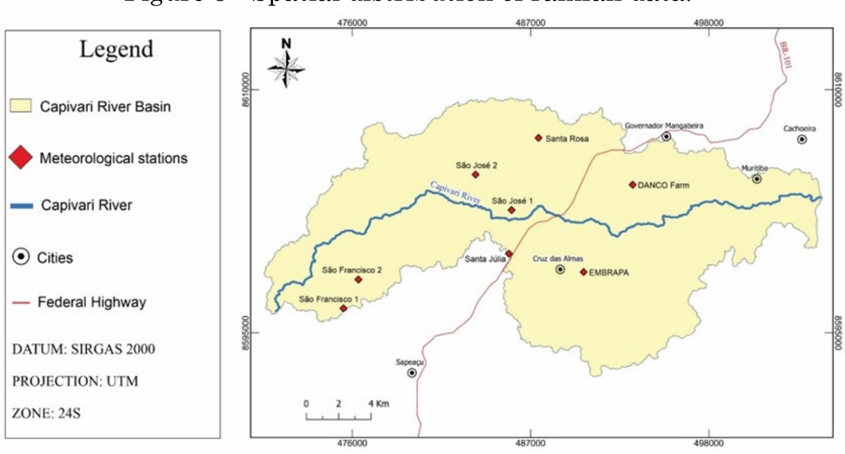
Source: The authors (2021).

The Planosols, on the other hand, comprise the old Planosols, Solonetz-Solodized and Gray Hydromorphic with deep and abrupt textural change (SARTORI et al., 2005). They have a significant accumulation of clay on the subsurface (horizon B planes) and are imperfectly poorly drained, presenting a pale color and dominant occurrence in smooth waves and flat relief (MARQUES et al., 2014; SANTOS et al., 2018). The restricted drainage of these soils and their high susceptibility to erosion plus the hardened to the extremely hard consistency of the plan a B horizon, make these soils not suitable for agricultural use, however, they are indicated for use with pastures (MARQUES et al., 2014).

Precipitation data

For the determination of the areas most susceptible to dynamic flow within the basin, rainfall data were acquired in the database of the Agência Nacional de Águas e Saneamento Básico (ANA, 2017), which is a National Water Agency in Brazil, and the Instituto Nacional de Meteorologia (INMET, 2017), which is the National Institute of Meteorology in Brazil, from different points inside and outside the study area (Figure 3).

Figure 3 - Spatial distribution of rainfall data.



Precipitation [mm]												
Station / month	January	February	March	April	May	June	July	August	September	October	November	December
Embrapa	14,5	47,3	44,6	152,6	169,9	146,4	148,8	49,6	157,9	32,5	68,5	0
São José	0	20	35	115	116	182	127	28	126	24	13	96
São Francisco 1	9	16	27	128	93	83	144	48	92	16	36	64
São Francisco 2	8	20	54	78	66	89	57	25	50	13	28	62
Danco	21	40,1	47,5	107	93	146	177	40	123	30	61	94
São José 1	6	24	21	98	90	144	120	28	122	36	54	96
Santa Júlia	16,4	39,2	41,6	145,4	130,6	140,2	157,2	46	156,2	33,4	65,8	116
Santa Rosa	12	39	68	88	131,5	144	149,5	38	132	31	64	91,5

Source: Organized according to ANA (2017); INMET (2017) and local agribusiness companies.

There are many gaps in government databases, most of which do not have the most up-to-date data, probably due to the disruption of data collection at some stations. Thus, in order to improve the accuracy of the data, a consultation was made with the agribusiness companies in the area, been issued a formal letter for the acquisition of the available data.

Previously acquired data was processed on spreadsheets, where the monthly total was calculated for all months of 2017. At the location of each collection point, data were added using QGIS, generating twelve vector files, with point values associated with the total precipitation for each month.

Observing the number and distribution of the points of the meteorological stations, it was decided to perform interpolations with the Spline method on ArcGIS, which presented a better smoothing of the edges compared to the Thissen method.

Cumulative infiltration determination - Curve Method Number

To estimate infiltration in the Capivari Basin, we used the model of the Curve Number (CN), which has an advantage on the achievement of satisfactory results using less information when compared to other models found in the literature. The other methods, in spite of excellent results, require an extensive database, often not available. This methodology is developed by the Soil Conservation Service (SCS) of the US Department of Agriculture (USDA), at the end of the 1950s, modeling direct flows, going through several updates over the years (MISHRA & SINGH, 2003; SARTORI et al., 2005; SOULIS, 2021; CARVALHO & RODRIGUES, 2021).

The method introduces the different soil types into hydrological groups, from their characteristics associated with more or less permeable to infiltration and from there, these soils are combined with different types of land use and cover, thus estimating infiltration. Because this is a method originally developed for US soils, it was necessary to adapt to the reality of Brazilian tropical soils. To estimate infiltration in the current study, the soil hydrological group was determined using the classification proposed by Sartori (2004) (Table 2).

Table 2 - Soil hydrological group within the Capivari River basin.

Capivari Basin Soils	Hydrological Group
Yellowish red Acrisols	C
Molisols	D
Dystrophic yellow Ferralsols	B
Planosols	D

Source: Organized according to Sartori (2004).

The data needed for the Curve Number modeling were: the scene of the MDE ALOS/ PALSAR, 25745/6930 (ALOS PALSAR, 2011), the LC08_L1TP_216069_20171228 image of landsat8/OLI (USGS, 2017), the soil vector file in the IBGE scale 1:250,000 (IBGE, 2018) and the precipitation data from government meteorological stations and agricultural companies in the region.

The basin boundaries were determined from the DEM which, after radiometric correction and interpolation to remove empty points, was processed with *r.watershed* algorithm (EHLSCHLAEGER, 1989), generating both streamlines and basin boundaries. This polygonal vector was used as a cutting mask on all maps.

Land use and coverage (LULC) was determined using satellite image LC08_L1TP_216069_20170619_20170629_01_T1 (OLI sensor) obtained on June 19, 2017 (USGS, 2017). The pre-processing consisted of radiometric correction, atmospheric correction and rectangular cutout with limits higher than those of the basin. The supervised image classifier Bhattacharya (CÂMARA et al., 1996), was used to determine the following classes: Water Bodies, Agriculture, Riparian Forest, Secondary Forest, Pasture, Exposed Soil and Urban Area.

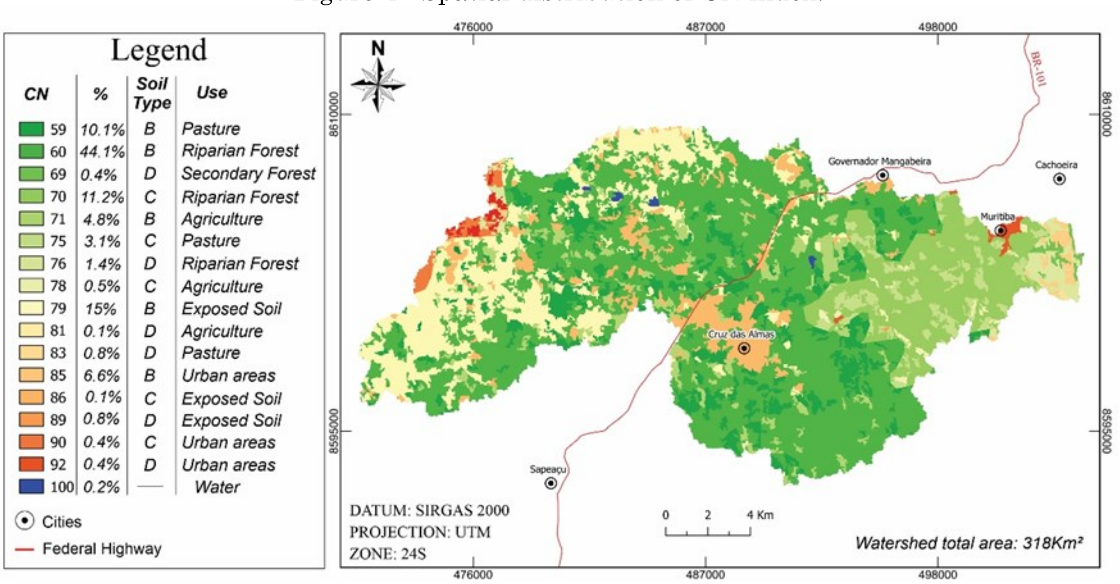
From the determination of the hydrological group of soils present in the Basin, the CN values were estimated for the classes of use and coverage proposed in this research (Chart 1 and Figure 4). To this end, the values suggested by Soares et al., (2017) have been used as the basis and Tucci et al. (1993).

Chart 1 - Table of revised CN values for the Capivari Basin

Land use and coverage	Soil hydrological group			
	A	**B**	**C**	**D**
Agriculture	62	71	78	81
Water	100	100	100	100
Pasture	25	59	75	83
Riparian Forest	36	60	70	76
Secondary Forest	26	52	62	69
Urban areas	77	85	90	92
Exposed Soil	68	79	86	89

Source: Organized based on Soares et al. (2017) and Tucci et al. (1993).

Figure 4 - Spatial distribution of CN index.



Source: The authors (2021).

Using the CN values, the maximum retention (S) was calculated, which expresses the water absorption capacity of the soil relative to cover and use (Equation 1):

$$S = \frac{25400}{CN} - 254 \qquad \text{Equation (1)}$$

Next, the values of the theoretical runoff coefficient (α) were determined. Due to the fact that the slope influences the runoff rate, the coefficient α was determined as follows:

1. Slope class ranges were defined according to the classes found in the basin and the terrain classification proposed by Embrapa (1979);
2. Values were defined, called a d-Index, for each slope class. This value is a ratio proportional to the cosine of the slope expressed in degrees, where the steeper the slope, the closer the value is to 1. Capivari Basin d-Index values were defined by slope reclassification (Table 3);

Table 3 - D-Index referring to the slope classes.

Flat (0° - 3°)	**Smooth wavy (3° - 20°)**	**Wavy (20° - 45°)**	**Strongly wavy (> 45°)**
0.1	0.35	0.8	1

Source: The authors (2021).

3. As the runoff coefficient (α) expresses the runoff ratio as a function of the CN and the D-Index (d), the value of α was determined from the following numerical expression (Equation 2):

$$\alpha = d\frac{CN}{100} \qquad \text{Equation (2)}$$

4. With the values of the maximum retention (S), the theoretical runoff coefficient and the appropriately specialized precipitation (P), the cumulative infiltration (F) was calculated in a GIS environment as follows (Equation 3):

$$F = \frac{S \times P}{S + P} \times (1 - \propto) \quad \text{Equation (3)}$$

5. Runoff (Q) was determined in a GIS environment, according to the difference between the amount of precipitation (P) and infiltrated water (F) (Equation 4):

$$Q = P - F \quad \text{Equation (4)}$$

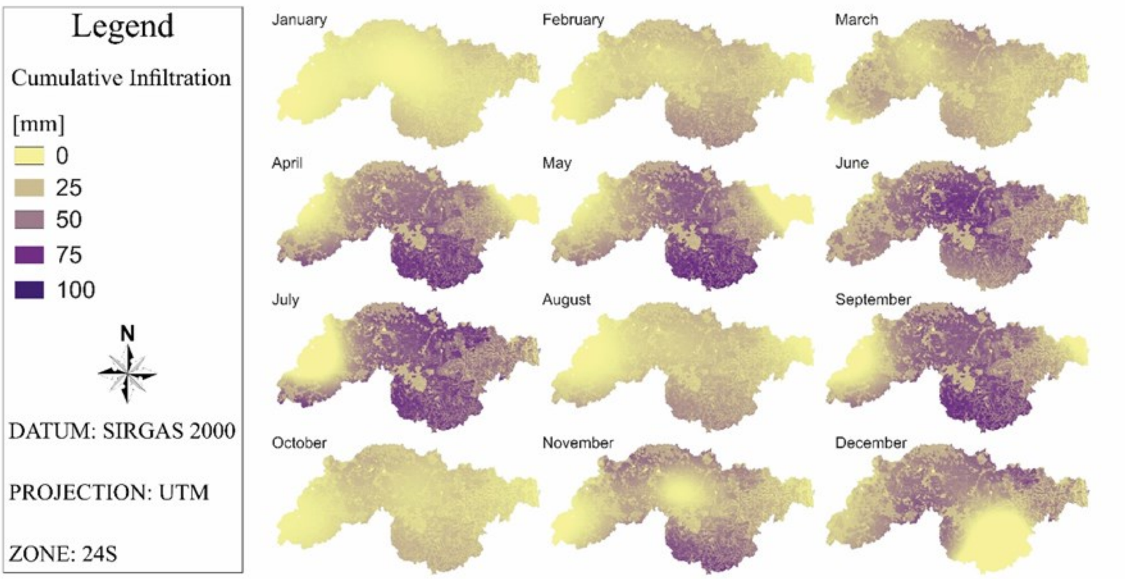
6. Finally, the runoff rate (C) was determined by the relation between runoff (Q) and precipitation (P), where the maximum value is 1 (100%) (Equation 5):

$$C = \frac{Q}{P} \quad \text{Equation (5)}$$

RESULTS AND DISCUSSION

The infiltration process is essentially important because at this rate decrease, there is an increase in the flow rate, making it essential to know the infiltration process for proper management within hydrographic basins (BRANDÃO *et al.*, 2006; KUMAR et al. 2021). In this sense, infiltration into the Capivari River basin was determined in 2017 (Figure 5), in order to understand the flow behavior and determine the most susceptible to water erosion areas.

Figure 5 - Cumulative infiltration, for the months of 2017.



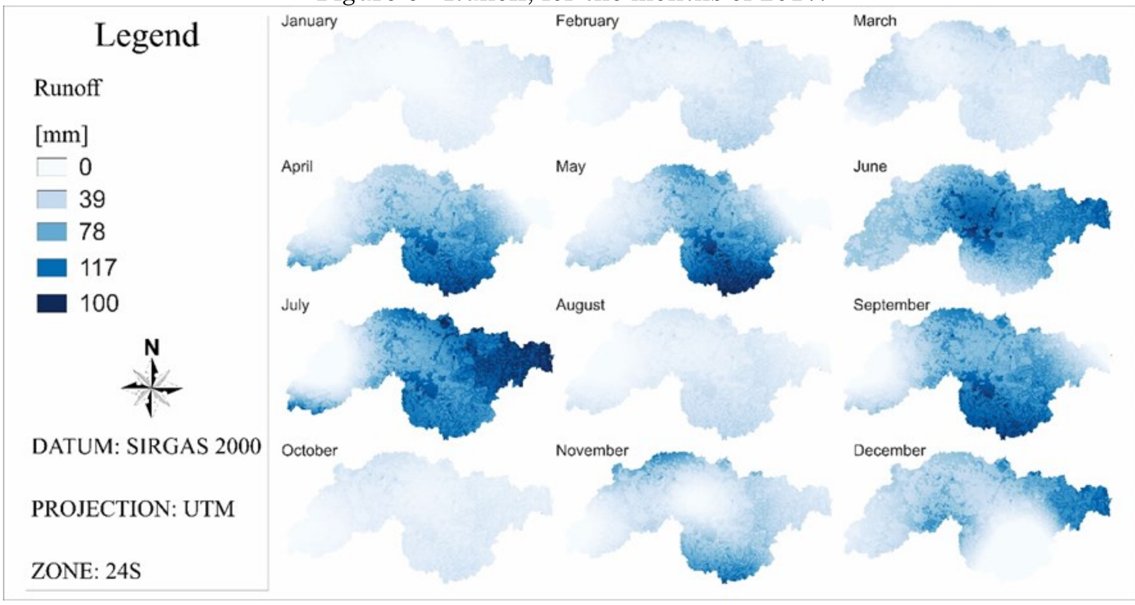
Source: The authors (2021).

The low infiltration rate in the Capivari basin is closely related to the characteristics of the basin, which has less permeable soils (naturally or as a result of improper handling), in addition to the undulating relief that favors the runoff process. In addition to these factors, the tree vegetation would have a fundamental role in this process (SALOMÃO, 2012; FERNANDES *et al.*, 2014; FELIPPE *et al.*, 2016; VIEIRA *et al.*, 2016; GUPTA et al., 2017) is degraded in most of the basin.

The same characteristics that affect the lower infiltration rate of the basin, determine the higher runoff rate. Runoff is part of the hydrological cycle and is responsible for the presence, movement and transport of surface water (VENEZIANI, 2014; KUMAR et al. 2021; WANG et al, 2022). The aggravating factor related to this process is its intensity and speed (DE MARIA, 2010), which contribute to the occurrence of erosion, floods, the spread of diseases and contamination of environments.

Precipitation, soil characteristics, use, cover and slope were important parameters in determining the runoff rate for the Capivari River basin, allowing to estimate runoff for each month of the year 2017 (Figure 6) as well as the rate runoff. Each parameter used in the modeling is interconnected with the amount of rainfall converted to runoff.

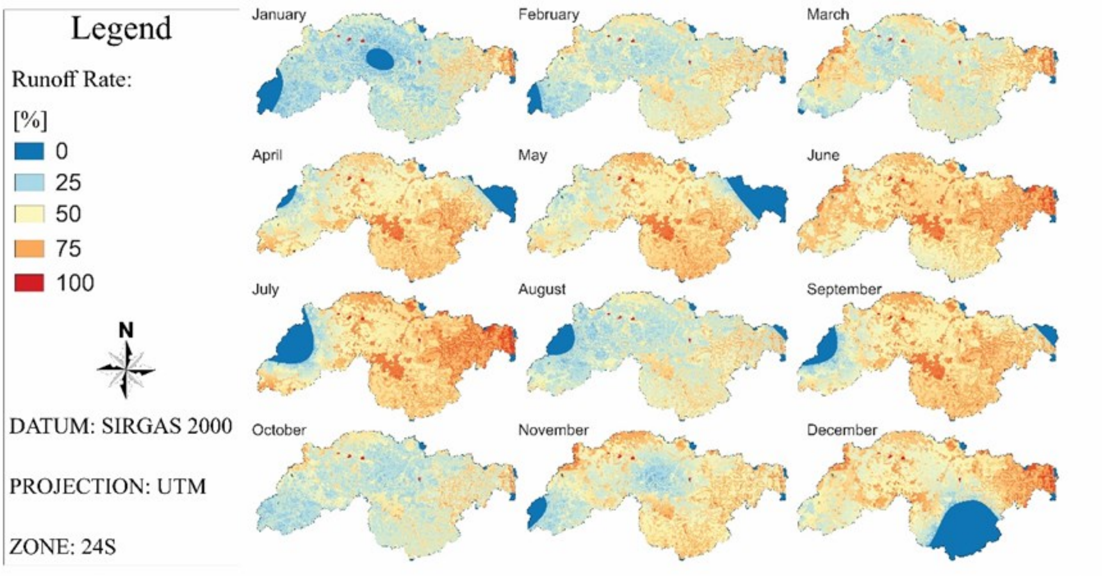
Figure 6 - Runoff, for the months of 2017.



Source: The authors (2021).

The precipitation, for example, directly influences the runoff rate (Figure 7) and concentrations of sediments and nutrients, leading to relevant interannual and seasonal differences (FERREIRA et al., 2018). In the studied basin, the behavior of precipitation reflects the variety of climates (semi-arid, sub-humid and humid), presenting a different behavior between these climatic zones.

Figure 7 - Monthly Runoff Rate, year 2017



	January	February	March	April	May	June	July	August	September	October	November	December
Minimum	6,40%	6,90%	7,90%	7,00%	11,70%	28,70%	6,10%	8,60%	6,50%	8,10%	8,10%	6,10%
Maximum	91,40%	93,50%	92,60%	96,70%	96,60%	96,70%	97,20%	93,40%	96,70%	92,40%	95,10%	95,30%
Mean	36,30%	43,70%	47,50%	57,80%	57,40%	63,30%	62,90%	43,00%	59,70%	41,60%	51,00%	56,10%
St dev	15,10%	14,00%	14,30%	13,50%	13,90%	12,30%	14,80%	13,90%	13,80%	13,80%	15,40%	14,90%

Source: The authors (2021).

The proposed model indicates the spring zone as the lowest flow propensity for 2017. This is primarily due to the flat terrain and lower precipitation, but the lack of adequate riparian vegetation (VIEIRA et al., 2016; GUPTA et al., 2017), the use of the soil with agricultural activities without proper management (BENDA et al., 2007) and the semi-arid climate, influence the state of intermittent course of river in this area.

The most vulnerable area of the basin, as proposed, is the area near the mouth, and this result reflects the features of this area. Acrisols and Molisols from this part of the basin (Muritiba and São Felix) are highly susceptible to erosion (MARQUES et al. 2014). This is aggravated by the occurrence of these in the most sloping areas and with high rainfall rates.

However, despite this greater vulnerability, the areas near the mouth are those with the most preserved riparian vegetation, which indicates the high risk of silting up the river if this vegetation is replaced by other uses or cover (BENDA et al., 2007; APARECIDO et al., 2016). Since then, this vegetation has been "the natural defense of the terrain against erosion" (SALOMÃO, 2012).

Silva (2012) talks about erosion as a common process. But it tends to be more prevalent in tropical regions given the high rate of precipitation compared to other regions of the planet. In addition, the removal of native vegetation to take advantage of timber or agricultural production tends to exacerbate this phenomenon.

According to the proposed model, the Medium Capivari area was considered a high-risk area in terms of water erosion. Given that it does not have a satisfactory vegetative cover in areas that are expected to be permanently preserved (BRASIL 2012), added to the undulating terrain and high levels of precipitation in some months of the year (April, May, June, July and September).

In this area, it is believed that the development of agricultural activities without careful manipulation, worsens the process of transport of sediments and pollutants to the bed of the Capivari River, given that the presence of a consistent horizon in the soils of this area restricts the infiltration process (RIBEIRO, 1998).

Vieira et al. (2016) emphasize that vegetation removal influences the reduction in infiltration rates. With a decrease in infiltration, soil becomes more vulnerable to erosion, because the hydraulic force of the water stream is capable of transporting its particles and depending on the intensity of the stream, even within moderate soil gradients, it can have severe consequences (MAFRA, 2012). This risk is heightened in this area, according to Ribeiro (1998), its soils have elevated levels of natural clay, which speeds up erosion processes and, as a result, these environments are degraded.

The greatest pressure exerted by occupancy in some areas, mostly through intensive agricultural activities without appropriate conservation practices, according to Mafra (2012), was responsible for losses in soil productive potential, having erosive processes as a primary cause. This factor is linked to pollution and contamination of other environments in addition to siltation of streams and create imbalances that directly impact the overall equilibrium of sediment transport within the watershed (OLIVEIRA, 2007).

The rate of runoff into Capivari Basin (Figure 7), whose highest value (100, showed in red) refers to water bodies where 100% of rain is drained. The highest computed value for all areas was 88.6% in July, while the lowest value was 10.7% in January. However, when we analyze the mean values, the highest flow occurred in June.

By knowing how runoff behaves, you can see more clearly the most critical points in the watershed, helping to control degradation. It supports the planning and management of activities developed in these areas and allows the soil management, according to its weaknesses and potential (ANDRADE et al. 2010). This management, primarily, aims to mitigate the effects of water erosion, which is considered the largest contributor to soil degradation in tropical regions (DE MARIA 2010).

According to DE Maria (2010), identifying areas most susceptible to erosion within the watershed is the basis for water quality improvement. With population growth, there is increased pressure on natural environments with increased demand for resources (MINELLA et al., 2010; RAMOS and REGO FILHO, 2010). On the other hand, the degradation of natural environments resulting from this situation influences the supply of these same resources.

In this sense, Minella et al. (2010) note that productive interests and the preservation of natural resources cannot be contradictory. Because soil and water preservation are important factors in securing a country's economic and social needs.

The urbanized areas within the basin showed high runoff values as most precipitation flows on the surface, due to the higher rate of waterproofing, except for parks, plazas and small permeable zones (TUCCI, 1993).

This water is usually directed to pipelines that run into the lower reaches, usually rivers or creeks, but when this drainage is deficient, it can cause flooding (SALOMÃO, 2012). It represents a source of disease proliferation and spread, which warrants the attention of municipal managers.

CONCLUSIONS

The highest precipitation rates, soil characteristics and the greatest slope at the mouth affected the greatest vulnerability to runoff, based on the proposed model. However, the most conserved Permanent Conservation Area (PPA) has acted effectively to sustain the Capivari River in these areas.

The areas considered as the most critical to the risk of water erosion in 2017 were those in the middle of Capivari basin. They had high precipitation in some months, but do not have an PPA in riparian forest areas or on hilltops. This further increases their vulnerability to erosion.

The proposed model was successful in identifying areas most sensitive to run off in the Capivari watershed.

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AUTHORS' CONTRIBUTION

Geisa Nascimento de Santana conceived, planned and wrote the article. Luiz Artur dos Santos da Silva analyzed the data. Rosangela Leal Santos supervised the study. Claudia Bloisi Vaz Sampaio conduced a critical review. Jesus Manuel Delgado-Mendez carried out a critical review and translation