

DETERMINANT PLUVIOMETRIC CHARACTERISTICS OF SEDIMENT TRANSPORT IN A CATCHMENT WITH THINNED VEGETATION IN THE TROPICAL SEMIARID¹

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ABSTRACT – Knowing determinant factors of erosive process is essential to adopt soil conservationist and loss-mitigation measures. Therefore, the objective of this work was to assess the correlation between rainfall characteristics and sediment transport in the Semi-arid region of Brazil. The study was conducted at the Iguatu Experimental Basin in the state of Ceará, Brazil, in a watershed with area of 1.15 ha. The vegetation was thinned by removal of plants with diameters below 10 cm, and the area remained with an arboreal cover of 60%. The following variables were evaluated from 2012 to 2016: rainfall depth (mm), rainfall duration (hours), maximum rainfall intensity in 5, 10, 15, 20, 30, 45, and 60 minutes (mm h^{-1}), mean rainfall intensity (mm h^{-1}), rainfall depth in the previous 5 days (mm), runoff depth (mm), and transported sediment (kg ha^{-1}). The records showed 158 rainfall events, 27 with surface runoff and 24 with sediment transport. The correlations were investigated by multivariate analysis of principal components (PC). The model explained 84% of total variance with four PC—PC1, PC2, PC3, and PC4 were formed, respectively, for disaggregating power of rainfall on soil particles, represented by the rainfall intensities; soil water content; runoff depth and sediment transport; and rainfall duration and interval between rainfalls. The highest factorial weight was found for the maximum intensity in 20 minutes, indicating the need for further hydrological studies focused on this variable at basin scale in areas of the Semi-arid region of Brazil subjected to thinning of the vegetation.

Keywords: Water erosion. Precipitation. Surface runoff.

CARACTERÍSTICAS PLUVIOMÉTRICAS DETERMINANTES NO TRANSPORTE DE SEDIMENTOS EM MICROBACIA COM VEGETAÇÃO RALEADA NO SEMIÁRIDO TROPICAL

RESUMO - Conhecer os fatores determinantes no processo erosivo é essencial na adoção de medidas conservacionistas e mitigadoras das perdas do solo. Portanto, objetivou-se com essa pesquisa entender a relação existente entre as características da chuva e a produção de sedimentos no semiárido brasileiro. O estudo ocorreu na Bacia Experimental de Iguatu, Ceará, em uma microbacia com área de 1,15 ha. No raleamento eliminou-se os indivíduos vegetais com diâmetros ≤ 10 cm, ficando a área com uma cobertura arbórea de 60%. As variáveis investigadas no período (2012 a 2016) foram: Precipitação (PPT – mm); Duração da Precipitação (Dur. PP - h); Intensidade máxima de 5 a 60 min (mm h^{-1}); Intensidade média da Precipitação (INT PPT – mm h^{-1}); Precipitações antecedentes dos últimos 5 dias (P.A1 a P.A5 – mm); Lâmina escoada (Lesc. – mm) e Produção de sedimentos (PS – kg ha^{-1}). Foram registrados 158 eventos pluviométricos, 27 com escoamento superficial e 24 com produção de sedimentos. As relações foram investigadas pela análise multivariada de componentes principais. O modelo explicou 84% da variância total em quatro componentes. As componentes (CP1, CP2, CP3 e CP4) foram formadas, respectivamente, pelo poder desagregador da chuva, representada pelas intensidades; pelo conteúdo de água no solo; lâmina escoada e produção de sedimentos e pela duração e intervalo sem precipitação. O maior peso fatorial foi atribuído ao I20, sugerindo maior atenção em estudos hidrológicos para esta variável em escalas de microbacias na região semiárida brasileira submetidas ao manejo de raleamento.

Palavras chave: Erosão hídrica. Precipitação. Escoamento superficial.

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INTRODUCTION

Water erosion is a natural process that consists in the disaggregation, transport, and deposition of soil particles; however, it can be intensified by anthropogenic actions, making it a prejudicial character. Regions with semiarid climate are predisposed to erosive process due to their natural characteristics of climate, soil, and vegetation (WEI et al., 2014; ZHOU et al., 2016), and require studies that show determinant variables of this process, since semiarid areas cover most of the world's surface.

The Semiarid region in Brazil encompasses an area of 982.563.3 km² (SUDENE, 2017) covering mainly the Northeast region, which is characterized by water deficit, high-intensity and low-frequency rainfalls, and uncertainties regarding surface runoff (GUERREIRO et al., 2013; ANDRADE et al., 2016). In these regions, water erosion due to rainfall are the main factor controlling sediment transport (WANG et al., 2016, OCHOA et al., 2016). Thus, studies on rainfall characteristics are needed because this is a widely recognized and important climatological variable due to its soil particle disaggregation and surface runoff potentials (OLIVEIRA; WENDLAND; NEARING, 2013; ZHOU et al., 2016).

Rainfall characteristics are determinant for the definition of mechanisms that cause runoff and sediment transport in watersheds (FANG et al., 2012; GONZÁLEZ-HIDALGO; BATALLA; CERDA, 2013). However, the fully understand of the systematics of these process requires a holistic view that encompasses not only the factors already cited, but the vegetation characteristics, which contributes to the runoff spatial and temporal variabilities due to its spatial pattern and heterogeneous morphology (CHAMIZO et al., 2012; ZHOU et al., 2016; SANTOS et al., 2016; PATHAK et al., 2016).

In this context, many studies have focused on the effect of management and vegetation characteristics on runoff (JOST et al., 2012; VAN OUDENHOVEN et al., 2015; ZHOU et al., 2016; ANDRADE et al., 2018). Ribeiro Filho et al. (2014) evaluated the effect of an herbaceous extract on

hydro-sedimentological factors in watersheds under different managements in the Semiarid region of Brazil and found that the thinning of the vegetation decreased the runoff in almost 25% when compared to the native vegetation area. Similarly, Wei et al. (2014) evaluated the effects of surface conditions of different plant species and rainfall intensities on surface runoff in China and found that the seabuckthorn shrubs were efficient in decreasing runoff.

Considering that the identification of determinant factors of the hydrologic dynamics of a river basin is difficult, mainly in semiarid regions due to the climate variability and problems for obtaining data (BRACKEN; CROKE, 2007), studies focused on these issues are needed. In this context, the objective of the present study was to evaluate the effect of rainfall characteristics (height, intensity, and previous rainfall) on surface runoff and sediment transport in a watershed in the Semiarid region of Brazil.

MATERIAL AND METHODS

The study was conducted in the Brazilian semi-arid, at the Upper Jaguaribe River basin, in the municipality of Iguatu, state of Ceará, Brazil (6° 23'42"S to 6°23'47"S and 39°15'24"W to 39°15'29"W (Figure 1). The study area belongs to the Federal Institute of Education, Science, and Technology of Ceará, Iguatu campus.

The climate of the region was classified as BSw'h', hot semiarid, according to the Köppen classification, presenting Aridity Index of 0.44, as described by Thornthwaite (1948). The historical mean annual rainfall of Iguatu from 1912 and 2017 is 880.1 mm. The soil of the area was classified as Typic Hapludert Vertissolo Ebânico Carbonático típico, according to the Brazilian Soil Classification System (SANTOS et al., 2018a) The mean potential evaporation is approximately 1988 mm year⁻¹. The annual rainfall distribution in the region is concentrated (84%) in January to May, with approximately 30% in March (FUNCEME, 2019). (Table 1) presents some climate, soil, and vegetation characteristics of the study area.

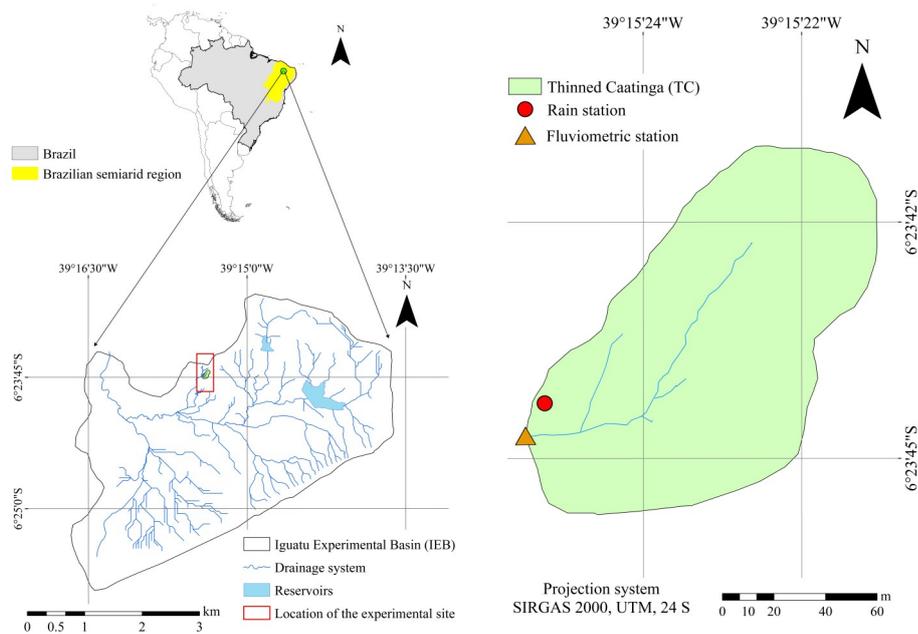


Figure 1. Location of the study area in the watershed in the municipality of Iguatu, Ceará, Brazil.

Table 1. Edaphoclimatic characteristics of the study watershed.

Climatic and vegetation characteristics				Physical and chemical soil attributes			
Variable		Value	Unit	Horizons			
				Layer (cm)	A	B	BCv
Mean rainfall depth		880.1	mm	0 to 5	5 to 21	21 to 31	
Maximum	monthly mean	31.7	°C	Sand (g kg^{-1})	137	205	182
Minimum	monthly mean	20.3	°C	Silt (g kg^{-1})	447	405	470
Mean annual solar radiation		5.63	$\text{kWh m}^{-2} \text{day}^{-1}$	Clay (g kg^{-1})	416	390	348
Mean annual insolation		2897.6	h year^{-1}	Silt / Clay	1	1	1
Mean annual air relative humidity		61.8	%	C (g kg^{-1})	24.1	13.3	10.2
Mean annual wind speed		2.1	m s^{-1}	pH	7.6	8.2	8.2
Mean ET_0		1988	(mm year^{-1})	Ca ($\text{cmol}_c \text{kg}^{-1}$)	35	43	39
Aridity index		0.44	-	Mg ($\text{cmol}_c \text{kg}^{-1}$)	12	10	8.6
Mean ground vegetation		100	%	K ($\text{cmol}_c \text{kg}^{-1}$)	1.04	0.37	0.29
Mean arboreous vegetation		60	%	Na ($\text{cmol}_c \text{kg}^{-1}$)	0.13	0.13	0.15
				H + Al ($\text{cmol}_c \text{kg}^{-1}$)	1.7	1.2	1.2
				CaCO_3 ($\text{cmol}_c \text{kg}^{-1}$)	145	144	151
				P (mg kg^{-1})	42	62	59
				Electrical conductivity (dS m^{-1})	0.48	0.3	0.29

C - Carbon; pH - Hydrogenpotential; Ca - Calcium; Mg - Magnesium; K - Potassium; Na - Sodium; H + Al - Hydrogen + aluminum; CaCO_3 - Calcium carbonate; P - Phosphorus; EC - Electrical conductivity.

In 2008, the vegetation of the study area consisted of a secondary Caatinga forest under regeneration for 30 years, presenting variable aspects, herbaceous and shrub-arboreous species typically deciduous and xerophilous, with several thorn species. A thinning of the vegetation was conducted in 2008, which is an adequate practice and, according to Araújo Filho (2013), is practiced by small farmers of the Semi-arid region of Brazil.

Plant species with diameter equal to or higher than 10 cm, and herbaceous species were maintained in the area. The branches and leaves were maintained

on the soil after the thinning of the vegetation (Figure 2B) as an additional source of organic matter to decrease the impact of raindrops on the soil.

The study was conducted from 2012 to 2016 (four years after the thinning of the vegetation). Rainfall depth data were obtained from an automatic meteorological station installed in the study area, equipped with a Ville de Paris pluviometer and a pluviograph. The rainfall data were used to calculate the intensities (I) of each event (mm h^{-1}) and the maximum intensity in the intervals of 5, 10, 15, 20, 30, 45, and 60 minutes (mm h^{-1}).



Figure 2. Images of the study watershed with thinned Caatinga vegetation before thinning of the vegetation (A); after thinning of the vegetation in the dry season (B); and after thinning of the vegetation in the rainy season (C).

The surface runoff was monitored using a Parshall flume installed at downstream of the watershed (Figure 3A) with a pressure sensor (Figure 3B) to measure the runoff level, with readings every five minutes. The sediment transport by dragging was monitored using a ground hole with capacity for

180 liters installed at upstream of the flume in the water course (Figure 3C). The suspended sediment was collected by automatic sediment collection tower (Figure 3D) with ascending branch with 06 100-ml bottles spaced 7.5 cm apart; the first bottle was at 15 cm from the ground.

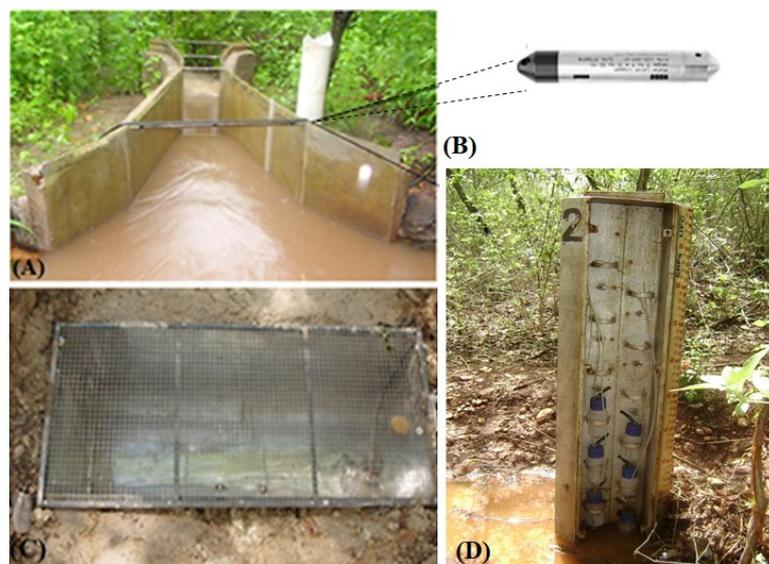


Figure 3. Parshall flume (A), automatic pressure sensor (HOBO U20 to measure the water level (B), ground hole for sediment collection by dragging (C), and suspended sediment collection tower (D).

Flaws in the data acquisition system interfered in the monitoring of rainfall events that cause runoff in 2014; thus, the runoff data were estimated for 2014 using the Curve Number (CN) method. The determinant factors for variability of erosive process and sediment transport capacity were identified using multivariate statistical model: Factorial Analysis/ Principal Component Analysis (FA/PCA). This statistical technique of multivariate analysis transforms linearly an original set of variables correlated to each other in a substantially lower set of variables not correlated that contains most of the information of the original set. The adequacy of the data of the FA/PCA model was evaluated by the KMO test at 5% significance.

The variables considered were: rainfall depth (mm), rainfall duration (hours), maximum rainfall intensity in 5, 10, 15, 20, 30, 45, and 60 minutes (mm h^{-1}), mean rainfall intensity (mm h^{-1}), rainfall depth in the previous 5 days (mm), runoff depth (mm), and transported sediment (kg ha^{-1}).

RESULTS AND DISCUSSION

The annual rainfall depths in the five years studied were irregular, with depths 13% to 68% below the historical mean of the region (880.1 mm) (Table 2), confirming the high temporal variability of rainfall events, typical of semiarid regions (GUERREIRO et al., 2013; ANDRADE et al., 2016). Only 18% (27) of the 158 rainfall events recorded in the watershed from 2012 to 2016 caused surface runoff; and 15% (24) caused transport of sediments (Table 2). The more critical years for surface runoff were 2015 and 2016, with 0% and 3.7%, respectively, followed by 2013, with 7.4%. The highest occurrence of surface runoff events was found for 2014, with 48.1% of all runoff events in the five years studied, followed by 2012, with 40.7%. Thus, these two years concentrated approximately 90% of runoff events, confirming the irregularity of surface runoff events (SANTOS et al., 2016; PATHAK et al., 2016).

Table 2. Hydro-sedimentological summary for months with rainfall events (RE) with runoff and sediment transport in the study period.

Years	Total rainfall depth (mm)	Number of RE	Number of RE with runoff	Number of RE with sediment transport	Runoff depth (mm)	Sediment transport (Kg ha^{-1})
2012	764.7	34	11	8	35.41	290.56
2013	613.1	31	2	2	39.37	111.78
2014	772.1	36	13	13	58.25	306.85
2015	521.1	29	0	0	0,00	0,00
2016	679.8	28	1	1	1.08	6.63
Total	3350.8	158	27	24	134.11	715.82

The annual rainfall depth (RD) is a variable responsible for the difference in total events causing runoff, since 90% of these events occurred in the two years with RD above 700 mm. This was also found by Tian et al. (2018), who evaluated the correlation between rainfall and runoff in dry years in 18 sub-basins in China and found 17.6% to 34.5% lower runoff coefficients in dry years, when compared with rainy years. RD between 600 and 700 mm occurred only in two events, and RD below 600 mm did not cause runoff. Allen et al. (2011) found that runoff decreases in 75% when the mean annual rainfall depth decreases 27%.

The rainfall events affected the transported sediment (TS) similarly to the surface runoff. The TS in 2014 represented 42%, and the TS in 2012 represented 41% of the total TS. These results show

the high dependency of total TS on the runoff depth (ROD). This was also found by Pathak et al. (2016), who evaluated runoff and TS in small basins and found that runoff usually represent approximately 65% to 85% of the total TS.

The variables evaluated presented adequacy to the Principal Component Analysis (PCA) by the KMO test, with values higher than 0.5, indicating that the factorial model (FA/PCA) can be applied to the data without restrictions. The correlation matrix (Table 3) showed that the ROD had highly significant ($p < 0.001$) correlation with RD (weight = 0.50) and TS (weight = 0.79), presenting strong correlation according to the classification used by Sousa et al. (2016). This result denotes the effect of total ROD on the sediment transport capacity.

Table 3. Correlation matrix of variables related to the hydro-sedimentological process in the study years.

	RD	I5	I10	I15	I20	I30	I45	I60	RI	PRD1	PRD2	PRD3	PRD4	PRD5	ROD	TS
RD	1.00															
I5	0.67	1.00														
I10	0.72	0.97	1.00													
I15	0.73	0.95	0.99	1.00												
I20	0.75	0.94	0.98	0.99	1.00											
I30	0.78	0.92	0.96	0.98	0.99	1.00										
I45	0.83	0.88	0.92	0.94	0.96	0.98	1.00									
I60	0.87	0.85	0.89	0.91	0.93	0.96	0.99	1.00								
RI	0.32	0.53	0.54	0.52	0.50	0.46	0.42	0.40	1.00							
PRD1	-0.03	-0.05	-0.02	0.00	0.01	0.03	0.04	0.02	-0.11	1.00						
PRD2	-0.01	0.02	0.04	0.06	0.07	0.08	0.07	0.05	-0.05	0.68	1.00					
PRD3	0.00	0.05	0.06	0.06	0.05	0.06	0.05	0.03	-0.03	0.54	0.83	1.00				
PRD4	0.03	0.10	0.11	0.11	0.10	0.10	0.08	0.07	-0.04	0.46	0.68	0.88	1.00			
PRD5	0.06	0.10	0.11	0.11	0.10	0.10	0.09	0.09	-0.02	0.41	0.63	0.82	0.95	1.00		
ROD	0.68	0.37	0.40	0.41	0.41	0.45	0.52	0.57	0.31	-0.02	0.05	0.08	0.17	0.18	1.00	
TS	0.50	0.26	0.28	0.28	0.27	0.31	0.33	0.36	0.25	-0.06	0.13	0.20	0.29	0.31	0.79	1.00

Rainfall depth (RD; mm); maximum rainfall intensity in 5 (I5; mm h⁻¹), 10 (I10; mm h⁻¹), 15 (I15; mm mm h⁻¹), 20 (I20; mm h⁻¹), 30 (I30; mm h⁻¹), 45 (I45; mm h⁻¹), and 60 (I60; mm h⁻¹) minutes; rainfall intensity (RI; mm h⁻¹); rainfall depth in the previous 1 (PRD1; mm), 2 (PRD2; mm), 3 (PRD3; mm), 4 (PRD4; mm), 5 (PRD5; mm) days; runoff depth (ROD; mm); transported sediment (TS; kg ha⁻¹). Numbers in bold letters are significant at $p < 0.001$.

TS presented significant correlation with RD, with a moderate correlation ($0.40 \leq r \leq 0.60$), indicating dependency of TS on RD and total runoff. Similar results were found by Sousa et al. (2016), who evaluated the effect of soil cover plants in water and soil losses in plots with erosion in the Semiarid region of Brazil and found significant correlation between TS and RD, with $r = 0.66$ and 0.70 for plots with bare soil, and soil with weeds, respectively, confirming the dependency of these variables, even in different spatial scales and soil cover.

The RD was also significantly correlated with ROD ($r = 0.68$), denoting that rainfall characteristics related to rainfall intensity and depth have significant effect on total runoff. This explains the characteristics of the runoff in semiarid regions, which occurs predominantly due to Hortonian processes. Thus, the higher the rainfall intensity, the higher the chance of occurrence of runoff and the higher its magnitudes (CHAMIZO et al., 2012; TAYFUR et al., 2014).

The maximum intensities showed increasing correlation with ROD; however, only I45 and I60 showed significant values, with r of 0.52 and 0.57 ($0.40 \leq r \leq 0.60$) respectively. These weights indicate that increases in rainfall intensity possibly increase ROD. This was also reported by Liu et al. (2014), who evaluated surface runoff in the North plain of China and found that that the surface ROD increases due to increases in rainfall intensity.

The PCA resulted in four principal components (PC), which explained 84% of the total variance (Table 4). The components found (PC1, PC2, PC3, and PC4) expressed the correlation

between the study variables and allowed the identification of variables with higher correlation in each component. These variables were identified through the absolute value of the coefficient; the higher this value, the more important the corresponding variable.

PC1 reached factorial weight of 0.987 represented by the rainfall and its maximum intensity characteristics in the different intervals (I5, I10, I15, I20, I30, I45, I60). Thus, these variables in PC1 are related to the disaggregating power of rainfall on soil particles, explaining 44.99% of the total variance.

Regarding the maximum intensities, the highest factorial weights were found for I20, with values of 0.987 , followed by I15 (0.981) and I30 (0.980). Studies on erosivity usually considers I30 as the most representative variable of the erosive process (WANG et al., 2016). However, the results obtained for PC1 indicate that more attention is needed for I20 in tropical semiarid regions.

PC2 is directly related to the soil water content (previous moisture) (Table 4), which is represented by previous rainfalls (within 1 to 5 days), and the precipitation seasonality index. The highest factorial weight in PC2 was found for PRD3 (0.926). The variables of PC2 have direct effect on surface runoff potential, mainly in vertic soils (SANTOS et al., 2016), describing increases or decreases in runoff speed. Higher previous soil moisture contents result in closure of part of the cracks formed in vertic soils (ZHANG et al., 2014), increasing the possibility of a high-connectivity runoff in the basin (FRYIRS et al., 2007).

Table 4. Matrix of factorial weights of variables in the principal components, after rotation by the Varimax algorithm.

Variable	Components			
	PC 1	PC 2	PC 3	PC 4
I20	<u>0.987</u>	0.033	0.083	-0.045
I15	<u>0.981</u>	0.033	0.090	-0.078
I30	<u>0.980</u>	0.039	0.124	0.007
I10	<u>0.972</u>	0.022	0.089	-0.100
I45	<u>0.962</u>	0.024	0.188	0.055
I5	<u>0.944</u>	0.008	0.070	-0.121
I60	<u>0.936</u>	0.004	0.244	0.093
RD	<u>0.755</u>	-0.062	0.473	0.268
PRD3	0.015	<u>0.926</u>	0.108	-0.034
PRD4	0.038	<u>0.904</u>	0.224	-0.052
PRD2	0.045	<u>0.871</u>	-0.007	0.017
PRD5	0.043	<u>0.870</u>	0.250	-0.063
PRD1	0.034	<u>0.704</u>	-0.191	0.114
TS	0.177	0.120	<u>0.915</u>	-0.052
ROD	0.349	0.016	<u>0.861</u>	-0.001
RAD	0.166	-0.060	0.067	<u>0.897</u>
RI	0.486	-0.109	0.173	<u>-0.695</u>
Eigenvalue	8.10	4.04	1.56	1.42
Variance explained %	44.99	22.45	8.68	7.87
Variance accumulated %	44.99	67.45	76.13	84

Rainfall depth (RD; mm); maximum rainfall intensity in 5 (I5; mm h⁻¹), 10 (I10; mm h⁻¹), 15 (I15; mm h⁻¹), 20 (I20; mm h⁻¹), 30 (I30; mm h⁻¹), 45 (I45; mm h⁻¹), and 60 (I60; mm h⁻¹) minutes; rainfall intensity (RI; mm h⁻¹); rainfall depth in the previous 1 (PRD1; mm), 2 (PRD2; mm), 3 (PRD3; mm), 4 (PRD4; mm), 5 (PRD5; mm) days; runoff depth (ROD; mm); rainfall duration (RAD; mm); transported sediment (TS; kg ha⁻¹).

PC3 was composed by ROD and TS; the transport of disaggregated sediment is directly related to ROD, which explains its strong correlation with TS (Table 3). Therefore, PC3 represents the sediment transport energy. The fit of TS and ROD in PC3 indicates that TS is limited by the runoff transport capacity. Medeiros et al. (2010) reported that sediment transport in the Semiarid region of Brazil is limited by transport conditions, and not by availability of the eroded material. Thus, the characteristic discontinuity of soil cover plants in semiarid regions (WEI, et al., 2014) and changes in soil cover can affect runoff, sediment availability, and transport capacity (WESTER; WASKLEWICZ; STALEY, 2014), thus breaking the dynamic balance of sedimentological processes.

PC4 explained only 7.87% of the total variance; it consisted of rainfall duration and rainfall intensity. These variables are essential to determine runoff, since rainfall duration directly affects the mean rainfall intensity and disaggregating power of rainfall on soil particles. Sen, Srivastava, and Jacob (2010) evaluated a hillside of 0.12 ha in North Alabama, USA, and showed that rainfall events with medium to low intensity and medium duration present lower probability of causing runoff. However, intense, short duration rainfalls, in general, cause more runoffs and higher availability of material to be transported (RAN et al., 2012; LIMA et al., 2013).

Similar results were found by Santos et al. (2018b), who evaluated factors that control erosive

processes in the Semiarid region of Brazil in a watershed with native vegetation and plots with erosion and also found I20 with higher factorial weight, explaining and confirming the importance of studies focused on this variable for tropical semiarid regions.

CONCLUSIONS

Sediment transport is highly correlated with runoff depth ($r = 0.79$), indicating a strong correlation between sediment transport and mass flux energy.

The previous rainfall depths presented low correlation, but formed the second principal component, explaining 22.45% of the total variance, showing that they cannot be overlooked in the hydro-sedimentological process of river basins.

The first principal component consisted of variables related to the disaggregating power of rainfall on soil particles and the rainfall intensities from I15 to I60, explaining 44.99% of the total variance. The third and fourth principal component explained 8.68% and 7.87% of the total variance, clustering runoff depth and sediment transport, and rainfall duration and rainfall intensity, respectively.

The I20 was the variable that presented the highest factorial weight, indicating that more attention is required for this variable in hydrological studies in watershed scale in the Semiarid region of Brazil.

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