

Effect of Rainfall Characteristics on Runoff and Water Erosion for Different Land Uses in a Tropical Semiarid Region

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Received: 28 April 2016 / Accepted: 11 October 2016 /
Published online: 17 October 2016
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Abstract Rainfall intensity, duration, frequency and magnitude influence both runoff generation and sediment yield. In this study, 176 rainfall events over a five-year period were classified into four regimes based on rainfall depth, duration and 30-minute maximum intensity, using hierarchical cluster analysis in the semiarid region of Brazil. Rainfall Regimes were grouped from higher to lower rainfall depth, longer to shorter duration, and higher to lower I30. Rainfall regime impact on surface runoff and sediment yield was studied in three watersheds under different land use - native tropical dry forest, thinned tropical dry forest, and slash and burn followed by grass cultivation. Thinning of native dry tropical forest reduced surface runoff and sediment yield due to the protective effect of the well-developed herbaceous layer. Runoff generation in the three watersheds showed strong dependence on antecedent soil moisture and the type of rain. Rainfall depth was the major factor for highest sediment yields.

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Keywords Rainfall characteristics · Rainfall regimes · Runoff · Water erosion · Clustering technique

1 Introduction

Soil erosion is a major problem worldwide, impacting on the sustainable agricultural production and environmental preservation (Molina-Navarro et al. 2014; Kumar and Mishra 2015; Mallinis et al. 2016; Ulke et al. 2016). Accelerated erosion results from a combination of intensive farming, removal of ground cover and heavy rains (Mallinis et al. 2016). Understanding the erosion and deposition rates in small watersheds is mandatory for the design of soil and water conservation measures (Kumar and Mishra 2015; Mallinis et al. 2016; Yang et al. 2016).

Runoff generation and erosion processes are mostly affected by rainfall, land use (Wei et al. 2007; Zhang et al. 2014a; Kumar and Mishra 2015) and antecedent soil moisture conditions (Harmel et al. 2006; James and Roulet 2009; Dinka et al. 2013). Rainfall characteristics are key drivers in runoff generation mechanisms (Sen et al. 2010; Fang et al. 2012). In semiarid regions runoff may be generated under high intensity rainfall even in short duration and small rainfall depth events (Smith et al. 2010), emphasizing the importance of rainfall intensity on surface runoff generation (Yang et al. 2016). Rainfall patterns also impact runoff generation and sediment yield (Wei et al. 2007; Fang et al. 2012; Peng and Wang 2012), with complex interactions between the spatial-temporal distribution of rainfall systems and the hydrological responses of watersheds (Morin et al. 2006).

Rainfall event characteristics such as total event rainfall (P), duration of rainfall event (PDUR), average rainfall event intensity (I), soil moisture conditions evaluated through continuous days with less than 1 mm of rainfall (continuous dry days - CDD) and continuous days with rainfall above 1 mm (continuous wet days - CWD) are affected by atmospheric systems: location of the Intertropical Convergence Zone (ITCZ); the Tropical Atlantic Dipole; Cold Fronts; Instability Lines; Mesoscale Convective Complex; Easterly Waves; Upper Air Cyclonic Vortices; land and sea breezes; and the planetary scale mechanism known as the Madden-Julian or 30–60 day oscillation (Ferreira and Mello 2005; Nóbrega and Santiago 2014).

Runoff generation and sediment yield processes are still understudied in semiarid environments, where rainfall shows high spatial and temporal variability (Medeiros et al. 2014). Guerreiro et al. (2013) analysed data from 55 weather stations in the state of Ceará, Brazil from 1974 to 2009, and found a general trend to a decrease in rainfall, for the dry months to become drier, and a decrease in rainfall intensity, which may affect runoff generation and resulting water storage and rainfed agriculture.

Changes in land cover may influence runoff generation, sediment availability and transport capacity (Wester et al. 2014), thus breaking the dynamic equilibrium of the sedimentological processes. Vegetation increases surface roughness that provides additional drag, and promotes local sediment deposition (Bracken and Croke 2007). Moreover, the overall vegetation cover dissipates runoff energy, resulting in larger time and opportunity for infiltration and sediment deposition processes. Surface runoff and sediment hydrologic connectivity along the hillslopes and in the watershed decrease with an increase in vegetation cover (Fryirs et al. 2007; Molina-Navarro et al. 2014).

Rainfall and runoff generation data are relatively scarce in arid and semiarid regions, despite its importance for environmental and water management, preventing a good understanding of the rainfall-runoff transformation and the internal watershed processes (Bracken and Croke 2007). Using Hierarchical Cluster Analysis (HCA) based on five years of field measurements, 176 rainfall

events were classified into different regimes, and their effect on surface runoff and sediment yield were assessed in three watersheds under different land uses in a tropical semiarid region.

The objective of this study is to evaluate the impact of rainfall characteristics on runoff generation, erosion and sediment transport processes in a semi-arid region under different land uses.

2 Material and Methods

2.1 Study Area

Research was developed at the Iguatu Experimental Watershed, located in the state of Ceará, Brazil, between coordinates 6°23'36" to 6°23'57" S and 39°15'15" to 39°15'30" W, with an average elevation of 218 m (Fig. 1).

The climate is BSw'h' type (hot semiarid) according to Köppen, with average temperature always above 18 °C in the coldest month. The average potential evapotranspiration is 1,802 mm yr⁻¹ (1974–2012), based on the Penman-Monteith/FAO methodology) and the historical average rainfall is 882 mm yr⁻¹ for the same period, resulting in a Thornthwaite aridity index of 0.49. Rainfall is concentrated from January to May, when 85 % of the annual precipitation occurs, with 30 % of the total being recorded in the month of March.

The soil in the study area was classified as a Typical Calcic Vertisol (Pellic) (Krasilnikov et al. 2009). The terrain is gently undulated; soils are relatively deep (2–3 m) with a high level of silt (42.5 %) and clay (26 %) in the surface and subsurface layers. Due to the type of clay (2:1 montmorillonite), surface cracks develop during dry periods (Santos et al. 2016). The study was carried out in three adjacent watersheds (Fig. 1) under different land uses: a) 2.06 ha of native tropical dry forest vegetation (NF) - fallow for 30 years (Fig. 2a); b) 1.15 ha of thinned tropical dry forest (TF), where plants with a diameter smaller than 10 cm were cut and laid on the ground, together with the herbaceous layer (Fig. 2b), whereas the other plants were removed; c)

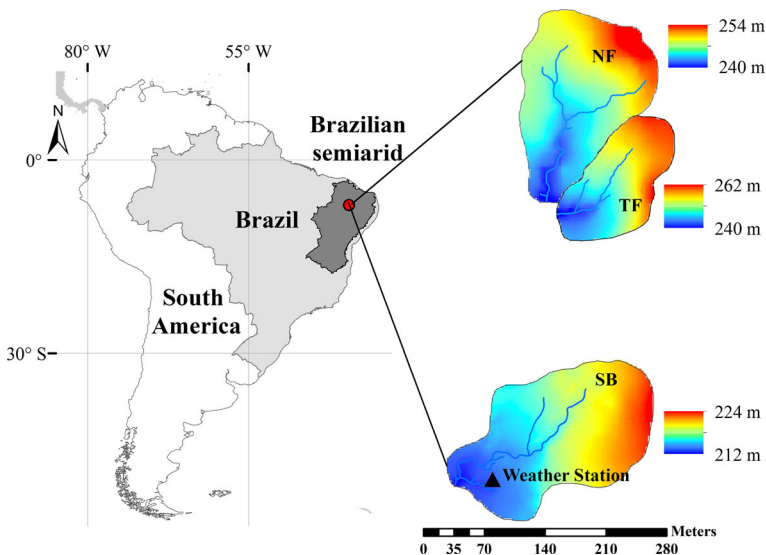


Fig. 1 Location of the study area showing the watersheds

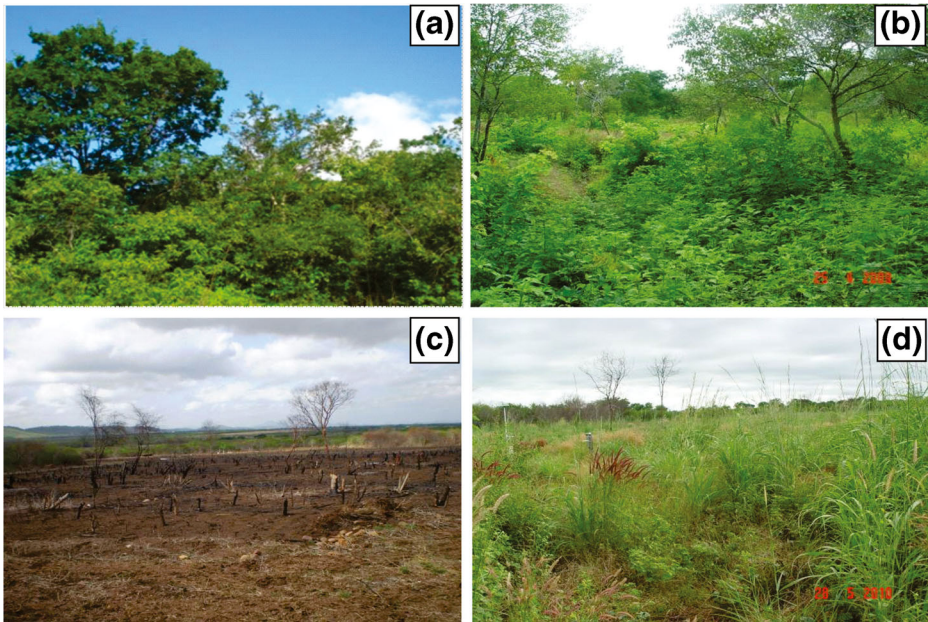


Fig. 2 Watershed under native tropical dry forest - NF **a**, watershed under thinned tropical dry forest - TF **b**, and watershed with slash and burn native tropical dry forest **c** followed by gamba grass cultivation – SB **d**

2.80 ha of NF during the first year of the study (2009) and slash and burn on the second year, followed by gamba grass (*Andropogon gayanus* Kunt) cultivation (SB) (Fig. 2c and d).

Rainfall data were collected for five years (2009–2013) at 5-minute intervals in an automatic weather station. P (mm), PDUR (minutes), I (mm h^{-1}), and maximum thirty minutes intensity (I30, mm h^{-1}) were computed for all 176 measured natural rainfall events.

Individual rainfall events similarities were evaluated using the hierarchical cluster analysis (HCA) statistical techniques, based on P, PDUR and I30. To reduce errors due to variables scales and units data was standardized by the z-score method.

Runoff was measured at the watersheds outlets with a Parshall flume and associated capacitive sensor that measured water level. Suspended load samples were collected from collecting towers installed upstream of the Parshall flumes, in 100 mL containers arranged vertically 7.5 cm apart, the first one at 15 cm from the ground. Samples were collected after each runoff event, and analysed in laboratory for total suspended solids. Bedload was measured in the 185 L ditches installed upstream of the flumes, which retained the entire volume of dragged sediment. After each runoff event, the water containing sediment in the ditches was homogenised and sampled for evaluation of total dragged sediment.

3 Results and Discussion

3.1 Classification of the Rainfall Events

Each of the 176 events was classified into one of four rainfall regimes (Table 1) using HCA based on P, PDUR and I30. Rainfall Regimes I to IV grouped events of higher to lower rainfall

Table 1 Statistical characteristics of the rainfall regimes

Rainfall Regime	Parameter	Average	Std. Dev.	Coefficient of Variation	Sum	Frequency (events)
I	P (mm)	60.5	20.8	0.3	363.1	6
	PDUR (min)	696.7	106.5	0.2		
	I30 (mm h ⁻¹)	43.3	31.5	0.7		
II	P (mm)	45.9	17.1	0.4	550.3	12
	PDUR (min)	352.0	31.0	0.1		
	I30 (mm h ⁻¹)	35.3	19.3	0.5		
III	P (mm)	37.4	25.8	0.7	1685.0	45
	PDUR (min)	185.4	44.0	0.2		
	I30 (mm h ⁻¹)	38.2	23.0	0.6		
IV	P (mm)	15.0	10.2	0.7	1696.1	113
	PDUR (min)	62.1	32.9	0.5		
	I30 (mm h ⁻¹)	21.2	13.6	0.6		

P: rainfall depth; I30: maximum intensity over 30 min; PDUR: rainfall duration

depth, longer to shorter duration, and higher to lower I30. Rainfall event classification based on the same variables and statistical techniques have been applied by Wei et al. (2007), Fang et al. (2012) and Peng and Wang (2012).

In this study, 64 % of total rainfall events (113 events) were of short duration (average 62 min), classified as Regime IV (Table 1). Short duration rainfall events are important in the semiarid Brazilian region (Medeiros et al. 2014) where in 75 % of the years, 5 to 10 % of the total annual precipitation occurred in events shorter than one hour.

PDUR best characterizes the rainfall regimes (Fig. 3), where interquartile ranges are well defined and not overlapping within regimes. I30 showed the greatest dispersion (Fig. 3), as also observed by Medeiros et al. (2014), showing the independence of rainfall intensity to rainfall depth.

Rainfall regimes annual distribution varied (Fig. 4). The less frequent Regime I was mostly from frontal rainfall events - when a cold air mass meets a warmer air mass that is forced over the cold air due to its lower density, producing longer duration rainfall. When the warm air is humid, rainfall of moderate to high magnitude is formed (50 % of events between 58 and 72 mm and an average PDUR of 12 h). These events only occurred in 2010 (five events) and 2012 (one event) (Fig. 4). Despite their low frequency due to the high magnitude of Regime I events, in 2010 they represented the highest total annual rainfall (Fig. 4a).

Rainfall of intermediate depths are observed in Regime II (50 % of events between 33 to 58 mm and average PDUR of 6 h), which differs from Regime III mainly by the longer duration from 310 to 400 min (Fig. 3). Events within this regime occurred rarely (7 % of total), but were present in all years of study (Fig. 4b). Rainfall of this nature (intermediate duration - average 352 min) may be related to frontal precipitation, such as derived from the ITCZ or cold fronts (Ferreira and Mello 2005).

The average rainfall duration in Regime III was 73 % smaller than that of Regime I, and also differed in magnitude, as the 75th percentile is as high as 50 mm (Fig. 3), with 50 % of P from 19 to 48 mm. Regime III rainfall events were the second most frequent (26 %) (Fig. 4b), and represented the greatest total rainfall depth (Table 1) in 2012 and 2013 (Fig. 4a), when warmer water in the north and colder in the south Atlantic affected the location of the ITCZ

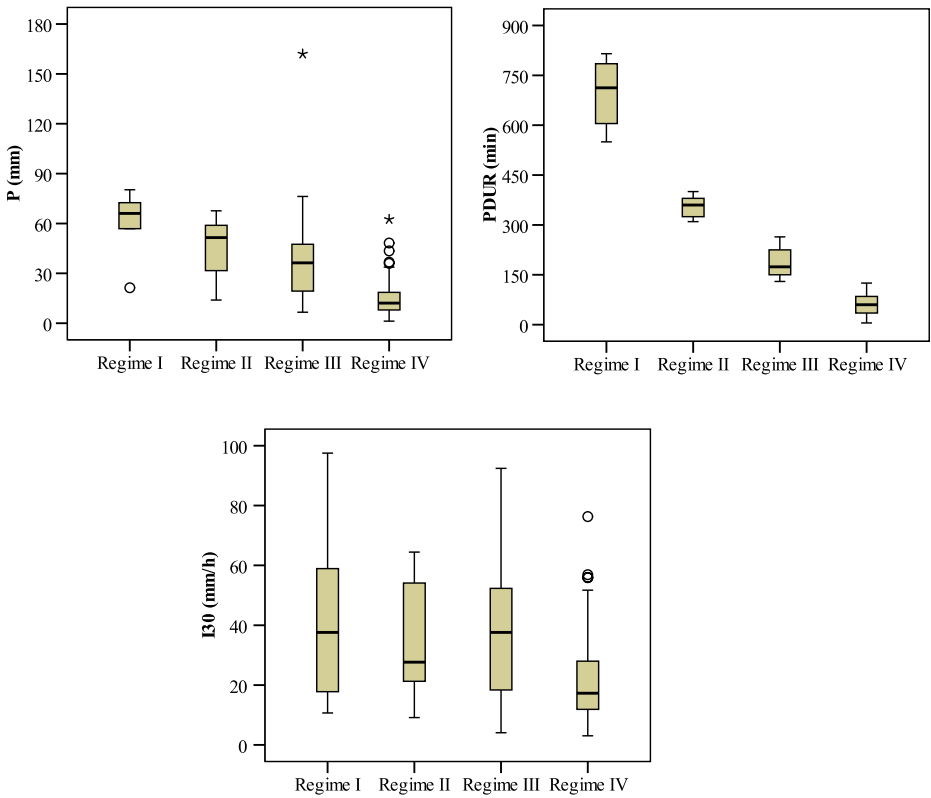


Fig. 3 Distribution of rainfall events for the four rainfall regimes identified

(Ferreira and Mello 2005; Nóbrega and Santiago 2014). Regime III events result from Cold Fronts, Easterly Disturbances and Upper Air Cyclonic Vortices, which generate smaller rainfall depths of intermediate durations (Table 1, Figs. 3 and Fig. 4a).

For Regime IV (Fig. 3), the lower P, PDUR and I30 relative to the other regimes, is evident, as is the higher frequency of occurrence (Table 1 and Fig. 4b). Nonetheless, the annual total

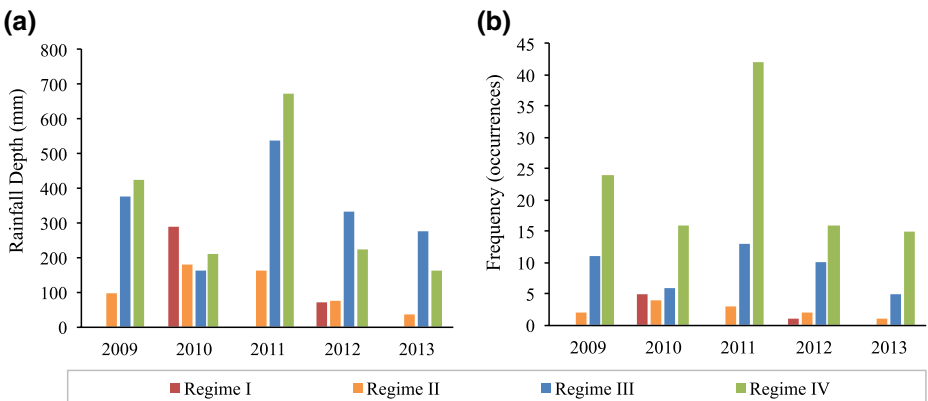


Fig. 4 Annual rainfall depth by rainfall regime **a**, and frequency of events **b** in the experimental watersheds

rainfall for Regime IV was only greater than the other regimes in 2009 and 2011 (Fig. 4a), and was the second largest in the other years. Guerreiro et al. (2013) found a trend towards a reduction in intensity and in monthly rainfall throughout most of the Federal State of Ceará, Brazil, where the watersheds are located. Rainfall events of Regime IV seem to be of convective nature and small duration (Fig. 3), influenced by the occurrence of the El Niño phenomenon, and displacement of the ITCZ. In dry years, such as those in the period of study, rainfall in this region is typically originated locally, formed from Mesoscale Convective Systems (MCS) that arise in preferential areas of the region (Ferreira and Mello 2005). High P and I30 outliers in Regime IV (Fig. 3) suggest frontal precipitation.

3.2 Runoff, Sediment Yield and the Effect of the Different Rainfall Regimes

Over the five years of study, the SB watershed generated more surface runoff than the other watersheds (Table 2). This result may be related not only to land cover, but also the natural characteristics of the soil, because in 2009, when still native dry tropical forest, it yielded the largest total annual runoff (Table 2). Medeiros et al. (2010), determined that the soil physical and mineralogical characteristics are the main controlling factors on runoff generation. The watersheds Vertic soils, show cracks upon drying, acting as preferential pathways infiltration (Harmel et al. 2006; Dinka et al. 2013; Santos et al. 2016) and may generate heterogeneity on hydrological characteristics for each watershed. Soil cracking is one of the main causes of the low correlation between hydrological models predicted runoff and observed values in watersheds with expansive clays (Harmel et al. 2006; Dinka et al. 2013; Santos et al. 2016).

Except for 2013, the TF watershed showed smaller runoff relative to the NF watershed (Table 2). These small adjacent watersheds, with similar particle size and soil mineralogy, suggest a dominance of ground cover in hydrologic processes. Thinning of native vegetation reduces soil shading, allowing development of the herbaceous layer, which, together with the protection from larger trees, result in increased abstractions (vegetation interception, infiltration and depression storage), generating less runoff. Arnaú-Rosalén et al. (2008) showed that, herbaceous vegetation and rock fragments on the surface increase soil infiltration capacity.

The first year of TF management experienced the largest soil loss (Table 2), until streams redefinition and establishment of the herbaceous layer (Rodrigues et al. 2013). Similarly, in the SB watershed (Table 2) a larger sediment yield was measured when slash and burn took place

Table 2 Surface runoff and annual sediment yield in watersheds under different land uses from 2009 to 2013

Year	Rainfall (mm)	Surface runoff (mm)			Sediment yield (kg ha ⁻¹)		
		NF	TF	SB	NF	TF	SB
2009	896	102.2	70.0 ^a	226.4 ^b	1390.2	1433.3 ^a	790.1 ^b
2010	711	15.1	11.3	115.4 ^c	169.1	36.1	3102.6 ^c
2011	1299	183.0	141.0	397.1 ^d	3376.4	2068.0	2042.7 ^d
2012	804	169.0	61.4	169.8 ^d	1177.1	306.7	502.7 ^d
2013	639	23.6	34.4	80.5 ^d	107.0	50.9	157.9 ^d
Average	869.9	98.6	63.3	197.8	1244.0	779.0	1319.2

NF Native tropical dry Forest, TF Thinned tropical dry Forest; SB- Slash and burn native tropical dry forest, followed by gamba grass cultivation; ^a year of application of the management TF; ^b year with Native tropical dry Forest, ^c year of application of the management SB, ^d years of grass development (*Andropogon gayanus* Kunt)

(2010). The first two events of 2010, after slash and burn, but before grass was established and the drainage system redefined, accounted for 73 % of the annual sediment yield. Due to the increased soil exposure in the first rainfall events, more soil particles could be detached, with increased sediment availability. Moreover, the lack of ground cover during these events reduced roughness, increasing runoff generation and, therefore, enhancing the hydrologic and sediment connectivity (Bracken and Croke 2007; Fryirs et al. 2007; Molina-Navarro et al. 2014). Collapse of stream banks and gullies formation, increased specific sediment yield, as also reported by Poesen et al. (2003), and occurs more intensely when the soil is unprotected upon land use changes. Soil erosion is sensitive to land use, soil type and topography, therefore, patches identification and characterization may contribute for a more cost effective soil erosion control management rather than whole watershed planning (Kumar and Mishra 2015).

The NF watershed presented average annual sediment yield 60 % higher than the TF watershed (Table 2), expressing the greater erosion susceptibility and/or sediment transport capacity of the NF watershed. The less developed herbaceous layer in the native tropical dry forest watershed subject to more shading results in fewer natural barriers to runoff and greater hydrologic connectivity, generating more energy for transport of detached sediment. Similar behaviour was observed in 2011 in the SB watershed, when soil losses were lower than in the area of NF (Table 2). This behaviour suggests a break of hydrologic connectivity due to development of a dense herbaceous cover (Fig. 2d), which promoted dissipation of rainfall kinetic energy and runoff. According to Bracken and Croke (2007), vegetation stripes act as barriers to sediment transport, also dissipating surface runoff energy (Molina-Navarro et al. 2014; Zhang et al. 2014a), which results in increased water residence time, and opportunity for infiltration and sediment deposition processes (Fryirs et al. 2007).

There were rainfall events unable to generate runoff in the four rainfall regimes (Fig. 5). Such behaviour is mainly explained by the antecedent soil moisture conditions and cracks formation, which act as preferential infiltration paths (Santos et al. 2016). The cracks, of variable width, reaching up to 5 cm on the surface, and depths that can exceed one metre, result in initial abstractions up to the total event rainfall. For the most frequent rainfall events of Regime IV, higher runoff depths were recorded for low rainfall events (Fig. 5), suggesting that other factors controlled runoff generation, such as soil moisture and vegetation status.

Regime III, with the highest total accumulated runoff in the disturbed watersheds, 25 out of 45 events generated runoff. In this Regime, the greatest runoff depths were recorded in the SB

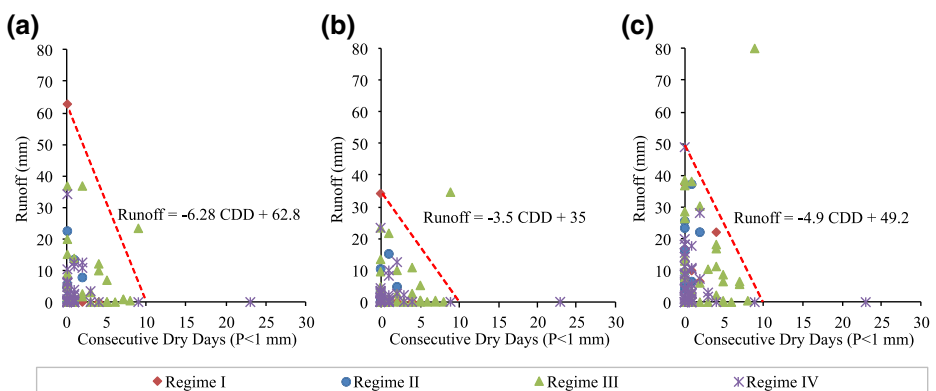


Fig. 5 Relationship between surface runoff and previous consecutive dry days for the study period (2009–2013), for different rainfall regimes in watersheds under NF **a**, TF **b** and SB **c**

watershed, with runoff depths ranging from 1 to 80 mm (Fig. 5c), mean and median of 14.4 and 7.8 mm, respectively. As rainfall Regime III characterizes events of high rainfall depth, short duration and high intensity (Fig. 3), it results in more opportunity for Hortonian flow generation (Wei et al. 2014). Sen et al. (2010) showed that rainfall events of low to medium intensity and duration were less likely to generate runoff in a 0.12 ha catchment in North Alabama.

In this study, for all soil types and regardless of rainfall regime, runoff decreased as CDD increased, as result of increased initial abstractions from drying of the soil (Fig. 6). Runoff could be generated when CDD = 0 under all regimes. Vertic soils, when close to saturation, have low infiltration capacity (Kishné et al. 2010), and may produce runoff even with a rainfall event of less than 10 mm, as recorded in this study (Fig. 5). Yang et al. (2016) also report that higher intensity rainfalls may also form a surface seal, leading to a large increase in runoff.

Rainfall events after more than four CDD (Fig. 5) generated runoff in the three watersheds for rainfall of Regimes I and III only. Events from these regimes have high to moderate rainfall depth and, depending on the state of moisture and plant cover, are able to close some of the cracks in the soil and overcome the initial abstractions (Santos et al. 2016). The strong influence of initial abstractions, caused by the soil drying and cracks formation can be observed for the events of Regime I (high magnitude rainfall), generating runoff in a single event after more than 3 CDD in the SB watershed. This was a response to the 15 February 2010 event, with 63 mm magnitude, and was the second event that generated runoff while the watershed was still under bare soil due to deforestation of the native forest.

Linear regression between the sediment yield and runoff, indicates that the NF watershed has greater sediment transport capacity when compared to the other watersheds for the same runoff depth (Fig. 6a). Such behaviour is consistent with land cover since, although sparse, the native tropical dry forest promotes shading and inhibits development of an herbaceous layer, favouring the sediment detachment process and decreasing surface roughness (Rodrigues et al. 2013).

In the TF watershed, development of the herbaceous layer results in a denser and more homogeneous ground cover, able to dissipate rainfall energy and increase both water residence time and infiltration opportunity (Fig. 6b). On the other hand, the NF watershed shows less sediment transport capacity (lower slope of the linear regression, Fig. 6c), an effect that is compensated by higher runoff generation in terms of volume and higher number of events, resulting in a greater total sediment yield.

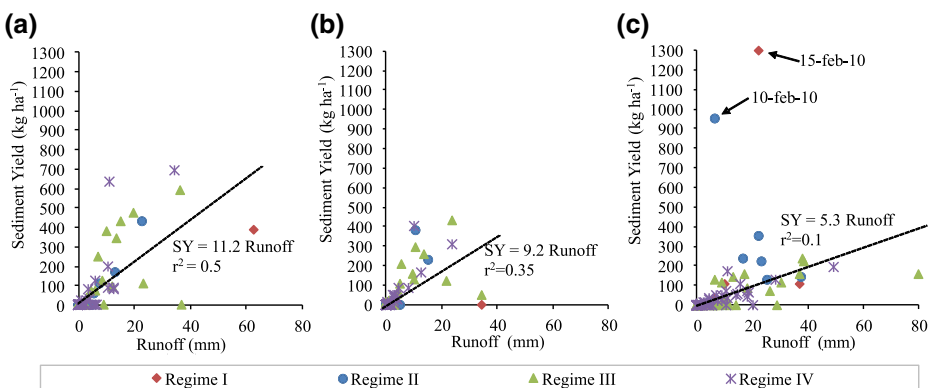


Fig. 6 Relationship between surface runoff and sediment yield for the study period (2009–2013), for different rainfall regimes in watersheds under NF **a**, TF **b** and SB **c**

In the NF watershed (Fig. 7), runoff resulting from rainfall Regime I represented 12.8 % of the total, a value close to that recorded for Regime III, with higher frequency and higher total rainfall. Events such as those of Regime I, of high rainfall depth and duration, increase the chances of overcoming the initial abstractions and natural barriers, producing runoff with higher hydrological connectivity (Fryirs et al. 2007). It should be noted that out of the six events classified as Regime I, five occurred in 2010 and one in 2012 (19 February 2012). Therefore, as 2010 was the first year of the NF management, most of the specific sediment yield (Fig. 7c) occurred within Regimes I and II, characterised by events of high to moderate magnitude.

Throughout the 2009–2013 period, rainfall events of Regime IV were the most frequent (113 events) (Table 1). Although rainfall events within this regime are characterised by low rainfall depth, duration and intensity (Table 1), the second highest value for total runoff depth was measured for this class in the three watersheds (Fig. 7a). Events of Regime IV resulted in runoff coefficients of up to 79 % (runoff depth of 49 mm, Fig. 6c), which occurrence was strongly influenced by antecedent CDD (indirect index of antecedent soil moisture). Rainfall events in this regime, due to their high frequency, showed little CDD, and resulting high antecedent moisture, with partially closed cracks generating few losses from early abstractions, as described by Zhang et al. (2014b) and James and Roulet (2009), favouring surface runoff and sediment yield (Santos et al. 2016). This behaviour was noticed in the NF and TF watersheds, with the second highest values for total (Fig. 7b) and specific sediment yield (Fig. 7c).

Regime III presented the highest total runoff depth (Fig. 7a), representing 45, 47 and 44 % of the total runoff for the watersheds under NF, TF and SB respectively, in the five years of study. This was a result of its high frequency of occurrence (45 events) associated with the higher rainfall depth and shorter duration, when compared to Regime IV events.

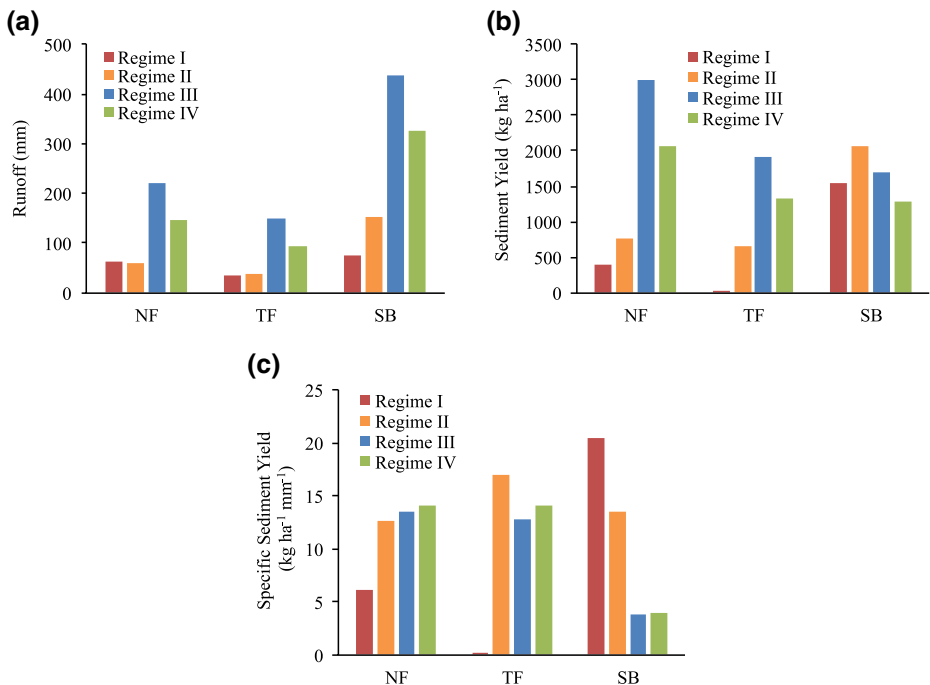


Fig. 7 Surface runoff **a**, sediment yield **b** and specific sediment yield **c** for the study period (2009–2013), for the different rainfall regimes and land uses

For sediment yield, except for the SB watershed (event occurrence of Regimes I and II, shortly after application of the management practice in 2010), Regime III accounted for 48 and 49 % of total sediment yield for the NF and TF watersheds respectively (Fig. 7b). Higher runoff depths may increase transport energy, generating high sediment yield.

The high sediment yield (Fig. 7b) and specific sediment yield (Fig. 7c) in the SB watershed are mostly caused by the event of 15 February 2010 (Regime I) (Fig. 6c). This event was the second largest that generated runoff after the land use change, being responsible for 42 % of the sediment yield in 2010, and representing 20 % of total yield in the five years of study. For that event, the plant cover was still not established, enhancing sediment transport capacity and erosion along the drainage system (Medeiros et al. 2010). Furthermore, this extreme event was classified as Regime I. Events of Regime I accounted for 6.3, 0.5 and 23.6 % of total sediment yield for the NF, TF and SB watersheds respectively (Fig. 7b).

Despite the low occurrence of Regime II, it yielded the third largest amount of sediment (Fig. 7b), and largest amount of specific sediment (Fig. 7c) in the TF and NF watersheds, following the order for total runoff and total rainfall. For the NF watershed, Regime II presented the highest sediment yield, caused by the event of 10 February 2010 (Fig. 6c), which was the first large event that generated runoff after application of the SB management. This event alone produced 955.5 kg ha⁻¹ of sediment, representing 46 % of the total sediment yield for Regime II. The extremely high sediment yield in such occasion was a result of the lack of plant cover at the time of the event and erosion/redefinition of the drainage system.

Regarding occurrence and total rainfall, the regimes follow the order below: Regime IV > Regime III > Regime II > Regime I (Table 1). Regime IV displays higher frequency and greater total rainfall depth, but lower water and soil losses than Regime III. Rainfall events of Regime III are of higher magnitude and intensity than events of Regime IV, resulting in increased runoff and erosivity of these events (Fig. 7a and b), with sediment detachment and transport. With respect to surface runoff and sediment yield, the following order of the regimes is observed: Regime III > Regime IV > Regime II > Regime I (Fig. 7). The higher frequency of rainfall events for a given regime and the total rainfall, are strongly related to the water and soil losses in the study area, similar to the behaviour noted by Peng and Wang (2012) on karst slopes in southwest China and Fang et al. (2012) in a small mountainous watershed in the Three Gorges Area, also in China.

4 Conclusions

Hierarchical Cluster Analysis (HCA) allowed the grouping of rainfall events into four distinct regimes, which are closely related to runoff and sediment yield in the study area.

Most of the rainfall events in the region were characterised by low magnitude and short duration (Regime IV). These events generated the second highest total yields of water and sediment, despite the low magnitude of the individual events, which is compensated by the high frequency. This behaviour is also associated with antecedent soil moisture at the time of the events: rainfall of Regime IV presented runoff coefficients of up to 79 %.

Rainfall events with the highest magnitudes (average 60.5 mm) and longest durations (average 697 min) were infrequent and grouped together on Regime I. As this regime presents high runoff depths, with values of up to 63 mm (runoff coefficient of 86 %), the rainfalls of Regime I are of concern, due to high runoff rates and sediment yield for isolated events.

Runoff generation in the three watersheds showed strong dependence on antecedent soil moisture and the type of rain. After more than four consecutive dry days, runoff was only generated for rainfall events of Regimes I and III, with high to moderate rainfall depths, short durations (Regime III) and relatively high intensity.

After land use changes, such as thinning of natural tropical dry forest and a slash and burn and grass cultivation, the first events resulted in higher sediment yield. High soil exposure in such conditions enabled intense sediment detachment and runoff with higher transport capacity, as well as erosion of the drainage system.

The first rainfall events after land use change deserve special attention: after slash and burn and grass cultivation, the first two events that generated runoff accounted for 73 % of the total sediment yield for the year.

Acknowledgments The authors would like to acknowledge the Brazilian National Council for Scientific and Technological Development (CNPq) and the Coordination for the Improvement of Higher Education Personnel (CAPES) for the financial support to this research, and the valuable contribution of the anonymous reviewers.

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