Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga

ISSN 0100-316X (impresso)
ISSN 1983-2125 (online)

HYDROLOGICAL RESPONSES OF A WATERSHED TO VEGETATION CHANGES IN A TROPICAL SEMIARID REGION[1]

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ABSTRACT - The objective of this work was to assess the effect of vegetation on the runoff coefficients of a Caatinga dry tropical forest before and after thinning. Thus, an experiment was conducted with evaluations in three hydrological years (2008, 2011 and 2013) in Iguatu, State of Ceará, Brazil. In 2008, the vegetation consisted of a 30-year regenerating Caatinga forest. The vegetation was subjected to thinning in 2009, 2011 and 2013, removing trees with less than 10-cm diameter at breast height. Hydrological responses were evaluated as a function of daily precipitation water depths, based on cumulative frequency distribution, by dividing precipitation events into three classes (CP) (CP≤30, 30<CP≤50 and CP>50 mm). Significant differences between runoff coefficients before and after vegetation thinning were assessed through the Student's t-test (p<0.01). Before thinning (2008), CP≤30 mm showed the highest runoff coefficient, differing statistically (p<0.01) from the other years. The results of precipitation events of great magnitude (CP>50 mm) indicate that the runoff is greatly dependent on rainfall characteristics and soil moisture conditions. The greater development of herbaceous vegetation due to thinning reduced the surface runoff.

Keywords: Runoff. Thinning. Rainfall depths.

RESPOSTAS HIDROLÓGICAS DE MICROBACIA EM REGIÃO SEMIÁRIDA TROPICAL À ALTERAÇÃO DA COBERTURA VEGETAL

RESUMO - Tendo como objetivo responder ao questionamento de como o raleamento da cobertura vegetal de uma floresta tropical seca, caatinga, pode interferir no coeficiente de escoamento superficial, desenvolveu-se este estudo em três anos hidrológicos (2008, 2011 e 2013). O experimento foi conduzido no município de Iguatu no estado do Ceará, Brasil. No ano de 2008 a cobertura vegetal era caatinga em regeneração há 30 anos. A vegetação foi submetida ao manejo de raleamento em 2009, 2011 e 2013, eliminando-se as árvores com diâmetro inferior a 10 cm a altura do peito. Para investigar a resposta hidrológica em função da altura pluviométrica diária, tendo-se por base a distribuição de frequência acumulada, os eventos foram divididos em três classes pluviométricas (CP): CP ≤ 30 mm, 30 < CP ≤ 50 mm e CP > 50 mm. Para identificar se os coeficientes de escoamento gerados antes e após o raleamento da vegetação apresentavam diferenças significativas, aplicou-se o teste “t” de Student ao nível de 1%. Antes do raleamento (2008), a CP ≤ 30 mm registrou o maior percentual do coeficiente de escoamento diferindo estatisticamente ao nível de 1% de significância dos outros anos. Para eventos de grande magnitude (CP > 50 mm), os resultados apontam que o escoamento apresenta uma maior dependência das características da chuva e das condições de umidade do solo. O maior desenvolvimento do estrato herbáceo devido ao raleamento resultou em uma redução do fluxo do escoamento superficial.

Palavras-chave: Escoamento superficial. Raleamento. Alturas pluviométricas.

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[1]Received for publication in 08/23/2016; accepted in 03/27/2017.
Paper extracted from the master's thesis of the second author.
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INTRODUCTION

Semiarid regions comprise 17.7% of the globe and may increase due to changes in hydrological cycles (ROTENBERG; YAKIR, 2010). These regions show very irregular climate, with concentrated precipitation in few months and poorly geographically distributed rainfall (SILVA; PEREIRA; ALMEIDA, 2012). The largest extensions of tropical dry forests, which is defined by climatic seasonality, are found in semiarid regions.

One of the world's largest continuous areas of dry tropical forest is found in the Brazilian semiarid region (MILES et al., 2006), which has an area of 844,453 km^2, representing 9.92% of the national territory and the Caatinga Biome. A marked characteristic of this region is that almost all watercourses (rivers and streams) are intermittent or ephemeral (OLIVEIRA; ALVES; FRANÇA, 2010). This characteristic makes this region fragile in terms of water availability during prolonged dry periods or droughts. Inadequate management of natural resources in watersheds in these regions can cause serious negative impacts, such as changes in hydrological processes, erosion in agricultural areas and reduction of hydraulic capacity of reservoirs (ARAÚJO; GUNTNER; BRONSTET, 2006).

Intensification of human pressure on natural resources to produce fibers and food has caused degradation of soils and water bodies and loss of vegetation and biodiversity. These changes added to climatic factors can result in significant modifications in hydrological processes, especially rainfall-runoff. Moreover, surface runoffs in arid and semiarid regions have high spatial and temporal variability and mostly of them are related to soil surface typology of high spatial heterogeneity, such as vegetation cover, rock fragments, topography, crusts and soil physicochemical attributes (CANTÓN et al., 2011; CHAMIZO et al., 2012; JOST et al., 2012).

Therefore, vegetation is one of the variables that greatly affect hydrological processes of watersheds (MUÑOZ-ROBLES et al., 2011; MONTENEGRO et al., 2013). Rodrigues et al. (2013) assessed hydrological responses of watersheds to vegetation in the Brazilian semiarid region and found greater effects by the first precipitation event of the rainy season, and also emphasized the effect of the prior soil moisture. Jost et al. (2012) assessed the effect of vegetation on runoff in Norway and found that different tree species (vegetation cover) lead to different runoff responses due precipitation in the same soil type.

Hydrological studies in the Brazilian semiarid region is insufficient to gather information on the ephemeral runoff of rural watersheds, since they are affected by various factors (CHAMIZO et al., 2012). Thus, information on the correlation between these factors, such as vegetation type, precipitation and surface runoff, is important to choose the correct water and soil conservation management in a watershed (PENG; WANG, 2012). In this context, the objective of this work was to assess the effect of vegetation on the runoff coefficients of a Caatinga dry tropical forest, considering three classes of precipitation events (CP) (CP≤30, 30<CP≤50 and CP>50 mm), before and after thinning.

MATERIAL AND METHODS

The study area was located in the semiarid region of the State of Ceará, in the Upper Jaguaribe Sub-basin, within the geographic coordinates 6°23'38" to 6°23'58"S and 39°15'21" to 39°15'38"W, which has mean altitude of 217.8 m (Figure 1). This experimental area belongs to the Federal Institute of Education, Science and Technology of Ceará (IFCE), Iguatu campus.

The region climate is BSw'h' (hot semiarid), with average monthly temperature always higher than 18ºC in the coldest month, aridity index of 0.44 (semiarid), average potential evapotranspiration of 1,988 mm year^{-1}, and annual average precipitation (1932-2013) of 864±304 mm.

The soil of the experimental watershed under study was classified as typical carbonate ebanic Vertisol by the Embrapa classification (SANTOS et al., 2013). The soil textural class is clay loam (27.4% sand, 42.5% silt and 30% clay), with saturated hydraulic conductivity <0.2 mm h^{-1}. Surface cracks in the dry season and waterlogging in the rainy season are common in this region due to the soil clay type (2:1, montmorillonite group), thus providing paths for the preferential flow, generating great water infiltration and retention capacities (ZHANG et al., 2014).

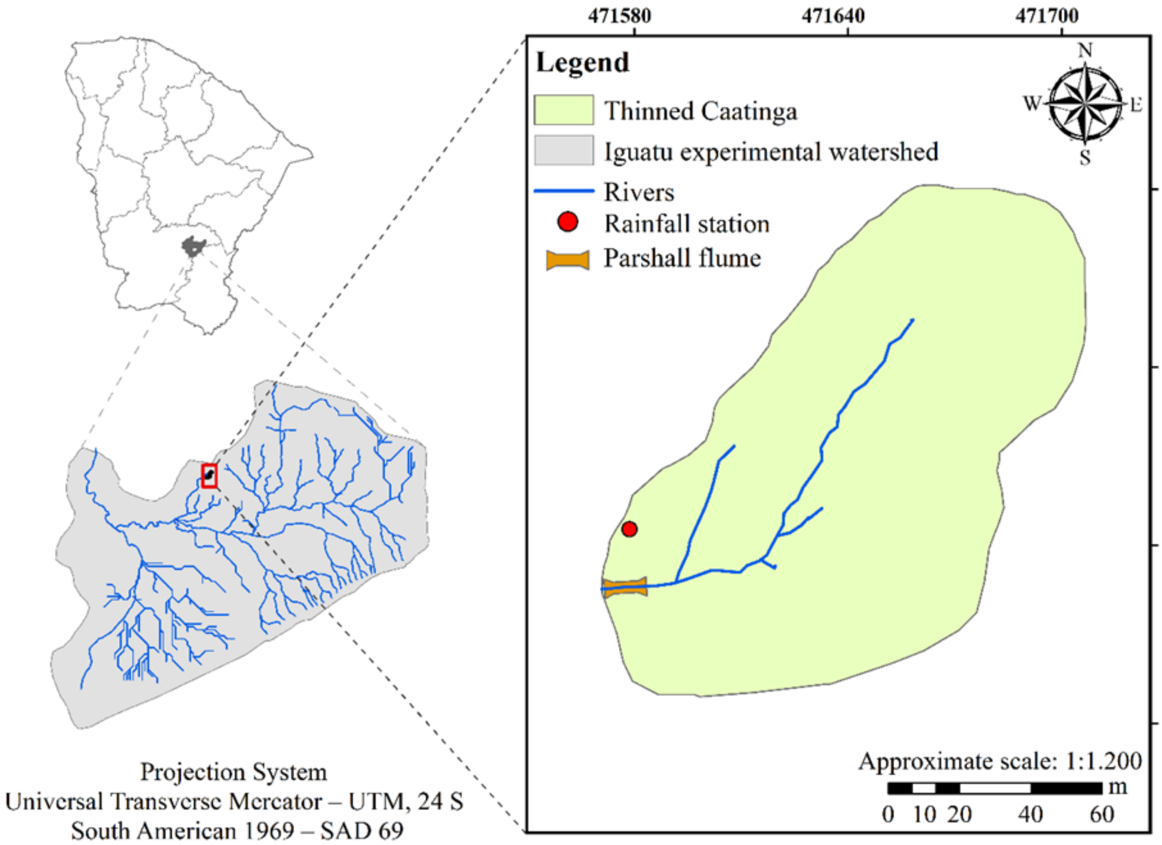


Figure 1. Location of the study area in the State of Ceará, Brazil.

In the first year of study (2008), the watershed vegetation consisted of a regenerating Caatinga forest that had been undisturbed for 30 years. This forest had variable aspects, showing herbaceous and arboreal-shrub species, typically deciduous and xerophilous, with large variety of thorny species. The vegetation was subjected to thinning in 2009, 2011 and 2013 allowing natural pastures to grow. This is a recommended practice for silvicultural management in the Brazilian semiarid region, which consists in the removal of all plant species with less than 10-cm diameter at breast height, allowing herbaceous vegetation to develop due to a greater light input, according to the methodology described by Araújo Filho (1992). These procedure was performed to assess the effect of vegetation on the runoff coefficients of a first-order small rural watershed (Table 1), which had a mildly undulating terrain and Caatinga forest vegetation, during the rainy (Figures 2A and 2B) and dry (Figures 3A and 3B) seasons, before and after thinning, which was carried out in the dry season, November 2008.

Source: José Ribeiro de Araújo Neto.

Figure 2. Partial view of the experimental watershed vegetation in the rainy season before (A) and after (B) thinning.

Source: Eunice Maia de Andrade.

Source: Ana Célia Maia Meireles.

Figure 3. Partial view of the experimental watershed vegetation in the dry season before (A) and after (B) thinning.

Table 1. Morphometric characteristics of the experimental watershed.

Variable	Thinned watershed	Unit
Watershed area	1.15	ha
Perimeter	478.35	m
Main stream length	147.18	m
Watershed length	188.17	m
Watershed declivity	8.72	%
Compacity coefficient	1.25	-
Concentration time	0.05	h
Main stream sinuosity	1.2	-

Source: Alves (2008).

Precipitation events in 2008, 2011 and 2013 that caused runoff were considered for evaluation. The watershed vegetation in 2008 was a 30-year regenerating Caatinga forest (natural conditions). This area had already been subjected to thinning in the other two selected years. The precipitation in 2011 was above the average and similar to 2008, and the precipitation 2013 was below the average. These years had extreme precipitation events (precipitations of great depths), which were used to assess hydrological responses as a function of precipitation water depths to the different vegetation.

Thus, precipitation events were divided into three classes (CP) (CP≤30, 30<CP≤50 and CP>50 mm), considering the cumulative frequency distribution. The first class was established at CP≤30 mm because of its high frequency, which represented 50% of the total precipitation events (Figure 4), and its possible contribution to changes in the surface runoff process after the vegetation change. The third class was established at CP>50 mm because of precipitation events >50 mm, which represent precipitation events with probability of occurrence <0.2, supposedly have different response than normal precipitation events. The second class was established at 30<CP≤50, an intermediate interval between the two other classes, representing precipitation events with probability of occurrence ≤0.8 and >0.5.

The watershed was hydrologically monitored by an automatic station, which recorded data every five minutes. Precipitation data was obtained with a pluviograph (Figure 5A) and runoff data with the Parshall gutter (Figure 5B) with an automatic water-level indicator for measuring the runoff. The measures recorded was used to transform the water height to flow with the specific equation of the gutter. The flow data over time generated hydrographs for each precipitation event. The data on the runoff monitored in the Parshall gutters were transformed to runoff volume.

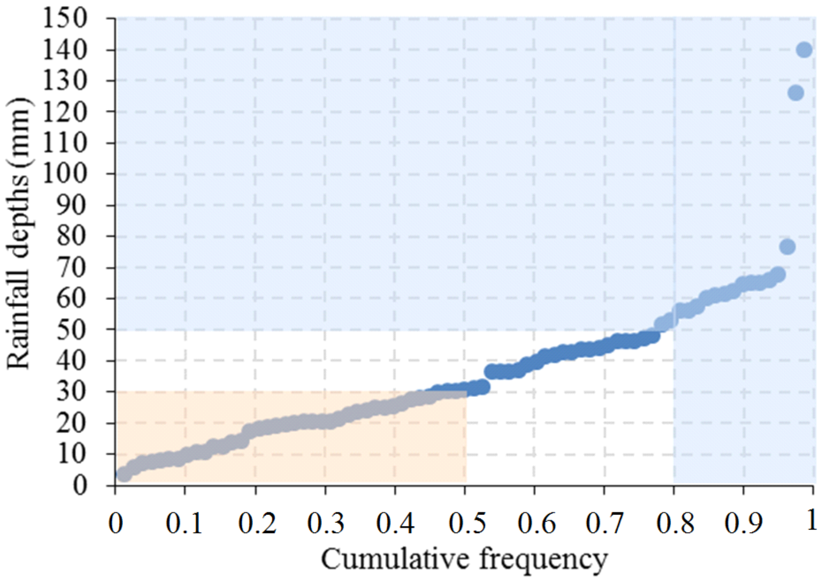


Figure 4. Cumulative frequency distribution of daily precipitation events of the experimental area.

Source: Ana Célia Maia Meireles. Source: Joseilson Oliveira Rodrigues

Figure 5. Pluviograph (A) and Parshall gutter (B) installed in the experimental watershed.

Runoff coefficient data (runoff to precipitation ratio) were subjected to the Student's t-test (p<0.01). Statistical procedures were performed using the statistical program SPSS v.16.0 (Statistical Package for Social Sciences).

RESULTS AND DISCUSSION

The three hydrological years studied had irregular annual precipitation, denoted by the high deviations from the mean (864 mm). The annual precipitation was above the average in the first two years evaluated (Table 2) and below the average in the last, which had less than 50% of the precipitation of the first and second years. This result confirms the high temporal variability of precipitation events that is typical of semiarid regions (GUERREIRO et al., 2013; ANDRADE et al., 2016). The total precipitation of 2008 and 2011 were similar, however, 2011 had 15 more precipitation events than 2008 (Table 2), denoting that conclusions based on total annual precipitation for these regions must be complemented with analyzes of number of precipitation events or prior consecutive dry days (SANTOS et al., 2016). The total precipitation events recorded in the watershed was 140, with 26% (36) causing surface runoff (Table 2). The temporal distribution of these events was 33% in 2008, 61% in 2011 and 6% in 2013.

Table 2. Hydrological synthesis of the experimental watershed over the study period.

Year	Number of precipitation events	Number of events generating runoff	Total Precipitation (mm)	P* (mm)	Pe (mm)	C (%)
2008	47	12	1412.0	404.7	87.8	27.1
2011	62	22	1416.8	849.3	143.3	13.0
2013	31	2	673.3	202.0	57.6	31.0
Total	140	36	3502.1	1455.9	288.6	-
Average	-	-	1167.3	-	-	23.7

P* = total precipitation with runoff; Pe = annual runoff; C = average runoff coefficient of precipitation events with runoff.

A low average runoff coefficient was expected for the experimental watershed in 2008 due to its vegetation (30-year regenerating Caatinga forest). However, after thinning (2011), the runoff coefficient (C) of the watershed was more than 50% lower than in 2008, even with similar total precipitation (Table 2). This result was also expected, and can be explained by the herbaceous vegetation that grew due to the thinning (Figure 2B). The removal of the trees with diameter <10 cm favored the penetration of sunlight through the forest canopy, with consequent germination of herbaceous seeds in the Caatinga soil. The greater development of herbaceous vegetation in the watershed after thinning (Figure 2B) reduced the runoff speed and consequently, increased the infiltration time and reduced the flow depth, compared with the 30-year regenerating Caatinga (Figure 2A) (LA TORRE TORRES et al., 2011; RODRIGUES et al., 2013). Cosandey et al. (2005) emphasized the importance of herbaceous vegetation to reduce runoff.

The annual precipitation 2008 and 2011 were similar, but with different number of precipitation events. The number of precipitation events in 2011 were 32% higher than in 2008. The highest number of precipitation events of 2011 represented greater precipitation depths generating runoff (849.3 mm), however, the runoff coefficient (%) of 2011 was lower than that of 2008 (Table 2). Low runoff coefficients denote higher percentage of infiltrated water, resulting in greater soil moisture. The correlation between soil moisture and runoff were also reported by Bertol et al. (2007). Therefore, not only the precipitation distribution caused a lower surface runoff in 2011, but the emergence of herbaceous vegetation due to the thinning (COSANDEY et al., 2005; RODRIGUES et al., 2013). High-density herbaceous vegetation can increase the time for water infiltration into the soil, thus reducing the runoff.

Only two precipitation events with runoff occurred in 2013, however, they resulted in a higher runoff coefficient (31%) compared with that of 2008 (Table 2). This result was due to the high magnitude of the precipitation events and time between them. The hydrological effect of these precipitation events were different. Therefore, information on rainfall characteristics and distribution is essential to understand processes that cause runoff (FANG et al., 2012).

The distribution of precipitation events in the three classes (Table 3) showed asymmetry, with greater concentration in CP≤30 mm in the three years evaluated. From the total precipitation events occurred in 2008 (47), 2011 (62) and 2013 (31) (Table 2), 64% (2008), 71% (2011) and 71% (2013) were in CP≤30 mm (Table 3). Only two precipitation events with runoff occurred in 2013, which were >50 mm, i.e., the runoff occurred in 2013 were caused by extreme precipitation events. Thus, the precipitation in the Brazilian semiarid region is irregular, with great spatial and temporal variability (ANDRADE et al., 2016).

Precipitation events >50 mm had the lowest frequency (17% in 2008, 11% in 2011 and 6% in 2013) (Table 3), however, this class had the highest percentage of precipitation events with runoff. These results are typical in semiarid regions, where rainfalls of great magnitude are concentrated in few precipitation events (ANDRADE et al., 2016).

Precipitation events ≤30 mm generated total precipitation of 76.7 mm and runoff of 23.8 mm in 2008 (Table 4). However, after thinning (2011), the total precipitation was 193.3 mm and surface runoff was only 13.4 mm in this class.

The herbaceous vegetation formed a dense layer generating a barrier to runoff due to the thinning of the Caatinga forest (Figure 2B), increasing the time for infiltration and reducing the runoff in 2011. Other studies also showed vegetation cover as one of variables that most affect hydrological responses of watersheds (MUÑOZ-ROBLES et al., 2011; JOST et al., 2012; LIU et al., 2014).

Table 3. Distribution of precipitation events into the studied classes.

Year	Total Precipitation (mm)	P* (mm)	Classes of precipitation events (CP)					
			CP ≤ 30 (mm)		30 < CP ≤ 50 (mm)		CP > 50 (mm)	
			Number of precipitation events	Number of precipitation events with runoff	Number of precipitation events	Number of precipitation events with runoff	Number of precipitation events	Number of precipitation events with runoff
2008	1412.0	404.7	30	7	9	2	8	3
2011	1416.8	849.3	44	9	11	6	7	7
2013	673.3	202.0	22	0	7	0	2	2

P* = total precipitation with runoff.

Table 4. Total precipitation with runoff (TP), Total water depth of runoff (TR) and average runoff coefficient (RC) in different classes of precipitation events.

Year	Classes Pluviométricas (CP)								
	CP ≤ 30 (mm)			30 < CP ≤ 50 (mm)			CP > 50 (mm)		
	TP (mm)	TR (mm)	RC (%)	TP (mm)	TR (mm)	RC (%)	TP (mm)	TR (mm)	RC (%)
2008	76.7	23.8	35.7	71.6	4.0	5.7	256.3	59.9	21.1
2011	193.3	13.4	7.2	226.8	9.9	4.3	429.0	119.8	27.7
2013	0	0	0	0	0	0	201.8	57.6	31.0

According to the runoff coefficients found in the three classes of precipitation events before (2008) and after (2011 and 2013) thinning, the changes in vegetation reduced the runoff, except for CP>50 mm (Table 4). The highest runoff coefficient (27.7%) was found in 2011 in CP>50 mm. This result is explained by the number of precipitation events, since all 7 precipitation events (Table 3) exceeded the initial soil absorption capacity, generating a runoff of 119.8 mm (Figure 4). This result denotes the greater runoff responses to precipitation events of greater magnitudes. Santos et al. (2016) found similar results and concluded that precipitation events with depths >70 mm always generate runoff.

The development of herbaceous vegetation after thinning reduced the surface runoff for precipitation events of classes CP≤30 mm (35.7 to 7.2%) and 30<CP≤50 mm (5.7 to 4.3%) (Table 4). According to Casermeiro et al. (2004), hydrological responses are related not only to the percentage of vegetation cover, but to the structural and physiognomic arrangement of the plants (herbaceous or arboreal), which represent different barriers to rainfall drops and runoff.

The vegetation cover had greater effect on the runoff coefficient in precipitation events of the class CP≤30 mm (Figure 6A). The highest runoff coefficients (0.58; 0.49; 0.46 and 0.42) were found in 2008, when the watershed vegetation was a 30-year regenerating Caatinga forest, and the greatest precipitation depth was 20 mm (Figure 6A). The runoff coefficients in 2011were lower than 0.20, and almost all precipitation depths greater than 20 mm (Figure 6A). The effect of herbaceous vegetation was not apparent for precipitation events of the class 30<CP≤50 mm. According to the results of precipitation events of the class CP≤30 mm, precipitation depths greater than 30 mm are needed to generate runoff in areas with thinned Caatinga forest (Figure 6A).

The vegetation cover did not affect the runoff coefficient in CP>50 mm (Figure 6C), confirming that, under extreme precipitation events, hydrological responses are defined by characteristics of the precipitation and soil moisture conditions and not only by the vegetation cover.

The significance analysis of the reduction of runoff coefficient in the two first classes of precipitation events by the Student's t-test (p<0.01), confirms the effect of vegetation cover on the runoff, with reduction of 20.1% for CP<30 mm (Figure 7).

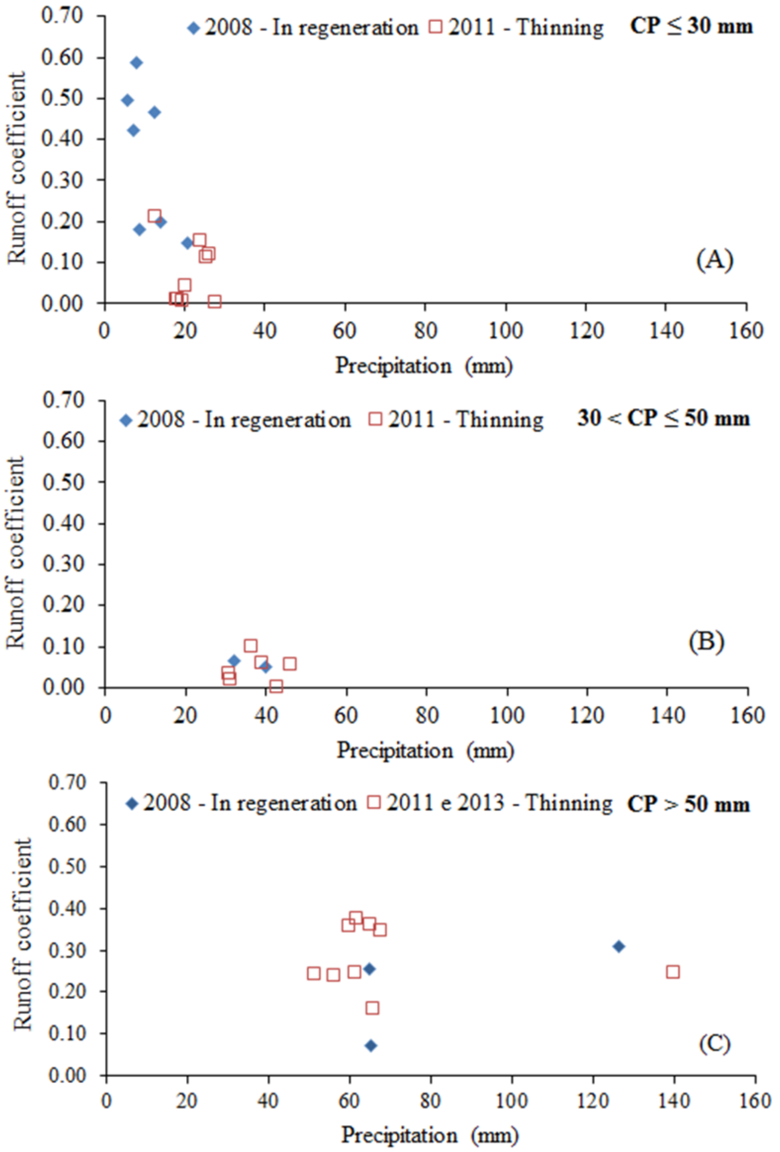
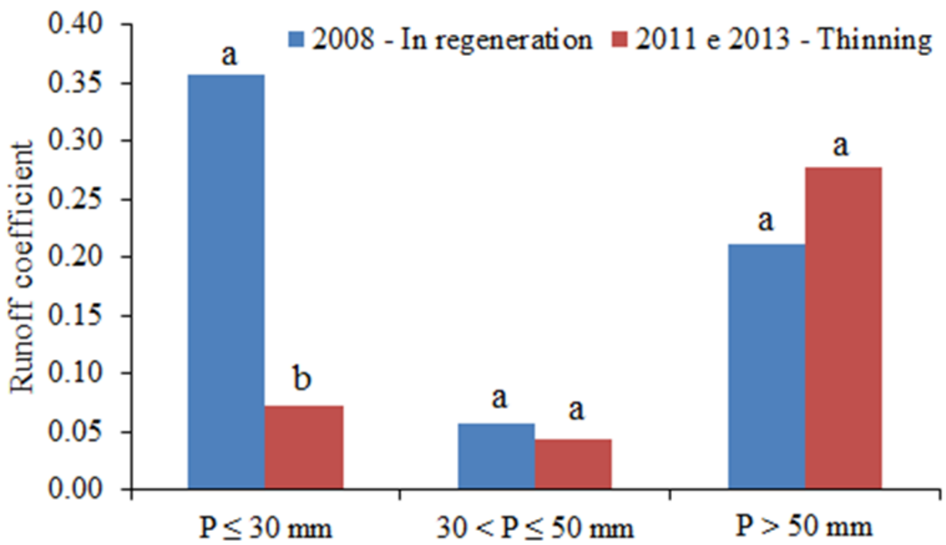


Figure 6. Relation between runoff coefficient and precipitation in the event scale for the studied watershed in the different classes of precipitation events (CP).



*Means followed by lowercase letters differ in the pair of bars by Student's t-test (p<0.01).

Figure 7. Average runoff coefficients for different classes of precipitation events (CP).

Vegetation cover has less effect on surface runoff due to precipitations depths greater than 30 mm, thus, these surface runoffs are due to other factors, which need to be studied addressing other processes that may be related with runoff. The lower runoff in precipitations below 30 mm due to the herbaceous vegetation grown after thinning (2011 and 2013) denotes the importance of this vegetation cover for the soil water retention and control of water losses due to runoff.

CONCLUSIONS

The thinning of the Caatinga forest resulted in significant reductions of surface runoff due to precipitation events lower than 30 mm, with greater effect in this class of precipitation events.

The runoff due to precipitation events of great magnitude (>50 mm) was more dependent on precipitation characteristics than on vegetation cover.

The herbaceous vegetation growth due to thinning resulted in loss of connectivity of surface flow, due to the obstruction of flow by the vegetation mass, with consequent reduction of flow speed and increase of infiltration of the water, requiring a greater precipitation depth to generate runoff.

ACKNOWLEDGEMENTS

The authors thank the National Council for Scientific and Technological Development (CNPq) for financial support and the Foundation for Scientific and Technological Development Support of Ceará (FUNCAP) for financial support through scholarships for production and scientific initiation.

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