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Research papers

Effect of dry spells and soil cracking on runoff generation in a semiarid micro watershed under land use change

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ABSTRACT

Soil and water resources effective management and planning in a river basin rely on understanding of runoff generation processes, yield, and their relations to rainfall. This study analyzes the effects of antecedent soil moisture in an expansive soil and the influence of dry spells on soil cracking, runoff generation and yield in a semiarid tropical region in Brazil subject to land use change. Data were collected from 2009 to 2013 in a 2.8 ha watershed, totaling 179 natural rainfall events. In the first year of study (2009), the watershed maintained a typical dry tropical forest cover (arboreal-shrub Caatinga cover). Before the beginning of the second year of study, gamba grass (*Andropogon gayanus* Kunth) was cultivated after slash and burn of native vegetation. Gamba grass land use was maintained for the rest of the monitoring period. The occurrence of dry spells and the formation of cracks in the Vertisol soil were the most important factors controlling flow generation. Dry spells promoted crack formation in the expansive soil, which acted as preferential flow paths leading to high initial abstractions: average conditions for runoff to be generated included soil moisture content above 20%, rainfall above 70 mm, I30max above 60 mm h^{-1} and five continuous dry days at the most. The change of vegetation cover in the second year of study did not alter significantly the overall conditions for runoff initiation, showing similar cumulative flow vs. rainfall response, implying that soil conditions, such as humidity and cracks, best explain the flow generation process on the semiarid micro-scale watershed with Vertisol soil.

1. Introduction

Water scarcity, high-intensity and low-frequency rainfall, and runoff generation uncertainties characterize semiarid regions. Soil moisture content (Castillo et al., 2003; Kishné et al., 2010) at the beginning of a rainfall event, rainfall duration and intensity play an important role in the runoff generating mechanisms (James and Roulet, 2009). Consecutive dry days (CDD) between rainfall events affect soil moisture (Aviad et al., 2009) and, consequently, soil infiltration capacity, which controls hydrological, geomorphological and ecological processes. After a rainfall event, evapotranspiration, drainage, and deep percolation processes regulate the water content in the soil and the initial conditions preceding the following event (Hardie et al., 2011).

Vertisols are most common in the semiarid tropics (Driessen et al., 2001; Kanwar et al., 1982), expanding when humid and contracting when dried, due to high contents of expansive 2:1 clay. Vertisols cover approximately 335×10^6 ha, of which 150×10^6 are potentially agricultural (Driessen et al., 2001). Most Vertisols are found in semiarid tropical regions with annual average precipitation from 500 to 1000 mm. Large extensions of Vertisols are present in Africa, Australia, South America, Southwestern United States, India and China (Driessen et al., 2001; Liu et al., 2010).

Cracks on expansive soils (clays 2:1) are key agents in processes such as infiltration, runoff, evapotranspiration and water

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redistribution in the soil profile (Kishné et al., 2010). Deep cracks formed in clay soils resulting from excessive drying, provide preferential flow paths and promote deep drainage even after sealing of the soil surface (Harmel et al., 2006; Greve et al., 2010; Dinka et al., 2013). Cracks due to soil dryness result in low agreement between the predicted and observed flow from rainfall events in watersheds with expansive clay soils (Harmel et al., 2006; Dinka et al., 2013).

The preferred flow of water enhances aquifer recharges and the groundwater storage, but has also negative environmental and health consequences, favoring transport of contaminants without the natural filtering from chemical and biological interactions with the upper layers of the soil (Allaire et al., 2009). This phenomenon contributes to the complex spatial and temporal variability of the redistribution of water in a landscape, and challenges surface hydrological modeling (Allaire et al., 2009; Kishné et al., 2010).

Although soil moisture data has many applications, field measurements are scarce (Aviad et al., 2009), being rainfall more commonly monitored in weather stations. Thus, indicators such as consecutive number of dry days (CDD) and consecutive number of wet days (CWD) are commonly used to represent antecedent soil moisture conditions (Guerreiro et al., 2013).

Dry spells are characterized by a period of continuous dry days during the rainy season, a condition that is frequent in the Brazilian semiarid region (Guerreiro et al., 2013). Among the many proposed criteria for definition of dry spells (Nasri and Moradi, 2011; Hernandez et al., 2003), in this study it was adopted a period of five or more CDD during the rainy season to be a dry spell. A day was considered dry if less than 1 mm of rainfall was registered (Nasri and Moradi, 2011; Hernandez et al., 2003).

The occurrence of dry spells and rainfall characteristics play key roles in flow generation and yield (James and Roulet, 2009; Calvo-Cases et al., 2003; Castillo et al., 2003), but studies to understand the processes associated with flow generation and yield in semiarid regions are still scarce. To the authors' knowledge, studies that relate dry spells and cracking of expansive soils to runoff generation processes are still missing. This experimental study was carried out in a 2.8 ha semiarid watershed with the following objectives: (i) assess the role of rainfall characteristics and soil cracks dynamics on runoff generation and yield; (ii) quantify the impact of land use change on runoff magnitude in a semiarid region.

2. Study area

The study was conducted in the Iguatu experimental watershed, located in the semiarid northeast region of Brazil with an average elevation of 218 m (Fig. 1).

The climate is BSw'h' type (hot semiarid), according to Köppen, with an average temperature always above 18 °C in the coldest month. The Thornthwaite aridity index is 0.49, also classifying the region as semiarid. The average value from 1974 to 2012 for potential evapotranspiration is 1802 mm yr^{-1}, based on the Penman-Monteith/FAO methodology and the historical average rainfall is 882 mm yr^{-1} for the same period (FUNCEME, 2016). Rainfall is concentrated from January to May, when 85% of total annual rainfall occurs, with 30% of the total being recorded in the month of March.

The experimental watershed has an area of 2.8 ha, with ephemeral streams of 1st and 2nd order and a gently undulated relief. Soil is a typical Calcic Vertisol (Pellic) (Krasilnikov et al., 2009), relatively deep (2–3 m) with a high content of silt (42.5%) and clay (26%) in the surface and subsurface layers (Table 1). Due to the type of clay (2:1 montmorillonite), surface cracks develop during dry periods.

3. Methods

3.1. Rainfall-runoff characteristics and soil cracks dynamics

Rainfall data were measured on 5-min intervals in an automatic weather station, from which rainfall magnitude (P), mean rainfall intensity and maximum thirty-minute intensity (I30) were obtained. Continuous dry days (CDD) prior to a runoff event were evaluated assuming a dry day as being a day with less than 1 mm of rainfall.

During the monitoring period (2009–2013), 179 rainfall events were recorded. A Parshall flume with an associated capacitive sensor was used to measure water level and to quantify discharges and total runoff at the watershed outlet.

Gravimetric soil moisture content was measured three times weekly in the hydrological year of 2009, and daily (with three replications) in the years 2010–2013. Soil samples were randomly collected throughout the watershed (with three replications) at a depth from 0 to 0.15 m.

Additionally, the antecedent soil moisture was characterized by the occurrence of dry spells, here defined as a sequence of at least five consecutive dry days during the rainy season.

To assess the extent and density of soil cracks in the dry season, measures of length, width and depth were taken in an area of 2×3 m, located in the lower third of the watershed, on an area of more gentle slopes. Fig. 2 shows the cracks in the soil during the dry season, in the area where the measurements were carried out.

3.2. Land use change

Two different land managements were applied during the study period in order to assess the impact of land use on flow generation and yield. In the first year of study (2009), the watershed maintained a typical dry tropical forest cover (Fig. 3A). Before the beginning of the second year of study, gamba grass (*Andropogon gayanus* Kunth) was cultivated after slash and burn of native vegetation (Fig. 3B). Gamba grass land use was maintained for the rest of the monitoring period (Fig. 3C). Hence, changes in flow generation and yield processes with the new vegetation were investigated.

In order to quantify the effect of land use changes on the hydrological behavior, rainfall and runoff were compared among the years during the study period with different land covers. Rainfall magnitude, consecutive dry days (CDD) and runoff data were used to group similar events using the hierarchical cluster analysis (HCA) multivariate statistical technique. Data were normalized (average = 0, standard deviation = 1) to eliminate the effect of scales and units of the selected variables on the analysis (Dillon and Goldstein, 1984).

4. Results

4.1. Rainfall-runoff characteristics and soil cracks dynamics

4.1.1. Rainfall and runoff magnitude

Analysis of the relationship between rainfall magnitude and runoff for individual events from 2010 (Fig. 4) suggest that rainfall up to 69 mm and I30 up to 75 mm h^{-1} may not generate runoff at the investigated watershed. Uncertainty about the runoff generation process can be attributed mainly to the low antecedent soil moisture, strongly influenced by the occurrence of dry spells, as will be further analyzed. Knowledge of total rainfall (P) and maximum 30-min rainfall (I30) is not enough to assess the occurrence of runoff nor its magnitude.

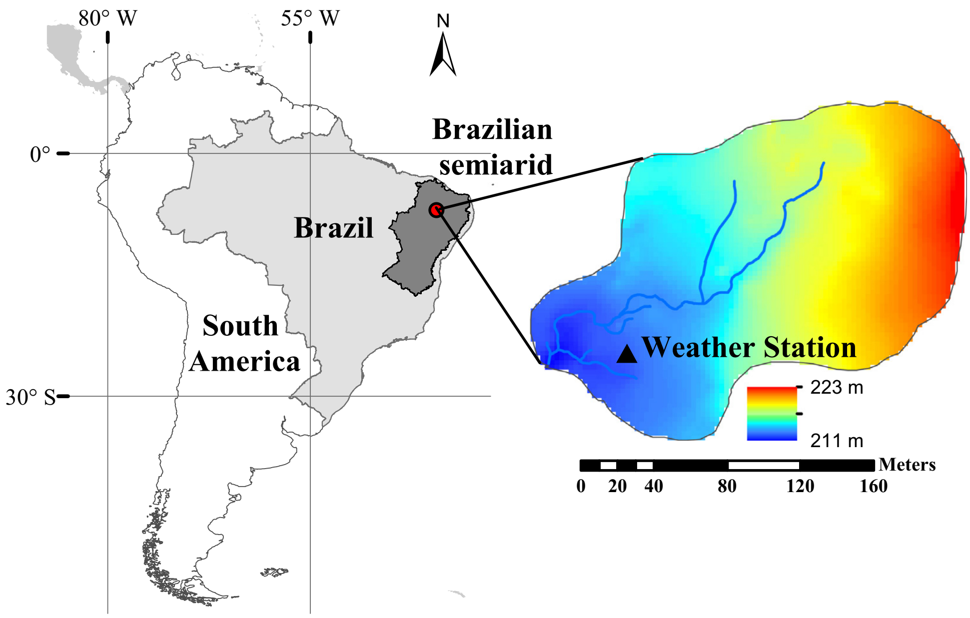

Fig. 1. Study area in the semiarid northeast of Brazil.

Table 1
Soil physical and chemical characteristics.

Horizon	A	B1	B2	C1
Depth (cm)	0–25	25–103	103–116	116–137
Physical parameters				
Sand (g kg^{-1})	315	291	166	322
Silt (g kg^{-1})	425	387	502	478
Clay (g kg^{-1})	260	322	332	200
Chemical parameters				
C (g kg^{-1})	8.31	5.75	5.44	3.86
pH	8.5	6.8	9.2	9.3
Ca ($cmol_c$ kg^{-1})	18	20	18	20.8
Mg ($cmol_c$ kg^{-1})	15.2	12.4	10	14.2
K($cmol_c$ kg^{-1})	0.21	0.19	0.23	0.21
Na ($cmol_c$ kg^{-1})	0.81	1.42	3.37	5.32
H + Al ($cmol_c$ kg^{-1})	2.6	2	1	1
$CaCO_3$ (g kg^{-1})	146	130	157	213
P assim (mg kg^{-1})	8	9	9	10
CE (dS m^{-1})	0.3	0.3	0.4	1
Saturated hydraulic conductivity Ksat (mm h^{-1})	6.5	0.44	–	–

Runoff generating rainfall events showed a moderate dispersion in runoff-rainfall relationship (Fig. 4A), with a Pearson correlation coefficient of 0.77. The runoff-I30 relationship showed higher dispersion, with an r = 0.61 (Fig. 4B). Events were also classified in terms of CDDs from last rainfall event (Table 2).

4.1.2. Runoff generation

As for the dry spells effect on runoff occurrence based on P, I30 and CDD, if a rainfall event occurred during a no dry spell or incipient dry spell (Table 2) flow generation was uncertain (Fig. 4). Flow never occurred when rainfall was less than 40 mm during a moderate or long dry spell (Table 2 and Fig. 5). As for a rainfall greater than 40 mm, flow always occurred when rain fell during a moderate dry spell, but no flow occurred if rain fell during a long dry spell, except for 18th Feb 2012, an event to be further analyzed in detail.

For these events, the antecedent soil moisture content (average of 30% for events with runoff, and a water holding capacity of Vertisols often within the range 30–50% - Driessen et al., 2001) and rainfall intensity (I30 average of 37 mm h^{-1} for events with runoff) were crucial in flow generation, as indicated in Fig. 6.

Soil moisture influences the occurrence of cracks in the Vertisol, thus altering the macroporosity and greatly changing infiltration rates. During the dry season of the year 2015, measurements in an area of 2×3 m indicated the existence of two cracks with lengths of 246 and 340 cm, with average widths of 8.2 and 10.9 cm, respectively. This totals 0.76 m^2 of cracks, representing 12.7% of the surveyed area. Average depths of the abovementioned cracks were 44.5 and 41.8 cm.

The effect of dry spells on flow generation was noteworthy for events with total rainfall below 20 mm, which represent 58% of all the events (Fig. 6).

Events occurring within less than five CDD were uncertain with respect to flow generation, and were dependent on soil moisture and rainfall characteristics such as magnitude and duration. Under these circumstances (CDD < 5), rainfall events below 40 mm did not generate runoff, except for five events to be further analyzed in detail. Five consecutive dry days has shown to reduce the soil

Fig. 2. Cracks in the soil during a dry spell.

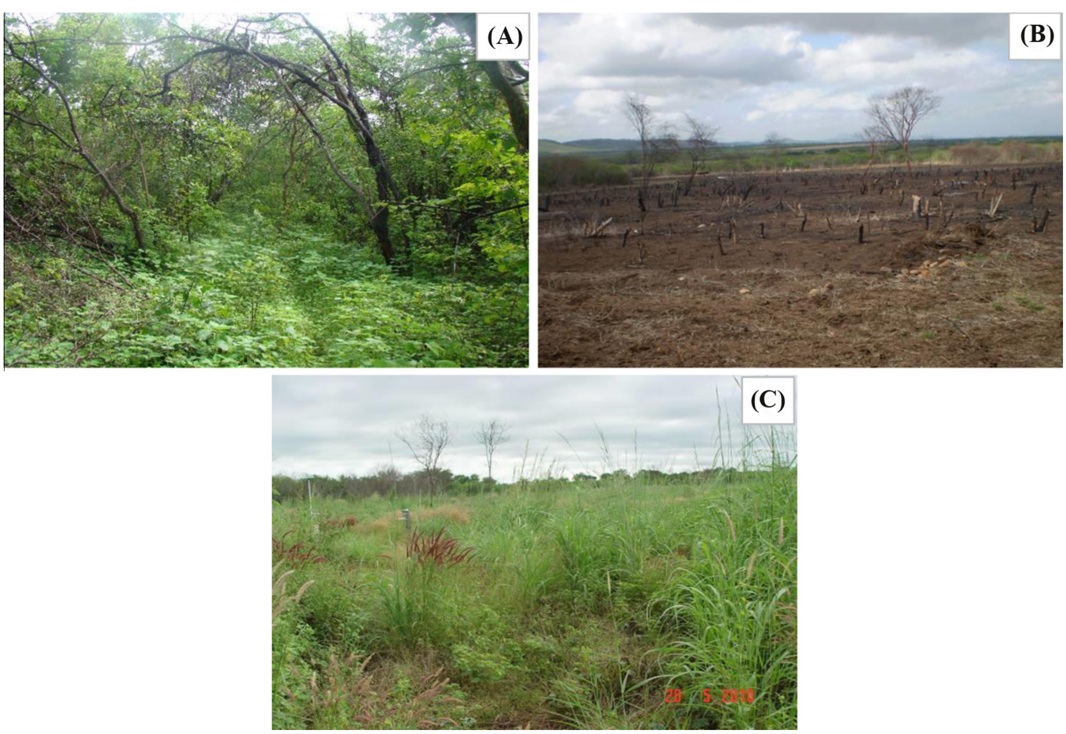

Fig. 3. Land use and soil in the experimental watershed: (A) tropical dry forest in 2009; (B) deforestation and burning in 2010; (C) *gamba* grass cover after 2010.

moisture significantly, mostly in the range of 8–25% as illustrated on Fig. 7, thus enabling soil cracking. In such conditions, these small magnitude events could not outweigh the thresholds to runoff generation.

Eighty-four percent of all rainfall events that exceeded 40 mm generated flow (Fig. 6), with five exceptions (Table 3). Events of this magnitude are more likely to overcome the initial abstractions and generate Hortonian flow depending on the rainfall intensity (average I_{30} of 54 mm h^{-1} for such events in this study). The exceptions were analyzed (Table 3), although the events that occurred after a dry spell of at least nine days were scarce and uncertain regarding flow generation. Except for the 26th Jun 2013 event, the no flow events were recorded at the beginning of the hydrological years.

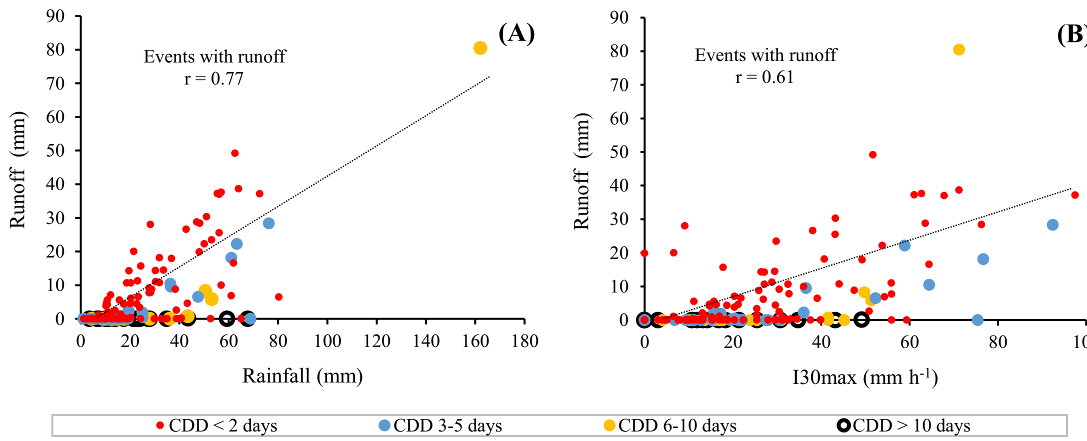

Fig. 4. Runoff versus rainfall magnitude (A) and runoff versus I30 (B) and relations with Consecutive Dry Day (CDD) at the experimental watershed.

Table 2
Dry spell classification based on CDD.

CDD	Classification
<2 days	No dry spell
3–5 days	Incipient dry spell
6–10 days	Moderate dry spell
>10 days	Long dry spell

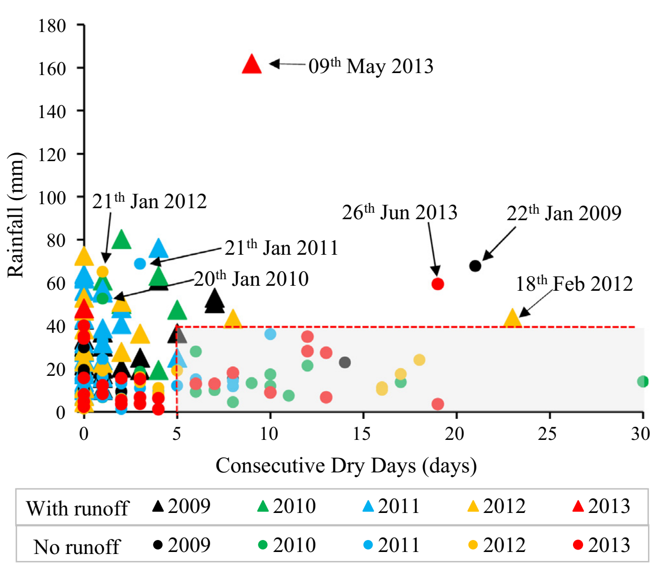

Fig. 5. Flow occurrence based on rainfall magnitude versus consecutive dry days at the experimental watershed.

On the other hand, the 44 mm rainfall event of 18th Feb 2012 was able to generate flow despite the 23 CDD (Fig. 5). Flow was generated due to the occurrence of six consecutive events that totaled 183 mm of rainfall prior to the CDD period. These events were capable of completely sealing the soil cracks and, despite the large CDD, generated a soil moisture content of 22%. Even though there was runoff, the dry spell effect was evident, because only 0.3% of the rainfall (0.13 mm) was converted into runoff.

The relationship between rainfall and I30 explains some flow generation (Fig. 8). Except for the 21th Jan 2011 event (beginning of the rainy season with low soil moisture), all rainfall events with magnitude above 40 mm and I30 higher than 40 mm h^{-1} or events with maximum I30 above 60 mm h^{-1} (23 events), generated flow. Flow generation was uncertain for the other rainfall events (Fig. 8), and could not be explained by these variables.

The effects of dry spells on runoff can be better observed in Fig. 9, in which an overall decrease in runoff with increasing CDD is evident. An outlier stands out at 9th May 2013, because of the exceptionally high rainfall magnitude and intensity (P = 162 mm and I_{30} = 71 mm h^{-1}), although it occurred after nine CDD. As already stated, the 18th Feb 2012 event generated little flow.

Three distinct regions stand out upon analysis of runoff occurrence based on total rainfall, I30 and soil moisture content (Fig. 6), (i) runoff generating events; (ii) no-runoff events; and (iii) uncertainty about the runoff generation. It indicates that events below 70 mm or I30 lower than 60 mm h^{-1} and soil humidity below 20% do not generate runoff. For rainfall events below 20 mm or I30 less than 20 mm h^{-1}, the limit soil moisture condition under which no runoff occurs is 25%. Nonetheless, rainfall events over 70 mm or I30 greater than 60 mm h^{-1} have always generate runoff, regardless of the antecedent soil moisture content. Other runoff generating events cannot be explained by the relationships between rainfall characteristics and antecedent soil moisture.

4.2. Land use change

4.2.1. Clustering analysis

Based on HCA, the 179 rainfall events were classed into four groups (Table 4 and Fig. 10). Groups 1 and 3 represent the events that hardly overcame the magnitude of the initial abstractions: Group 1 is composed of low rainfall events and Group 3 is composed of high CDD (low soil moisture content). Group 2 represents high rainfall events and high antecedent moisture content, leading to runoff generation. As for Group 4, it represents the event of 9th May 2013, with high magnitude and intensity, which overcame initial abstractions and generated high surface runoff despite the relatively high CDD (Fig. 10).

All the groups (except group 4, with only 1 event) presented events of the years pre and post vegetation suppression, burn and cultivation of grass, indicating that the land use change was not a clustering factor and, therefore, it is not determinant for the runoff magnitude. This result emphasizes the hypothesis that soil characteristics, particularly soil moisture content and soil cracks have great influence on water yield in the study area.

4.2.2. Accumulated rainfall and runoff

In 2009, under native dry tropical forest cover, the flow initiated in the wet period after an accumulated rainfall of 102 mm in previous events and soil moisture content of 22% (Table 5 and Fig. 11). On the onset of the rainy season, initial abstractions are increased

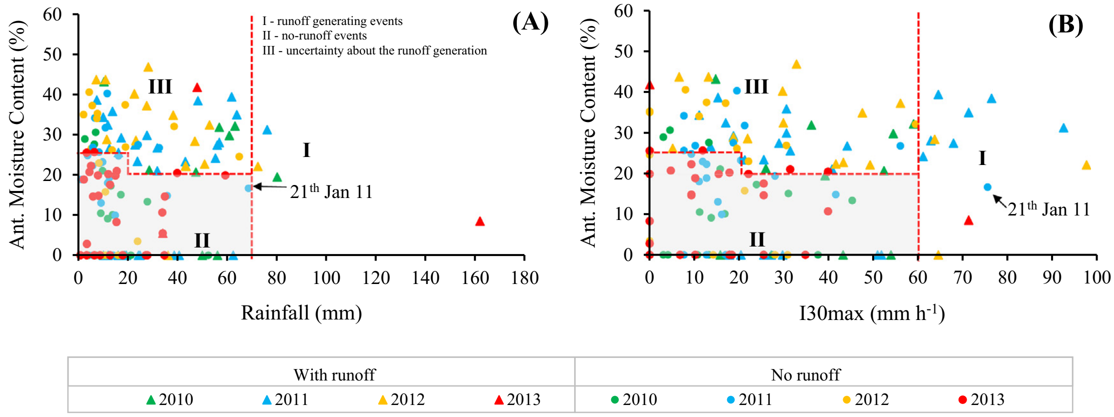

Fig. 6. Flow occurrence based on total rainfall versus soil moisture content (A); and soil moisture content versus I30 (B) at the experimental watershed.

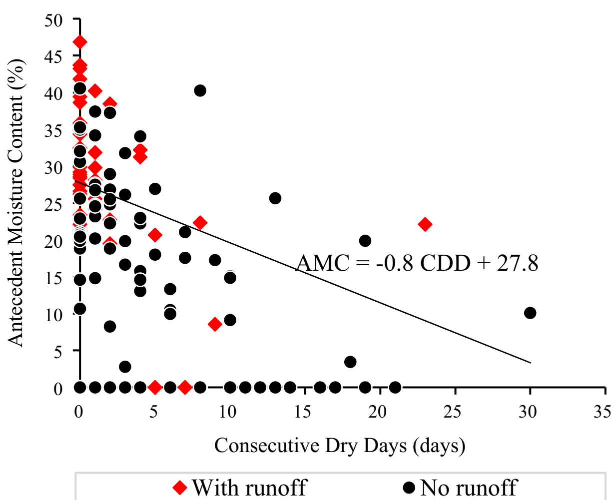

Fig. 7. Antecedent soil moisture content versus consecutive dry days at the experimental watershed.

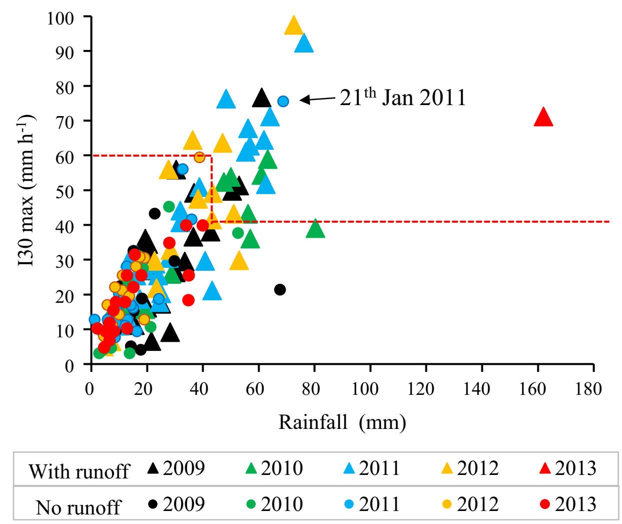

Fig. 8. I30 versus rainfall magnitude at the experimental watershed.

due to the 2:1 expansive montmorillonite clay and the formation of cracks on the dry soil, resulting in the need of significant accumulated rainfall for the cracks sealing and prevention of water loss through the preferential flow pathways. After 44 days of the first runoff event, total accumulated rainfall was 410 mm and only 45 mm of runoff was observed (Fig. 11A). This hydrologic response resulted from the occurrence of five dry spells with durations from five to 59 days in that period, resulting in a reduction of soil moisture content below 20% and the generating of cracks. After 13th Apr 2009, 13 rainfall events totaled 346 mm, with one occurrence of 7 CDD, which raised the soil moisture up to 23% and produced 199 mm of accumulated flow.

In 2010, after burning and gamba grass cultivation followed total deforestation, a total of 100 mm of rainfall occurred before flow generation (Fig. 11B) like in the previous year (Table 5). Low runoff depth was observed in the periods with high occurrence of dry spells (Fig. 11B). During the periods with concentrated rainfall events, the cumulative rainfall increased from 240 mm to 626 mm, and the cumulative runoff from 29 mm to 113 mm (Fig. 11B). During this period the soil moisture was always above 20%. After this interval, an additional 2.5 mm of accumulated runoff was the result of an accumulated 85 mm of rainfall derived from eight events interleaved by five dry spells with durations of 6, 7, 8, 10, and 12 days.

In the years following grass cultivation (2011, 2012, and 2013), a total of 138 mm, 90 mm and 314 mm, of rainfall was needed for runoff generation at the beginning of the wet season (Fig. 11). Runoff generation is linked to dry spell occurrence. This behavior is evident in 2013, when runoff was generated only after the occurrence of two extreme events (11 dry spells were registered). Just like in 2009 (native dry tropical forest land use) and 2010 (total

Table 3
Events that did not generate runoff with total rainfall > 40 mm.

Date	Land use	P (mm)	CDD (days)	I30 (mm h^{-1})	Soil moisture	OBS
22th Jan 2009	Native dry tropical forest	68	21	21	Not measured	1st rainfall event
20th Jan 2010	Total deforestation burning and grass cultivation	53	1	37	10%	2nd rainfall event
21th Jan 2011	Fully grown grass	69	3	75	17%	5th rainfall event
21th Jan 2012	Fully grown grass	65	1	75.5	24%	2nd rainfall event
26th Jun 2013	Fully grown grass	59	19	65	20%	28th rainfall event

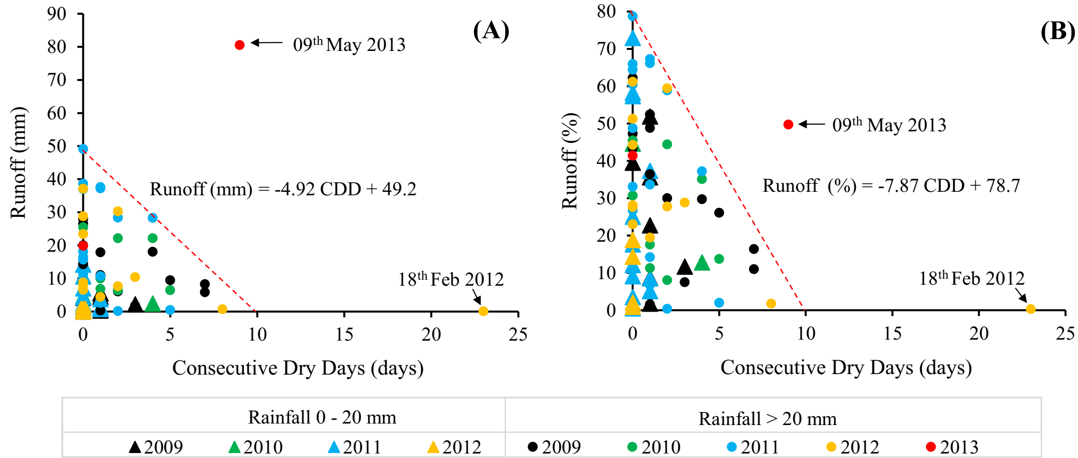

Fig. 9. Runoff versus Consecutive Dry Days at the experimental watershed.

Table 4
Hierarchical clustering analysis output.

Group	Number of events	Average rainfall (mm event^{-1})	Average runoff (mm event^{-1})	Average CDD prior to runoff event (days)	Average antecedent moisture content (%)
1	156	20	2.5	3	26
2	18	55	30.0	1	31
3	4	46	0.1	23	10
4	1	162	80.5	9	[a]

[a] Not measured antecedent moisture content for this event.

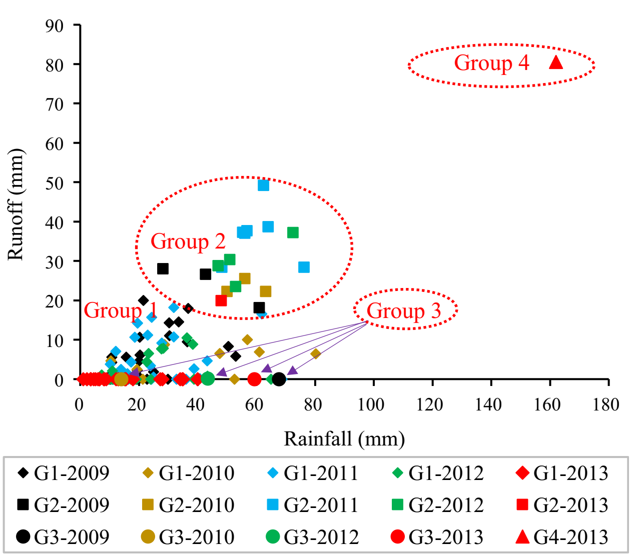

Fig. 10. Hierarchical cluster analysis - runoff versus rainfall.

deforestation, burning and grass cultivation), the following years showed similar hydrologic behavior, increasing runoff in the concentrated rainfall period and low runoff in the sparse rainfall and dry spells period.

Fig. 12A indicates similar trends of the accumulated flow as a function of the accumulated rainfall in the five years of monitoring. For periods of concentrated rainfall events, the slope coefficients of the linear regressions are similar, varying from 0.40 to 0.59 for the

Table 5
Summary of annual rainfall and runoff indices from first rainfall of the season until 1st runoff event before (2009) and after land use change (2010–2013).

Year	Land use	Accumulated rainfall (mm)	NDS	AMC (%)	NWD to	NDD to
2009	Native dry tropical forest	102	2	22	2	29
2010	Total deforestation, burning and grass cultivation	100	3	29	4	36
2011	Fully grown grass	139	2	23.4	7	16
2012	Fully grown grass	90	1	29	2	19
2013	Fully grown grass	314	10	8.6	24	105

NDS – number of dry spells; AMC – antecedent soil moisture content; NWD - number of wet days; NDD - number of dry days after the occurrence of the first rainfall event of the rainy season.

different years studied (Fig. 12B). Such behavior indicates that there were no significant changes in the hydrological response of the watershed in terms of runoff magnitude, despite the vegetation changes in 2010. The horizontal lines in Fig. 12A correspond to the occurrence of dry spells, in periods when negligible runoff occurs, as illustrated on Fig. 11.

5. Discussion

5.1. Rainfall-runoff characteristics and soil cracks dynamics

Surface runoff was uncertain in the study area regarding rainfall magnitude and consecutive dry days (Fig. 5). The soil of the study area is a Vertisol with 2:1 minerals that expand (swell) when wet, and shrink when dry. These changes in volume that accompany the soil moisture variation promote deep cracks during dry spells and very plastic and sticky soil consistency when wet. The high clay content is associated with low permeability, but high water adsorption, and resulting high initial abstractions when dry. Spohr et al. (2009) observed that surface runoff in Vertisols was lower than non-expansive soils like Argisols and Chernosem when the soil was dry and cracked.

For instance, large rainfall events at the onset of the wet season, like the 22th Jan 2009 (67.7 mm), 20th Jan 2010 (52.6 mm), 21th Jan 2011 (68.8 mm), and 21th Jan 2012 (65.0 mm) were not able to generate runoff (Fig. 5) because the soil was cracked due to the dry precedent season (Fig. 6A). This cracking process develops preferential flow paths, leading to abstraction of rainfall and may lead to deep drainage even after cracks are replenished (Greve

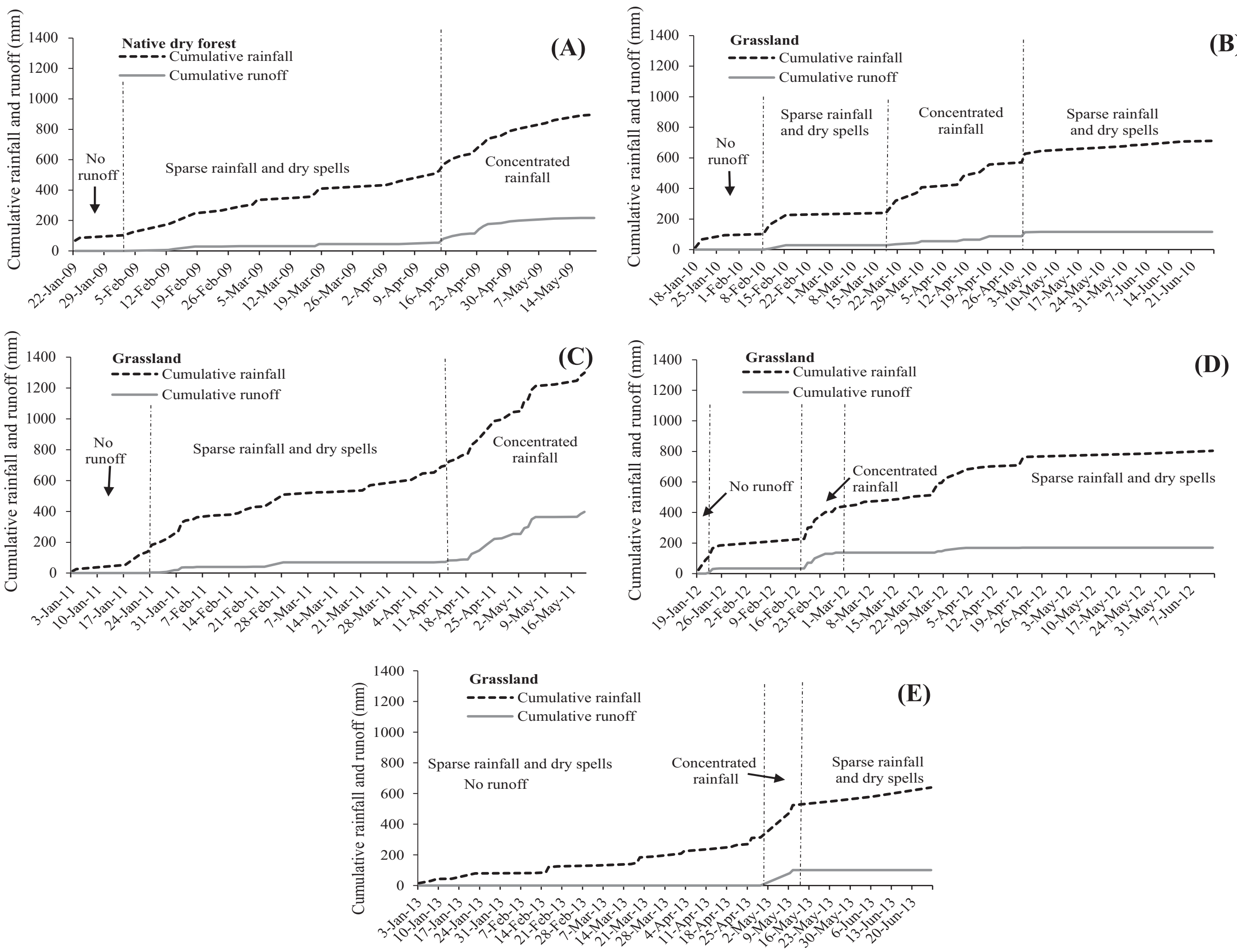

Fig. 11. Cumulative rainfall and surface runoff (2009–2013).

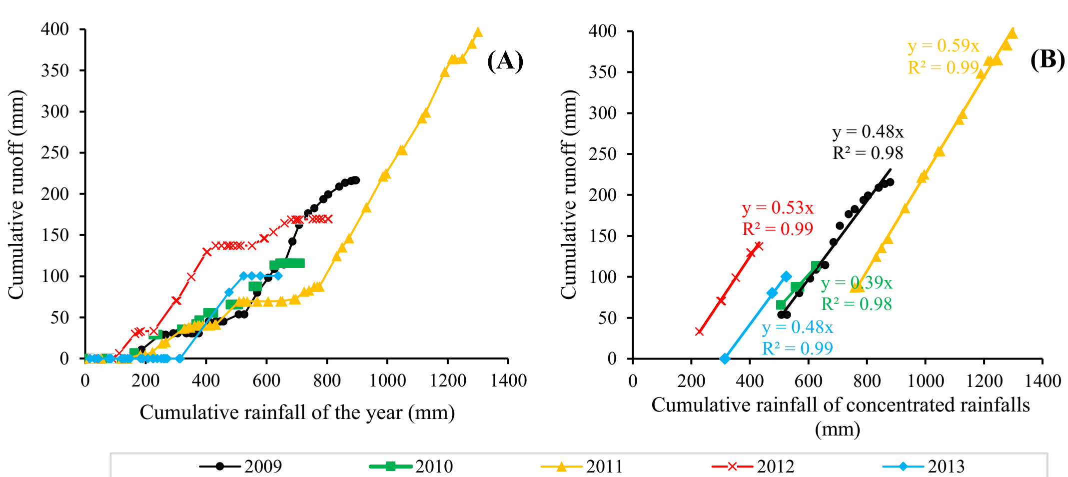

Fig. 12. Accumulated runoff as a function of accumulated rainfall (A) and highlight to the periods of concentrated rainfall events (B), for the years during the study period (*correlations significant to the level of 0.01).

et al., 2010). Therefore, wide and deep cracks in the vertisol lead to high infiltration capacity and water retention during the first rainfall events of the season (Zhang et al., 2014; Dinka et al., 2013; Li and Zhang, 2011; Hardie et al., 2011; Greve et al., 2010; Kishné et al., 2010; Allaire et al., 2009; Harmel et al., 2006).

Cracks and the preferential flow effect from large rainfall events were observed particularly in the 21th Jan 2011 (68.8 mm) event which, although presenting a high I30 (75.5 mm h^{-1}), did not generate flow (Fig. 6). This event was characterized by low soil moisture content (Fig. 6) and high hydraulic conductivity due to the dryness and the development of the cracks, enhancing the macroporosity, as observed by Liu et al. (2003) and Zhang et al. (2014).

Rainfall events below 40 mm and over five CDD did not overcome the preferential paths and did not generate runoff (Fig. 5). Rainfall events preceded by several CDD found a cracked soil with greater opportunities to preferential infiltration, decreasing or even preventing the runoff generation (Fig. 9). After soil cracking, soil water evaporates in two dimensions – vertically by soil surface and horizontally at the walls of the cracks (Li and Zhang, 2011). Because evaporation rate in two dimensions is higher than in one dimension, cracks develop faster in the primary phase.

The 18th Feb 12 (44 mm and I30 of 49 mm h^{-1}) event (Figs. 8 and 9) generated partial sealing of soil cracks and little surface runoff was generated (0.3 mm). Sealing of cracks occurs partially or totally, generating preferential active and non-active flow paths, and cracks change location or reappear during the wet and dry cycles (Greve et al., 2010). Those processes explain the uncertainties of flow generation for specific rainfall events. Fig. 8 shows that, as rainfall magnitude and intensity increase, the probability of total infiltration of rainfall and the lack of runoff is reduced.

Monitoring of CDD (Fig. 9), and antecedent moisture content (Fig. 6) increased understanding on flow generation in the semiarid experimental watershed. The graphs highlight the thresholds of generating and non-generating runoff events and indicate that, in general, events preceded by many CDD (Fig. 5) do not generate runoff due to abstraction caused by cracks. Dinka et al. (2013) confirmed a high retention capacity by cracks in vertisols in the state of Texas (USA). These authors concluded that rainfall around 40 mm either generated or did not generate runoff depending on the soil cracks. In wet soils, when the infiltration rate is reduced, runoff coefficient duplicates comparing to the same soil under dry condition (Hardie et al., 2011).

All rainfall events greater than 70 mm generated runoff (Fig. 6), despite antecedent soil moisture content. During these high magnitude events, hillslope-stream connectivity increased, maximizing the effective contributing area, which increased flow accumulation and runoff energy (Fryirs et al., 2007). When surface runoff is predominantly Hortonian, response is more uniform and is less dependent on the initial soil moisture content (Castillo et al., 2003). These events tend to seal surface cracks (Greve et al., 2010), overcome preferential flows and generate surface runoff (Fig. 4). Nonetheless, soil cracks may still be preferential flow paths even if cracks are sealed (Greve et al., 2010). These results imply that runoff responds better to total event rainfall, due to the increase in hydrological connectivity during higher magnitude rainfall events.

5.2. Land use change

Rainfall characteristics and temporal distribution show a rainfall-runoff relationship in three distinct periods (Fig. 11): the first period characterizes the necessary rainfall to increase soil moisture content until flow is generated; the second period has frequent dry spells and low flow generation; the third period has concentrated rainfall events and a fast increase in cumulative runoff.

It is clear from Fig. 11 that the general hydrologic behavior was characterized by a rapid runoff response to concentrated rainfall and low runoff in periods of frequent dry spells. This result was reinforced by the hierarchical cluster analysis (Fig. 10), in which all years are represented in all groups (except for Group 4, which is composed of only one event), therefore, indicating that land use change is not the major factor controlling the hydrologic behavior of the watershed.

It is important to note that the constant trend on the hydrological response to rainfall occurred along the entire study period, despite the severe land use changes: total deforestation, burn and grass cultivation. Influence of land use changes on processes like rainfall interception could not be detected from the runoff measured data, even though such losses are not negligible. In the natural dry tropical forest vegetation, the interception losses in the study area in the year 2010 accounted for 18% on average, ranging from 28% to 14% of the rainfall for events bellow 10 mm and above 40 mm, respectively (Izidio et al., 2013). Since most low magnitude events do not generate runoff, this higher water input has little influence, while for the higher magnitude events, the interception losses are of less relative importance.

Medeiros et al. (2010) observed that the spatial pattern of runoff magnitude is similar to that of the soil distribution in a semiarid, 933 km^2 watershed in Brazil, indicating that the soil characteristics are more effective than land use in determining the surface flow. This observation is in accordance with the temporal pattern of runoff: first runoff generating rainfall events were of low flows, whereas, runoff that occurred after a sequence of wet days presented higher magnitude flow. Figueiredo et al. (2016) investigated runoff generation in a preserved dry tropical forested 12 km^2 watershed in the semiarid region of Brazil and concluded that the infiltration threshold approaches the river-bank saturated hydraulic conductivity, indicating that the soil is the primary control for runoff initiation. The expansive characteristic of the soil in the study area explains this behavior (Zhang et al., 2014; Dinka et al., 2013): after the occurrence of the first rainfalls, soil moisture increases and clays expand, reducing macroporosity and preferencial flows, favoring surface flow. Therefore, flow generation in the watershed is highly dependent on antecedent rainfall and soil cracking status, being less influenced by the land use.

According to Table 5 and Figs. 11 and 12, a minimum of approximately 100 mm of rainfall is necessary for surface runoff to initiate on the onset of the rainy season in the five years of study, despite the land use changes. These initial rainfall events seal part of the cracks (Zhang et al., 2014; Dinka et al., 2013; Li and Zhang, 2011; Hardie et al., 2011; Greve et al., 2010), which were formed over the dry period (over six months with no rainfall). In deeper soils, Calvo-Cases et al. (2003) demonstrated that soil saturation occurs after 110 mm of rainfall and saturation excess overland flow occurs.

In 2013, a total of 314 mm accumulated rainfall was needed to initiate runoff (Table 5 and Fig. 11), due to frequent dry spells (eleven dry spells totaling 105 dry days). Frequent occurrence of CDD avoided sealing of the cracks, exposing rainfall to preferential infiltration paths in the soil. Runoff was registered in only two events of high magnitude (162 mm and 48 mm – Figs. 5 and 6), intensity and duration.

Despite land use changes at the end of 2009, Fig. 11B shows that rainfall events interspersed with dry spells have little effect on cumulative runoff. Throughout the five years of study, the largest increment was verified after consecutive wet days, due to wetting of the soil and sealing of surface cracks.

6. Conclusion

Monitoring of rainfall and runoff during a 5-years period on a 2.8 ha semiarid watershed with expansive vertisol, characterized by the formation of cracks when dry, and under land use change, allowed the following conclusions:

1. The initial soil moisture and resulting soil cracks in the expansive soil explain initial abstractions and resulting flow generation and yield.
2. The temporal variability of rainfall is the underlying factor in flow generation in the semiarid region throughout the study period: runoff initiated on the onset of the rainy season after

an initial cumulative rainfall of at least 100 mm, capable of increasing soil moisture and sealing the soil cracks developed in the preceding dry period.

3. Soil cracks generate preferential flow paths and high infiltration, reducing runoff even for high magnitude rainfall events: rainfall that occurred after wet days lead to flow generation, whereas rainfall that occurred after dry spells lead to little increments of runoff.
4. Vegetation plays a secondary role on flow initiation in the study area with expansive clay soils. Furthermore, land use change seems not to be the major factor controlling the hydrologic response to cumulative rainfall in terms of runoff magnitude.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2016.08.016. These data include Google maps of the most important areas described in this article.

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