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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.