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Characteristics of the surface–subsurface flow generation and sediment yield to the rainfall regime and land-cover by long-term *in-situ* observation in the red soil region, Southern China

Yao-Jun Liu, Jie Yang *, Jian-Min Hu, Chong-Jun Tang, Hai-Jin Zheng

Jiangxi Provincial Key Laboratory of Soil Erosion and Prevention, Nanchang 330029, China
Jiangxi Institute of Soil and Water Conservation, Nanchang 330029, China

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SUMMARY

Land cover and rainfall regime are two important factors that affect soil erosion. In this paper, three land cover types – grass cover, litter cover and bare land – were employed to analyze surface runoff, subsurface flow and sediment loss processes in relation to the rainfall regimes in the red soil region of China. Five rainfall regimes were classified according to 393 rainfall events via a k-means clustering method based on the rainfall depth, duration and maximum 30-min intensity. The highest surface runoff coefficient and erosion amount were found on bare land in all five rainfall regimes, and the lowest were found on grass cover. The litter cover generated the highest subsurface flow rate, followed by the grass cover; the lowest was on bare land. For grass cover and litter cover plots, rainfall events of rainfall regime IV which had the longest duration, greatest depth and lowest intensity had the highest surface runoff coefficient, soil erosion amount and subsurface flow rate. For bare land, storm rainfall events of rainfall regime V had the highest intensity, lowest depth and duration, had the highest surface runoff coefficient and soil erosion amount, but the lowest subsurface flow rate. The highest subsurface flow rate of bare land happened in rainfall regime IV. Surface cover was urgently needed to reduce soil erosion. When the lands under dense surface cover, more attention should be paid to rainfall events that of long duration, high depth but low in intensity which commonly occurred in spring. The interactions of surface–subsurface flow and its effects on soil erosion and nutrient loss were worth considering in the red soil region.

1. Introduction

A high land use rate accompanied by serious soil erosion is present in the red soil region of Southern China (Shi et al., 2008; Liang et al., 2009, 2010). Farmlands and orchards are two important land use types in the red soil region, and both experience heavy runoff and sediment loss during the rainy season (Zheng et al., 2008, 2014; Liang et al., 2010). Many studies have demonstrated that both runoff and sediment loss decreased exponentially in a wide range of environments as the percentage of vegetation cover increased (e.g., Francia Martínez et al., 2006; Cerdà, 2007; Desir and Marín, 2007; Shi et al., 2012; Liu et al., 2014). The addition of surface cover by using litter or living plants has been a worldwide approach to control soil erosion on cultivated lands (e.g., Valentin et al., 2008; Morgan, 2009; Shi et al., 2012; Bosch et al., 2012).

Land cover provides a buffer that prevents the direct exposure of the soil to rain drops, retarding splash erosion and concentrated flow erosion (Kinnell, 2005). The presence of land cover was beneficial for maintaining soil moisture (Zhang et al., 2016) and the micro-environment (Hesslerová et al., 2013; Ngo-Mbogba et al., 2015), which was very advantageous for crop growth in a changing environment. The role of land cover in surface rainfall–runoff processes and sediment loss has attracted much attention and has been well reviewed (Gyssels et al., 2005; Wei et al., 2007; Valentin et al., 2008; Shi et al., 2012), but little attention has been paid to the effects of land cover on subsurface flow generation. Subsurface flow is an important rainfall flow component in the red soil region (Zheng et al., 2014). In some extraordinary rainfall events, the output of subsurface flow even exceeded surface flow and became the major process of water loss (Xie et al., 2015).

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* Corresponding author at: No. 290, Qingshanhu South Road, Qinhshanhu District, Nanchang City, Jiangxi Province 330029, China. Tel.: +86 0791 88828193; fax: +86 0791 88828162.

E-mail addresses: liuyj461@163.com (Y.-J. Liu), zljyj@126.com (J. Yang), hjmhx@jxsl.gov.cn (J.-M. Hu), tangchongjun@126.com (C.-J. Tang), haijinzheng@163.com (H.-J. Zheng).

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A variety of approaches have been used to investigate subsurface flow, such as trench investigation (e.g., Kirkby, 1988) and hydrographic separation technique by natural isotopes (e.g., Sklash et al., 1986), which are commonly used in large-scale field investigations. The dye-tracer testing method (Nobles et al., 2010), time domain reflectometry (Fu et al., 2012) and ground penetrating radar (Leh et al., 2008) have been useful at the plot scale or in simulations. The results of subsurface flow during simulations or single rainfall events are greatly important for a deep understanding and model predictions; however, long-term, *in-situ* investigation provides data that more closely approximate the actual situation. Seasonally distinct rainfall patterns in a subtropical humid climate (Yin et al., 2014) and vertical soil layers in red soil that vary in their hydrological response cause the characteristics of subsurface flow to significantly differ from those of other regions, such as karst (Li et al., 2011) or purple soil region (Fu et al., 2012). In general, long-term field observations of surface–subsurface flow generation have been relatively scarce in the red soil region, so more data were necessary for erosion and nonpoint source pollution control and water resources management.

The subsurface flow was highly variable depending on the surface permeability and topography, soil water content and vegetation (Fu et al., 2015; Williams, 2008). The rainfall regimes also played a vital role in affecting the surface flow and sediment loss in the Loess Plateau (Wei et al., 2007), and research by Huang et al. (2010) in the red soil region also indicated that surface flow and soil loss differed significantly between rainfall regimes, similarly to the results of Fang et al. (2012) and Peng and Wang (2012). However, the impact of rainfall regime on the subsurface flow was neglected in that research. The results from single rainfall events or simulated rainfall demonstrated that rainfall intensity and depth were the two main rainfall indexes that altered the subsurface flow (Fu et al., 2012; Xie et al., 2015). Research on the effect of rainfall regimes on subsurface flow loss is needed for a better understanding of hydrological-erosion processes due to rainfall.

In this study, runoff plots in the red soil region received three land cover types: grass cover, litter cover and bare land. *In-situ* field observations comprising 393 rainfall events during 11 years were selected and classified into five rainfall regimes based on the rainfall depth, duration and maximum 30-min intensity. The principal goals were to analyze the characteristics of the surface–subsurface flow generation and sediment yield under the different land cover types and rainfall regimes; identify the effects of the land cover and the rainfall regime on the surface–subsurface flow and soil losses and determine the characteristics of subsurface flow under different land covers.

2. Methods and materials

2.1. Area of study

The study was conducted in the Yangou watershed (29°16′N to 29°17′N, 115°42′E to 115°43′E), which is located in the Jiangxi Eco-Science Park of Soil and Water Conservation, 5 km southeast of De'an county in Jiangxi province (Fig. 1). The area studied is characterized by a subtropical humid monsoon climate zone and a long-term annual precipitation of 1500 mm. The rainy season occurs from April to September, during which >70% of the total rainfall occurs. The annual temperature of this region is 17 °C, the highest monthly temperature occurs in July and the lowest in January. The region has approximately between 245 and 260 frost-free days. The altitude ranges from 30 to 90 m.

The red soil in this region was primarily produced from the weathering of Quaternary sediments. The soil depth in the study area was over 100 cm, and the profile type was Ah–Bs–Cs according to *Soil Taxonomy* (ISSAS, 2001; IUSS Working Group, 2014). The surface layer (Ah) depth was 25–30 cm, and the Bs layer appeared at a soil depth of 30–60 cm. The soil bulk density in the Ah layer was 1.05–1.32 g cm^{-3}. High erosion intensity is characteristic of the Ah layer because of its loose structure and high precipitation; in many places, the entire Ah layer had been lost to soil erosion. The soil bulk density of the Bs layer was much higher than that of the Ah layer and had an average value of 1.48 g cm^{-3}. The water infiltration rate was low in the Bs layer.

2.2. Plots and measurements

Three 15-m-long × 5-m-wide × 1.00-m-deep *in-situ* runoff plots were installed on a 14° slope. Cement walls 1.00 m deep were constructed around the plots to isolate hydrological disturbances from adjacent plots. Three types of land cover were used in this study: grass cover, litter cover and bare land. The grass used on the grass cover plot was *Paspalum natatu*, a perennial warm-season grass species, and the grass was seeded at a high density to produce a full surface cover. A 5-cm-deep litter layer was placed on the surface to reduce soil erosion. The litter came from mowing the *P. natatu*, and the litter cover layer was maintained in every three months for the decade. The surface of the bare land plot was not loosened, had no cover and was weeded every three months.

To test the surface and subsurface flow on the red soil with different land covers, two runoff storage containers were set in the bottom of the plots. The container volume for the surface flow was 3 m^3 by the five-hole shunt method, and the container volume for subsurface flow was 1 m^3. The outlet of the subsurface flow was set at a soil depth of 60 cm at the bottom of the Bs layer. An *L*-type subsurface flow collector was inserted into the soil at the outlet section of the runoff plot, and the subsurface flow was transferred from the runoff plot into the runoff storage container by a pipe connected to a hole that in the *L*-type subsurface flow collector (Fig. 2). Plot construction and grass planting were finished in 2000, and the runoff and sediment observations under natural rainfall began in 2001. A repair period of 15 months last from 2000 to 2001 year was set to moderate the disturbances of plot construction, so the data used in this paper began in 2002.

2.3. In-situ observation

The surface flow and sediment subsurface flow generated from the plots were collected and transported into the associated runoff storage containers. An auto-recording water level gauge was installed in each container to record the runoff depth at 5 min. The sediment samples were collected after each rainfall event and analyzed by weighing in the laboratory after oven drying at 105 °C for 24 h. For the lag of subsurface flow, a erosive rainfall event was not considered independent unless the interval times over 12 h or more after the last rainfall event and of average rainfall intensity >2.4 mm h^{-1} (Xie et al., 2002).

Precipitation in the study area was measured by an automatic meteorological station 50 m from the runoff plots. The start and end time of a rainfall event, the rainfall intensity and the raindrop size distribution were recorded.

2.4. Clustering approach and statistical analysis

A clustering approach is a convenient and fundamental tool in statistical analysis and is widely used in many fields (Yeh et al., 2000). This approach places objects into clusters based on statistical similarities of their properties in a variable pattern, so objects in the same cluster are statistically similar to each other, and objects in different clusters tend to be dissimilar (Johnson and Wichern, 1992).