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Effects of subsequent rainfall events with different intensities on runoff and erosion in a coarse soil

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ABSTRACT

A deeper understanding of the hydrological response to subsequent rains would be useful in the prediction of runoff production for planning vegetation restoration and assessing flood risks. We used subsequent rains to study the role of rain intensity and antecedent soil moisture content (ASMC) on runoff and erosion for coarse soil of the semiarid Loess Plateau in China. The study used a rain simulator in a field planted with alfalfa (*Medicago sativa*), which is widely grown for animal feed to develop livestock operations, reduce soil erosion, and improve soil fertility/quality. A slope of 18% was selected because most of the land with slopes < 18% in the region is used for cropland. We tested three rain intensities (20, 40, and 60 mm h^{-1}, corresponding to low, moderate, and high intensities, respectively) with five successive rains (an initial and four subsequent rains) in triplicate. We quantified the changes of runoff depth (RD), sediment yield (SY), and sediment concentration (SC) over time and then analyzed the relationships between ASMC and runoff in 0–50 cm soil layers for all 45 simulated rains. Runoff commencement time (RCT) was shorter, the runoff coefficient (RC) was larger, and runoff was higher for the moderate and high intensities than the low intensity. Intermittency and the characteristics of the sequential rains also influenced these processes. A general linear model identified significant effects of rain sequence and intensity on RCT, RD, RC, SY, and SC ($P < 0.01$), but their interaction did not have a significant effect on RCT and SY. An exponential fit between ASMC and RC was best for the 0–10 cm and 10–20 cm layer ($R^2 = 0.38$, $P < 0.000$), and R^2 decreased from the 0–20 cm to the 30–40 cm layers. Soil moisture content (SMC) was an important factor controlling runoff, and the sequential rains led to high runoff and sediment transport, because runoff from storms on highly permeable soils is controlled by the saturation of the topsoil horizon and is more dependent on initial conditions.

1. Introduction

Heavy but brief local rainstorms, irrational land use, and the soft and loose soils of the Loess Plateau are responsible for runoff and soil erosion, especially where schemes of soil conservation have not been widely used (Shi and Shao, 2000; Fu et al., 2017). Recent studies, however, have challenged these conclusions. Both river discharge and sediment yield across the plateau have been reported to have decreased pronouncedly over the last several years (G.J. Zhao et al., 2013a; Y.G. Zhao et al., 2013b; Wang et al., 2014; He et al., 2017), and human activities have had a greater impact than climate change on runoff changes (Gao et al., 2016; Wu et al., 2017). Reductions of runoff and soil erosion have been important components of environmental changes on the plateau, so understanding the mechanisms behind these changes are crucial for developing strategic plans for the sustainable management of soil erosion in watersheds, which is becoming an important issue in the region (Fu et al., 2017). Vegetation coverage generally plays an important role in rainfall-runoff processes (Zheng, 2006; Jin et al., 2009; Duan et al., 2016). Runoff and sediment yield tend to decrease (linearly or exponentially) with increasing plant coverage (Arnau-Rosalén et al., 2008; Mohammad and Adam, 2010; Xin et al., 2011). Vegetation coverage has increased substantially in most regions of the Loess Plateau in recent years when a series of measures of soil and water conservation, including terracing, forestation, grass restoration, and the conversion of sloping farmland to forest or grassland, under the national Grain for Green program were implemented (Wang et al., 2011; Liu et al., 2014).

Vegetation restoration, though, can affect the soil water resources of the plateau (Chen et al., 2007). For example, long-term alfalfa production may severely deplete soil water and phosphate in 0–100 cm and even in 2–10 m profiles, which can lead to the desiccation of loessial soils (Fan et al., 2004, 2010). Feng et al. (2016) reported that the new plantings have increased both net primary productivity and evapotranspiration. The increase in evapotranspiration has also induced a

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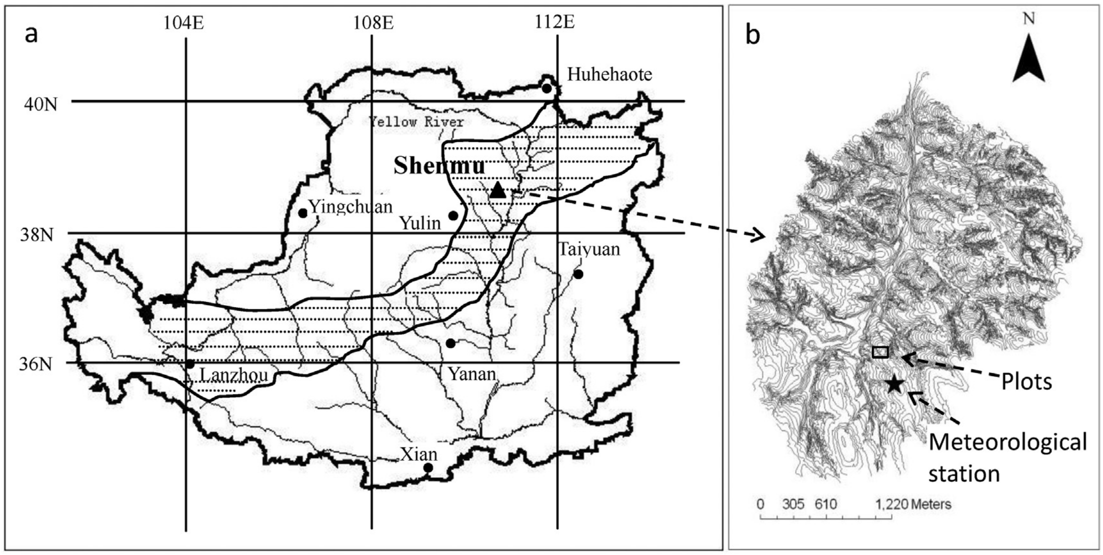

Fig. 1. Location of study catchment on the Loess Plateau (a) and meteorological station, field plots at the Shenmu Erosion and Environmental Station (b).

significant ($P < 0.001$) decrease in the ratio of runoff to annual precipitation across hydrological catchments. The conditions of soil moisture can affect the partitioning of rainwater into infiltration, consequently influencing runoff and soil erosion (Zonta et al., 2012). Liu et al. (2011) found that infiltration capacity was lower under higher ASMC. Water infiltration decreased in experimental plots with increasing antecedent SMC (ASMC) at a depth of 10 cm, which produced more runoff and sediments (Wei et al., 2007). The effects of SMC on runoff and soil erosion must therefore be considered, especially in semiarid environments where water resources are scare. Many studies have thus investigated the interaction between SMC and soil erosion at different scales (Calvo-Cases et al., 2003; Khaledi Darvishan et al., 2015; Sachs and Sarah, 2017). Western and Grayson (1998) demonstrated that the surface runoff in a catchment was controlled by SMC, with a threshold of 41–46%, depending on the depth over which the SMC was averaged. Zhang et al. (2011) determined the effects of ASMC on runoff generation in a semiarid environment by process-based modeling and found an average change of 0.05 mm in runoff for each 1% change in SMC. Castillo et al. (2003) and Scherrer et al. (2007), however, reported that runoff response did not depend on ASMC when infiltration-excess overland flow was predominant. The effects of soil moisture on runoff formation are therefore still not clear, especially for coarse soil with a dry profile.

Rain frequency and the timespan between two rains are important factors for infiltration, runoff, and soil loss (Erpul and Çanga, 1999; Römkens et al., 2001). The characteristics of natural rains at a hillslope scale (total rainfall and rain intensity) and antecedent precipitation are the main variables affecting the runoff depth and coefficient (Li et al., 2011). Findell and Eltahir (1999) found a positive correlation between subsequent rainfall and ASMC. SMC is an important factor affecting the loss of nitrogen in northeastern China, because erosion-induced pollution is dominant (Ouyang et al., 2017). Ran et al. (2012) analyzed a series of rains of different durations with no dry intervals, comprising an initial rain with initially dry soil and a multiple-peak intermittent rainfall pattern; the sediment concentration (SC) decreased over time as erodible particles were washed away, and the SC increased until stabilizing for low/moderate intensity rains because runoff was low and erosion was transport-limited. Sadeghi et al. (2016) reported significant effects ($P < 0.01$) of a sequence of rains on runoff commencement time (RCT), runoff depth (RD), a runoff coefficient (RC, the runoff:precipitation ratio), and sediment yield (SY) and a non-significant effect ($P = 0.13$) on SC when considering the durability of the effects of soil amendments during subsequent rains.

Climate change can have direct and indirect impacts on soil erosion, with many influencing factors. Higher rainfall, rain intensity, and frequency of extreme rains can directly increase soil erosion (Feng et al., 2015; Li and Fang, 2016; Anache et al., 2018). Rain characteristics become more variable and stochastic under climate change condition, which increases the uncertainties and risks of water erosion in China (Li et al., 2015; Feng et al., 2015; Zhang et al., 2018). Heavy or continuous rains with high rainfalls may trigger surface runoff and induce major flood hazards (Dehotin et al., 2015; Ries et al., 2017). For example, two continuous rains in 2012 and 2017 on the Loess Plateau in China led to extreme soil erosion (Wang et al., 2016, 2017).

The characteristics of soil erosion and runoff after vegetation restoration should therefore be identified for heavy or continuous rains. We studied the effects of subsequent rains on hydrologic components to advance our understanding of the role of SMC in the reduction of water and soil erosion during vegetation restoration on the plateau. Other objectives were to assess the effects of ASMC on runoff and SY during five successive rains at three intensities and to determine the relationship between ASMC and RC to identify the threshold of notable runoff.

2. Materials and methods

2.1. Description of the study area

The study was carried out at the Shenmu Erosion and Environmental Station on the Loess Plateau in northern Shaanxi province, China (Fig. 1) in July and August 2015. The catchment has a size of 6.9 km^2, an elevation of 1094.0–1273.9 m a.s.l., and a mean slope of 27%. The average annual precipitation is about 437.4 mm. The minimum and maximum monthly temperatures average 3.1 and 13.8 °C, respectively. The watershed is characterized by a semiarid continental monsoon climate with precipitation mostly from June to September (Zhu and Shao, 2008; Fan et al., 2010), most of which falls during highly intense storms, so soil erosion predominately occurs in this period.

The study area was in a 900-m^2 alfalfa field with a mean slope of 10°. The alfalfa was planted a year before as part of the Grain for Green program. The main characteristics of the plant cover and soil are presented in Table 1.

2.2. Experimental materials and design

The experiments were conducted in the field using a portable