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Response of soil detachment rate by raindrop-affected sediment-laden sheet flow to sediment load and hydraulic parameters within a detachment-limited sheet erosion system on steep slopes on Loess Plateau, China

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ABSTRACT

The response of soil detachment rate by raindrop-affected sediment-laden sheet flow to sediment load and hydraulic parameters was investigated within a detachment-limited sheet erosion system on steep slopes to understand sheet erosion processes fully and derive an accurate experimental model. An experiment was conducted at slopes of 12.23%, 17.63%, 26.8%, 36.4%, 40.4% and 46.63% under rainfall intensities of 48, 60, 90, 120, 138 and 150 mm h^{-1}, respectively, by using simulated rainfall. Results showed that the soil detachment rate by raindrop-affected sediment-laden sheet flow decreased as the sediment load by sheet flow increased, and the decrease was a power function of sediment load by sheet flow with $NSE = 0.58$, $MSE = 0.0099$ and $R^2 = 0.58$. In addition, the soil detachment rate by raindrop-affected sediment-laden sheet flow increased as a linear function of shear stress, stream power and unit stream power. Shear stress and stream power could be used to predict the soil detachment rate by raindrop-affected sediment-laden sheet flow accurately through a linear equation. Stream power ($R^2 = 0.87$, $MSE = 0.003$ and $NSE = 0.87$) was a better predictor of soil detachment rate by raindrop-affected sediment-laden sheet flow than shear stress ($NSE = 0.83$, $MSE = 0.004$ and $R^2 = 0.83$). However, prediction based on unit stream power ($NSE = 0.43$, $MSE = 0.01$ and $R^2 = 0.43$) was poor. These findings can improve our understanding and modelling of sheet erosion processes on steep slopes in the loess region of China.

1. Introduction

Soil erosion is a serious global environmental problem that can lead to land degradation and landslides (Nowak and Schneider, 2017; Xu et al., 2018; Xu and Coop, 2017; Mekonnen et al., 2015; Heathcote et al., 2013; Ali et al., 2011; Karlen et al., 2003; Lal, 1998). The Loess Plateau in northwest China is one of the areas worldwide that suffered from serious soil erosion in recent decades (Zhao et al., 2013; Liu et al., 2012a; Shi and Shao, 2000). Soil erosion is commonly divided into rill erosion and interrill or sheet erosion (Meyer and Wischmeier, 1969; Laflen et al., 1991). Sheet erosion is one of the major erosion processes in the Loess Plateau of China (Liu et al., 2012b). Ellison (1944, 1947a,b,c) defined sheet erosion as “a process of detachment and transportation of soil particles” and reported that soil detachment by rainfall, transport by rainfall, detachment by runoff and transport by runoff are separate but interrelated phases of the process of soil erosion by water. Kinnell (2000, 2001, 2006) also identified four detachment and transport systems operating in sheet erosion; these four are raindrop detachment and splash transport, raindrop detachment and raindrop-induced flow transport, raindrop detachment and sheet flow transport and sheet flow detachment and sheet flow transport. However, most researchers have suggested that raindrop detachment (i.e. soil detachment is caused by raindrop impact), splash transport and sheet flow transport are the major processes for sheet erosion (Wan et al., 1996; Sutherland et al., 1996; Van Dijk and Bruijnzeel, 2003; Kinnell, 2006; Fu et al., 2011; Defersha et al., 2011; Zhang and Wang,

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2017). The third process (i.e. detachment by runoff) reported by Ellison (1944, 1947a,b,c) and the fourth process (i.e. sheet flow detachment and sheet flow transport) reported by Kinnell (2000, 2001, 2006) cannot appear in a sheet erosion system. According to Wu et al. (2018), sheet flow detachment is concealed in the sheet erosion system on steep slopes of Loess Plateau in China. Accordingly, detachment by raindrops and raindrop-affected sediment-laden sheet flow and sediment transport by raindrop-affected sheet flow are the dominant processes (i.e. detachment-limited processes). Gao et al. (2005) suggested that raindrop impact contributes considerably to soil erosion by enhancing soil detachment and water flow disturbance. Thus, assessment of soil detachment rate by raindrop-affected sediment-laden sheet flow in a detachment-limited erosion system is essential in deeply explaining sheet erosion processes on steep slopes in the Loess Plateau of China.

Soil detachment and sediment transport by water flow are crucial erosion processes, and a change in the sediment load transported by water flow during erosion leads to soil detachment from the soil body via sediment-laden flow (Nearing et al., 1999; Zartl et al., 2001; Govers et al., 2007; Wells et al., 2010). Understanding how soil detachment rate responds to the actual sediment load by water flow is essential in revealing the mechanism of soil erosion. Many researchers have suggested that detachment-limited processes occur in rill erosion. Thus, the effects of sediment load on soil detachment rate by rill flow have been extensively studied in literature (Van Liew and Saxton, 1983; Nearing et al., 1990; Govers, 1990; Nearing et al., 1991; Nearing and Parker, 1994; Foster et al., 1995; DeRoo et al., 1996; Nearing et al., 1999; Zhang et al., 2003; Govers et al., 2007; Zhang et al., 2008; Wang et al., 2016; Hai et al., 2017). However, studies that examined the effect of sediment load on the soil detachment rate by raindrop-affected sediment-laden sheet flow are scarce. Soil detachment by water flow is controlled primarily by flow hydraulics and soil properties (Liu et al., 2016; Chen et al., 2016; Su et al., 2014). Flow hydraulics control the process of soil detachment (Li et al., 2015; Zhang et al., 2003; Govers, 1992). Most studies have revealed the effect of hydraulic parameters on soil detachment rate by rill flow. However, studies on the effect of hydraulic parameters on soil detachment rate by raindrop-affected sheet flow are limited. Given this situation, the response of soil detachment rate by raindrop-affected sediment-laden sheet flow to sediment load and hydraulic parameters needs to be determined and evaluated. The objectives of the present study are to evaluate the effect of sediment load on soil detachment rate by raindrop-affected sediment-laden sheet flow and identify the best hydraulic parameter in relation to soil detachment rate. The results can provide a scientific basis for soil erosion control in the Loess Plateau.

2. Materials and methods

2.1. Experimental soil

Experimental soil was collected from a depth of 0–25 cm at the farming cropland layer in Ansai County (109°19′ E, 36°51′ N) of Shaanxi Province, China, located in the northern part of the Loess Plateau. The experimental soil was classified as typical loessial soil, which is the most common soil type on the Loess Plateau, and it is highly erodible and susceptible to erosive forces. The soil consisted of 36.21% sand (diameter: 0.05–2.0 mm), 55.3% silt (diameter: 0.002–0.05 mm) and 8.49% clay (diameter: < 0.002 mm).

2.2. Experimental setup

Experiments were conducted in the Simulation Rainfall Hall operated by the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at the Institute of Soil and Water Conservation, Chinese Academy of Sciences, and by the Ministry of Water Resources in Yangling, Shaanxi Province, China. A rainfall simulator system with nozzles on two sides was used to reproduce simulated rainfall (Fig. 1).

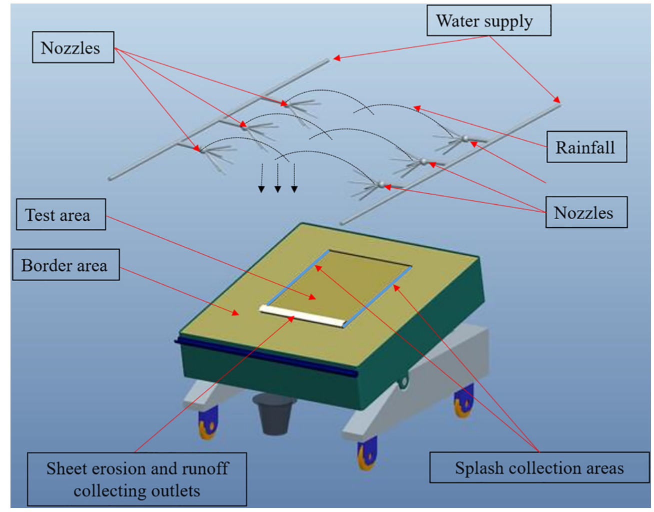

Fig. 1. The experimental setup and rainfall Simulator.

Nozzles with 7, 9, 11 and 13 mm of aperture diameter were fixed on both sides of the rainfall area and served as side-spraying simulated rainfall nozzles. The design institution of nozzles was Yellow River Institution of Hydraulic Research in Zhengzhou, Henan Province, China (Zhou et al., 2000). A specific rainfall intensity corresponded to the specific water pressure and aperture diameter of the nozzles, which were calibrated after the facilities were fixed and before they were used in the Simulated Rainfall Hall. The fall height of raindrops sprayed from the nozzles was approximately 16 m above the soil surface in all the experiments. The raindrop diameters of the simulated rainfall ranged from 0.125 to 6.0 mm, and the raindrop median volume diameters were 1.52–2.7 mm. The dispersed raindrops with different diameters were precisely created by adjusting the aperture of the nozzle orifice and the water pressure. The simulated rainfall, with uniformity higher than 85%, exhibited a similar raindrop size and distribution as natural rainfall.

An experiment soil pan with metal frames was utilised. The soil pan was 140 cm long, 120 cm wide and 25 cm deep and included test, border and splash collection areas. The test area, which was the collection area for runoff and sheet erosion, was 80 cm long, 60 cm wide and 25 cm deep. A 35 cm wide border area around the test plot was filled with soil in the same manner. Two splash collection areas (80 cm long and 2.5 cm wide) were attached to the left and right sides of the test area and served as the collection area for splash erosion. The slope gradient for this soil pan could be adjusted between 0% and 84%. Primary sheet erosion occurs when the slope exceeds 17.63%, and the slope of 46.63% is the largest observed for returning farmland to forest (Tang et al., 1998). Thus, we designed five slope gradients within this range in the Loess Plateau of China. We considered the scenario that sheet erosion still exists when the slopes are less than 17.63%. Hence, we added a slope gradient of 12.23%. These six slope gradients, namely, 12.23%, 17.63%, 26.8%, 36.4%, 40.40% and 46.63%, can help us perform an effective statistical analysis. Soil erosion in the Loess Plateau where the research area is located is produced by rainstorm. The rainfall intensity for an hour of rainfall ranges from 11.9 mm h^{-1} to more than 250 mm h^{-1} (Wang and Jiao, 1996). Thus, six rainfall intensities (48, 60, 90, 120, 138 and 150 mm h^{-1}), which are within the range of the actual rainfall intensity in the Loess Plateau of China, were selected in this study.

Before packing the soil, its water content was adjusted to 14%, which is the typical level during the flood season on the Loess Plateau when most erosion occurs (Liu et al., 2012a). A bulk density of 1.2 g cm^{-3} was designed for the study. A 5 cm thick natural sand layer was packed at the bottom of the soil pan to enable free drainage of excess water. It consisted of 2.58% clay (diameter: < 0.002 mm), 3.94% silt