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Effect of stem basal cover on the sediment transport capacity of overland flows

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ABSTRACT

Vegetation cover can effectively prevent soil erosion and plays an important role in soil and water conservation. Accurate estimation of the sediment transport capacity (*Tc*) is critical for soil erosion models. *Tc* data for different levels of vegetation cover, however, are quite limited. The objectives of this study were to evaluate the influence of stem basal cover, slope gradient and discharge on the transport capacity of overland flows for *Tc* prediction. A non-erodible flume (5 m long and 0.37 m wide) was used in this study. The discharge ranged from 0.5×10^{-3} to $2 \times 10^{-3}\,\mathrm{m^3\,s^{-1}}$, the slope gradient was from 8.8% to 25.9% and an artificial stem basal cover of 0, 1.25%, 2.5%, 5%, 10%, 15%, 20%, 25% and 30% was used to represent the natural vegetation. Stems 2 mm in diameter were randomly arranged. The sediment size for the experiment ranged from 0.25 to 0.59 mm with a median diameter of 0.35 mm. The results show that the measured *Tc* decreased exponentially as the stem basal cover increased, and the rate of decrease was far greater than what has been reported in the literature. The transport capacity was affected more by the stem basal cover than by slope and discharge when the cover exceeded approximately 2–3%. The research shows that the surface or stem basal cover plays a critical role in reducing the transport capacity of overland flows.

1. Introduction

Soil erosion is a global issue because of its severe adverse economic and environmental impacts. Soil erosion is defined as the process of detachment and transport of soil material by erosive agents (Ellison, 1947). The rate of soil erosion depends mainly on the detachment of soil particles and the transport capacity of overland runoff (Borrelli, 2013; Julien and Simons, 1985; Lal, 1998). Sediment transport capacity is the maximum sediment load that a flow can carry given particular discharge, slope, surface roughness, and sediment size, among other conditions (Huang et al., 1999; Li and Abrahams, 1999; Zhang et al., 2009). Sediment transport capacity is pivotal to sediment delivery and deposition, and its determination is widely considered and implemented in soil erosion models (De Roo, 1996; Mahmoodabadi et al., 2014a; Nearing et al., 1989; Yu et al., 2015; Zhang et al., 2009).

Many studies of the sediment transport capacity have been undertaken and several equations for calculating the sediment transport capacity of overland flows have been developed (Abrahams et al., 1998; Ali et al., 2012; Finkner et al., 1989; Govers, 1990; Guy et al., 2009; Wu et al., 2018; Zhang et al., 2009). Different experimental materials and methods to measure the transport capacity have been used to simulate natural overland flows. Experimental materials include mainly non-cohesive soil (Ali et al., 2012; Zhang et al., 2009) and cohesive soil (Lei et al., 2001; Mahmoodabadi et al., 2014a). The main methods include non-erodible (Zhang et al., 2009; Zhang et al., 2011b) and erodible bed conditions (Ali et al., 2012; Lei et al., 2001; Mahmoodabadi et al., 2014a). Different hydraulic variables have been used to determine the sediment transport capacity. One of the most frequently used variables is the shear stress (Ali et al., 2012; Finkner et al., 1989; Govers et al., 1992; Zhang et al., 2009). Foster and Meyer (1972) found that the Yalin equation (Yalin, 1963) was suitable to determine the transport capacity of overland flows based on the basic runoff transport capacity equation in the erosion model of Meyer and Wischmeier (1969):

$$\tau = \rho g R S \tag{1}$$

where τ is the shear stress of flow (Pa), ρ is the water mass density ($\mathrm{kg\,m^{-3}}$), g is the acceleration due to gravity ($\mathrm{m\,s^{-2}}$), S is the slope

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steepness, or the tangent of the slope angle ($\mathrm{m\,m^{-1}}$), and R is the hydraulic radius (m). Bagnold (1966) believed that the flow would use available energy to transport the sediment; stream power, or the energy expenditure per unit time, could therefore be an important variable that determines the sediment transport capacity (Bagnold, 1966; Li and Abrahams, 1999; Mahmoodabadi et al., 2014a; Yu et al., 2015; Zhang et al., 2009):

$$\omega = \tau V \tag{2}$$

where ω is the stream power ($\mathrm{kg\,s^{-3}}$), V is the mean flow velocity ($\mathrm{m\,s^{-1}}$), and τ is the shear stress of flow (Pa). In addition, the effective stream power (Ali et al., 2012; Everaert, 1991; Govers, 1990), unit stream power (Ali et al., 2012; Govers, 1990; Shih and Yang, 2009) and discharge and the slope gradient (Govers and Rauws, 1986; Julien and Simons, 1985; Prosser and Rustomji, 2000; Zhang et al., 2009) are commonly used to represent the flow hydraulics to calculate the transport capacity. Not only different hydraulic variables have been used to predict the transport capacity of overland flows, parameter values to quantify these relationships area also different, mostly because of the different soils and sediments used; of the differences in experiment design, particularly the range of flow rate and slope steepness, and of other conditions that are not well controlled such as surface roughness and soil properties.

Vegetation, which is effective in preventing soil erosion, plays an important role in soil and water conservation (Braud et al., 2001; Pan et al., 2010; Rogers and Schumm, 1991; Zhang et al., 2011a; Zhao et al., 2016). Vegetation effectively reduces rainfall energy and runoff and increases land surface roughness, which decreases flow velocity (Fathi-Maghadam and Kouwen, 1997; Liu et al., 2013; Nanson and Beach, 1977; Wu et al., 2011; Zhang et al., 2018). The results presented by Pan and Shangguan (2006) indicate that the above-ground parts of grasses significantly decreases the sediment yield. The relationship between vegetation cover and soil erosion has been described using both linear and exponential functions (Noble, 1965; Ouyang et al., 2010; Wischmeier, 1959; Zhou et al., 2006). The relationship between vegetation cover and soil erosion under different land-use patterns is shown in Table 1. These studies were conducted mainly under rainfall and using field plots with gentle slopes. The slope gradient was constant for these studies, and the effect of the slope gradient was measured continuously throughout the simulated rainfall event (Pan et al., 2010). An exponential decay function has been extensively used to describe the decrease in soil erosion with vegetation cover for different rainfall intensities (Table 1). Traditional studies of vegetation cover considered the combined effect of leaves and stems, while the separate effect of canopy cover or that of stem basal cover on soil erosion has not been extensively investigated. Zhao et al. (2016) finds that vegetation stems function as the dominant roughness element in overland flow, and they greatly control soil erosion. Soil loss is most severe from cultivated land on steep slopes in China and elsewhere in the world. The land surface in cultivated areas is covered mainly with crop stems. Crop stems can intercept runoff and decrease soil erosion effectively once the overland flow has formed. Thus, vegetation stems may greatly impact the transport capacity of overland flows, especially on cultivated land. However, few studies have examined the effect of vegetation stems on the transport capacity of overland flows.

The objectives of this study are to quantify the effect of vegetation stems on the transport capacity of overland flows for a range of discharge and slope steepness, to better understand the mechanism underlying the role of above-ground vegetation stems in soil and water conservation, and to aid in the design of effective vegetation measures to control soil erosion on steep cropland. In addition, this study provides a complete experimental data set as a reference and such a data set could be used to test and improve the prediction accuracy of soil erosion models.

2. Materials and methods

2.1. Experimental conditions and treatments

This study was conducted at the Fangshan experimental station of Beijing Normal University. The experiments on the sediment transport capacity of overland flows were carried out in a flume (5.0 m long and 0.37 m wide) with a smooth Plexi-glass floor and glass walls (Fig. 1). The bed slope of the flume could be manually adjusted from 0 to 60%. The flume consisted of a 2.4-m-long section covered with vegetation stems and a 2.3-m-long bare section with a layer of sieved sediment, the top 0.3 m was used to house the water tank. To simulate the effect of vegetation stem on the sediment transport capacity of overland flows, Gramineae stems were chosen to ensure that the vegetation stems could protrude through the overland flow. The Gramineae stems all had a diameter of 2 mm and a total height of 12 mm. The stems were artificial and had similar flexibility to those from natural vegetation stems. Moreover, the Gramineae stems can be reused. The basal cover and layout of Gramineae stems can be more easily controlled than those of natural vegetation stem. According to the typical vegetation cover on the Loess Plateau, China, the stem basal cover used in this study was approximately 0, 1.25%, 2.5%, 5%, 10%, 15%, 20%, 25% and 30% and were controlled by the total number of stems and the stem diameter (Table 2). For each level of plant basal cover, a plastic mesh with punched holes was used to secure the artificial Gramineae stems, and the mesh was then placed on the flume bed covered with oil paint. A thick layer of the sieved sand was added into the paint to increase the bed roughness. The stems were glued to the flume bed when the paint was dry, and the bed material for areas not covered with stems was the same as that used for the experiment to measure the sediment transport capacity. The stems were arranged in a random pattern (Fig. 2a), and the stem basal cover of 30% brought about nearly 100% canopy cover (Fig. 2b). The bare ‘ground’ between the stems (70%) cannot be seen from above the artificial stems because the artificial Gramineae stems are flexible enough to conceal the bare ground surface for a closed canopy.

Sand-laden flow was supplied to the flume to fully simulate overland flow on a natural slope. The sediment, which was collected from the bed of the Yongding River near Beijing, was air dried and first passed through a 2 mm sieve to remove gravel and residues. The sand that passed through 0.59 mm sieve but not 0.25 mm sieve was used as the experimental material. The particle size distributions of the experimental sand are presented in Table 3; the median diameter (d_{50}) was 0.35 mm.

The experimental flume was adjusted to 8.7%, 17.4% and 25.9%, which correspond to the common slope gradient found in the Loess Plateau region. Three discharges were used, i.e., 0.5×10^{-3}, 1.0×10^{-3} and $2.0 \times 10^{-3}\ \mathrm{m^3\,s^{-1}}$. These correspond to overland flow from areas of 4 m wide and 9–36 m long with a steady state rainfall intensity of 50 $\mathrm{mm\,h^{-1}}$ to contextualize the magnitude of the discharge applied. The discharge was controlled by a series of valves installed in a flow diversion box (Fig. 1). The discharge was collected at the lower end of the flume using plastic buckets and was measured with a volumetric cylinder.

2.2. Experimental measurements

Flow rate, slope gradient and stem basal cover were adjusted to the designated values prior to sediment introduction. The sediment was delivered from a sediment delivery machine that was designed to ensure that the transport capacity was reached for each combination of flow discharge, slope gradient and stem basal cover (Fig. 1). The sediment delivery machine was installed over the flume at a distance of 0.5 m from the top. The sediment feeding rate was controlled by the rotation speed of the rotor and the degree of openness installed within the sediment delivery machine. The sediment feeding rate was adjusted