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Comparison of rill flow velocity regimes between developing and stationary rills

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ABSTRACT

Flow velocity is fundamental in calculating related parameters of physical soil erosion models. It has been well known that rill flow velocity varies with developing rill form, which complicates and impedes the development of soil erosion models. In filed, rainfall erosion frequently occurs with pre-existing rills not damaged by tillage practices. However, the rill flow velocity in this case has received little attention. In this study, we investigated rill flow velocity regimes for both developing and stationary rills using 5 m-length plots in the laboratory. The experiments included two consecutive rainfalls, which had similar runoff rate. The first rainfall had an intensity of 90 mm h^{-1}, which generated well-developed rills; the second had an intensity of 60 mm h^{-1} and did not damage the rills formed by the first rainfall. The results show that, for a developing rill, rill flow velocity is higher in the lower slope than that in the upper slope, and rill flow velocity in the lower slope fluctuates much more over time as a result of the variation of rill morphology following rill development. With rill development, the rill flow velocity of the lower slope decreased responding to the stabilizing rill channel and exhibited a similar trend to that in upper slope. For a stationary rill, the rill flow velocities at both sections varied little over time, demonstrating that rill flow velocity is primarily influenced by rill morphology. Hence, the results suggested that the strength of fluctuation in rill flow velocity could be used to characterize the instantaneous intensity of soil erosion and active level of rill development. The channel of the stationary rill simply acted as transport pathways of sediment supplied by inter-rill erosion. The physical models of soil erosion should take into account the micro-topography on land surface related to the antecedently formed rills.

1. Introduction

Rill erosion constitutes an important part of the erosion system on hillslopes. Rills are not only a source area but also transport pathways of eroded sediment. Previous studies have shown that rill formation would increase soil erosion intensity by several to tens of times (Bewket and Sterk, 2003; Kimaro et al., 2008; Auerswald et al., 2009). In the Chinese Loess Plateau, rill erosion is particularly active and accounts for > 70% of the total soil loss on hillslopes (Zheng, 1998; Lei et al., 2008). For example, a five-year field observation in the central Loess Plateau demonstrated that rills appeared during 45%–60% of runoff events and contributed 68%–91% of the total erosion on an agricultural runoff experimental plot (22° inclination and 60 m length) (Sha and Bai, 2001).

Rill formation marks a change in the dominant erosion process. Rill flows have much greater detachment and transport capacities than raindrop splashes and sheet flows, leading to a considerable change in overland flow characteristics and erosion dynamics. Rills are typically several to tens of centimeters in width and depth with erratic shape along their channels. Rill bottoms often feature pool-step morphologies, resulting in a highly variable slope gradient in the downslope direction. Rill flows are generally shallow with a depth of a few centimeters or less and thus, are very subject to rill forms (Lei et al., 1998; Stefanovic and Bryan, 2009).

As a key factor affecting the flow energy, flow velocity determines to a large extent many hydraulic parameters commonly used in modeling rill erosion such as shear stress, stream power, Reynolds number and Froude number (Polyakov and Nearing, 2003; Wang et al., 2016). For example, Reynolds number is calculated as the ratio of flow velocity multiplied by hydraulic radius to the kinematic viscosity of water; Froude number is the ratio of flow velocity to the square root of the quantity of flow depth multiplied by the gravitational constant. Rill

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flow velocity has also been related to the transport capacity of the flow and thus to sediment delivery (Lei et al., 1998; Mancilla et al., 2005). Therefore, the determination of flow velocity is of great importance for rill erosion.

Researchers have long paid attention to the velocity dynamics of rill flows. Both Govers (1992) and Nearing et al. (1997, 1999) found that the rill flow velocity increases following a power function with increasing water discharge. Zhang and Tang (2000), using laboratory flume experiments, found that rill flow velocity exhibited a good power relationship with water discharge and slope gradient. Based on flume experiments of a stationary rill, Shao and Wang (2005) demonstrated that the mean velocity of rill flow first increased and then decreased with increasing slope gradient, with a peak at a slope gradient of 30–40°. Giménez and Govers (2001) argued that whether slope gradient has an effect on rill flow velocity or not depends primarily on the stability of the rill channel; rill flow velocity would increase with increasing slope gradient given a stationary rill channel, but for a developing rill, slope gradient would have little effect on the rill flow velocity as a result of interactions between the channel morphology and the rill flows. Furthermore, Gimenez et al. (2004) experimentally demonstrated that pools and steps along a rill channel strongly influence the rill flow velocity; in particularly, the pools act to dissipate the flow energy and complicate the flow direction, thereby offsetting the influence of the slope gradient on the rill flow velocity to a considerable degree. Stefanovic and Bryan (2009) also showed that the widening and meandering of a rill channel can reduce the rill flow velocity.

A large number of rill-related studies conducted runoff experiments in laboratory and used man-made rills. However, the runoff experiments cannot reproduce rill processes well due to drawbacks as below. First, the man-made rills generally have straight channels and downslope invariable cross sections; even if the rills were caused by rainfall, the rills would be regulated for purpose to maintain a constant form. Second, the experiments used a constant outflow discharge into the flumes and ignored the rainfall's effect on rill processes (Shao and Wang, 2005; Giménez et al., 2007; Stefanovic and Bryan, 2009; Lei et al., 2010), whereas the raindrop impact can greatly increase the erosivity of overland flows (Asadi et al., 2007). In addition, the experiments examined the mean velocity of rill flows, paying little attention to the temporal variation of the rill flow velocity during the experiments.

In the field, rills probably preserve for a long time without being damaged by tillage practices after their formation, so that the subsequent erosion event may occur with antecedently formed rills. Little is known about the rill flow velocity regime in this case. Using rainfall instead of runoff experiments in laboratory, the specific objectives of this study were: (1) to investigate the rill flow velocity during rill development; (2) to compare the rill flow velocity pattern between developing and stationary rills.

2. Materials and methods

2.1. Experimental soil

This study used Lou soil in the experiments. The sampled site (34°16′N, 108°4′E) has been cultivated with crops for many years. The experimental soil was sampled from the topsoil (0 to 20 cm) and varied from 1.2 to 1.4 g cm^{-3} in bulk density. The Lou soil is widely distributed in the southern Loess Plateau. The soil is originally formed by human stack of the loess in farmland and then became mellow as a result of cultivation and fertilization. The Lou soil properties are shown in Table 1.

2.2. Simulated rainfall system

The experiment was conducted in the simulated rainfall hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, China. The rainfall simulators we used are downward-spraying and the rainfall intensity was adjustable through changing the nozzle size and pressure. The simulators are 18 m high above the ground, allowing raindrops to reach a terminal velocity as in the field. The experiment rainfall covered an area of 27 × 18 m. The simulators sprayed water into the air, and the water drops broke into various-sized raindrops in the air, which is very similar to natural rainfalls.

2.3. Experimental design

Before the experiments, the soil sample was air-dried to a moisture content of approximately 10% (gravimetric moisture content). Then, weeds and stones were removed through a 10 mm sieve. The experiment flume was 5 (length) × 1 (width) × 0.5 (depth) m in size. Wang and Shi (2015) found that rills develop most readily at a slope gradient of 20° under otherwise identical conditions. For this reason, the flume was set to be at 20° gradient. First, a 10-cm-thick layer of fine sand was packed onto the flume. Then, the layer was laid on a permeable fine gauze so as to maintain a good drainage. Finally, a reasonable amount of the sampled soil was added and compacted into a 5-cm-thick layer of a ~1.3 g cm^{-3} bulk density of, a value similar to that in the sampling site; the procedure was repeated for six times and finally, the soil layer in the flume was 30 cm thick.

The experiments included two sub-experiments. The first (Sub-experiment 1) applied a rainfall intensity 90 mm h^{-1} (a characteristic rainfall intensity for erosive rainfall events in the Loess Plateau; Cai et al., 1998) and a rainfall duration of 60 min. Rills were well developed during Sub-experiment 1, allowing us to examine the rill flow velocity regimes for developing rills. The saturated soil layer of Sub-experiment 1 was set quietly for 24 h and then the second sub-experiment was conducted with a rainfall intensity 60 mm h^{-1} and a rainfall duration of 60 min. The rills showed little change before and after Sub-experiment 2, allowing us to examine the rill flow velocity regimes for stationary rills.

Before the onset of the experiments, the rainfall intensities were calibrated to ensure a spatial uniformity coefficient of the rainfall intensity > 80% and thus, a spatially invariant rainfall over the flume. Additional information on the experimental devices was presented by He et al. (2014).

2.4. Observed parameters

Samples of sediment and runoff were collected using a 1000 mL bottle every 1 min for Sub-experiment 1 and 2 min for Sub-experiment 2. The longer sample interval for Sub-experiment 2 was due to less variation in water and sediment discharges over time. Sediment concentrations in runoff were determined by oven-drying the samples in the laboratory. The total runoff volume for each sample interval was determined by collecting all runoff using a large barrel.

The rill flow velocity were measured by using $KMnO_4$ as a dye tracer and recording the time needed by the leading edge of the dye cloud to travel a distance of 0.5 m. These measurements were replicated 2–3 times and then were averaged. However, the average represents surface velocity rather than average velocity throughout the cross section and thus needs to be corrected by multiplying by a correction factor. The factor was suggested to be 0.67, 0.8, and 0.74 by several studies (Horton et al., 1934; Abrahams et al., 1986; Gilley et al., 1990). Govers (1992) indicated that a correction factor of 0.94 is better while calculating rill flow velocity. Rill flows are typically subcritical or supercritical with a shallow water depth, leading to a small difference between surface velocity and mean velocity. Hence, the correction factor was set to be 0.94 in the present study.

During Sub-experiment 1, a rill first emerged at the lower flume 14 min after the onset of the experiment; the rill progressively moved upslope and become connected with a rill near the flume crest 35 min after the onset of the experiment, forming a flow pathway running