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Experimental investigation of morphological characteristics of rill evolution on loess slope

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ABSTRACT

The development of rill is the result of a complex interaction of soil properties with high spatial and temporal variability. The rill morphology may act as a determinant as well as a stochastically driven process. The description of their complex morphology requires geostatistics and nonlinear theories. A study of the morphological characteristics of rill evolution was performed via indoor soil pan rainfall simulations. Experiments were run with loessial soil (bulk density of 1.25 g/cm^3) under a rainfall intensity of 90 mm/h with a 20° slope gradient. A detailed scan of the slope, topographic analysis, and statistical analyses were the main methods utilized in the study. Statistical analyses showed that characteristic parameters exhibited differences in the expression of the dynamic change of soil loss. According to the comparison of quantitative methods, we found that the fractal dimension can reflect the complexity of rill network, but it is not able to reflect the dynamic changes of the erosion process perfectly. In contrast, geomorphologic comentropy is sensitive to the dynamic changes of soil erosion intensity, and its variation can reflect the dynamic changes of erosion perfectly. The topological parameters can reflect the degree of stability in the rill network structure, but it is not suitable for reflecting the dynamic changes of erosion intensity. The geomorphologic comentropy was evaluated as the most appropriate characterization parameter for the rill morphology description.

1. Introduction

Rill erosion is the main source of sediments and the primary mechanism for sediment transportation in hillslope erosion processes (Kimaro et al., 2008). Mutchler and Young (1975) determined that more than 80% of the sediments eroded from hillslopes are transported in rills and Meyer et al. (1975) reported a threefold increase in soil loss following the development of rills on a hillslope. When the effect of flowing water exceeds a certain threshold of soil resistance, the slope micro-terrain changes and forms a rill (Bryan, 2000; Govers et al., 2007; Knapen et al., 2007). Rill initiation is controlled by established threshold hydraulic conditions, and the further development of the rills is complex and dependent on different thresholds (Wirtz et al., 2012). Rills provide a pathway for the transport of sediment since flowing in rills have higher velocities and transport significantly more sediment downslope than overland flows (Gatto, 2000). Thus, the geomorphic importance of rill erosion is well established (Bryan, 1987; Slattery and Bryan, 1992; Lei et al., 1998).

Rill networks evolve morphologically in time and space (Boardman, 2006; Lei et al., 1998) and are geomorphologically and hydrologically important as sediment transport rates frequently increase rapidly once rill incision occurs (Loch and Donnollan, 1983; Nachtergaele et al., 2001, 2002). Rill erosion processes such as detachment, transport, and deposition depend mainly on the hydraulic features of flow and the transport capacity of the flow (Lei et al., 2001); the rill bed surface changes as soil erodes, which in turn alters the hydraulics of the flow that affect the erodibility and stability of soil along the rill. Thus, complex feedbacks exist in the mechanics of rill erosion (Lawrence and Gatto, 2000). The rill evolutionary process is complicated and has long been a focus of concern in developing and improving process-based erosion prediction (Dong et al., 2014). Current models do not attempt to describe rill evolution and the associated spatial variability in rills. For example, the process-based models of WEPP (Water Erosion Prediction Project) (Nearing et al., 1989), GUEST (Griffith University Erosion System Template) (Hairsine and Rose, 1992), and EUROSEM (European soil erosion model) (Morgan et al., 1992; Morgan, 1994.) are frequently used to predict rates of soil loss. These models assume that rill width remains constant and hydraulic roughness remains unchanged during the erosion process. Due to lack of developments in describing the rill evolution, parameter calibration is often based on a priori reasoning rather than empirical values. This affects the understanding and prediction of the soil erosion process (Favis-Mortlock et al., 2000).

In recent decades, several mathematical models to simulate and predict rill formation and evolution have been developed, and a great

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effort has been made to evaluate their suitability for that purpose. For example, Ni (2001) and Ni et al. (2002) constructed a mathematical model to simulate the characteristics of slope evolution based on the concept of self-organization. They adopted the rill length and depth as the characterization parameters to simulate the rill evolution under different slopes based on the self-organization model. Lei et al. (1998) chose the rill width as the characterization parameter when constructing a mathematical model that mimics the physics of rill evolution. The model self-generates the temporal and spatial variability of rill width by linking the processes of erosion, changes in bed morphology, and hydraulics through dynamic feedback loops. The development of rill is the result of a complex interaction of soil properties with a high spatial and temporal variability (Poesen et al., 1999; Nachtergaele et al., 2001, 2002). The rill morphology may be a determinant of development as well as stochastically driven processes (Sidorchuk, 2005). Even if a model can accurately predict the sediment at rill/runoff plot outlets, very poor prediction of the rill development and sedimentation processes along a rill is a common problem in the existing literature (Yan et al., 2008). However, there are few field studies that quantify the associated soil loss (Di Stefano et al., 2012; Vinci et al., 2014) or that directly observe rill formations (Bruno et al., 2008; Di Stefano and Ferro, 2011; Mancilla et al., 2005; Vinci et al., 2015).

Micro-topography caused by rill erosion is complicated and irregular, and representation of the hillslope surface on a rill-by-rill basis is difficult and especially impractical in the field (Shen et al., 2015). The stochastic theory was proposed for rill morphology quantification at various cross-slope locations along a hillslope (Govindaraju and Kavvas, 1994). Rill length, width, depth, cross-sections and density are measured and employed as indicators of rill morphology (Bruno et al., 2008; Ludwig et al., 1995; Cerdan et al., 2002; Gilley et al., 1990). Improvements in micro-topography observation technology have led to an increase in experimental work on rill morphology evolution (Vinci et al., 2015). Studies have been conducted in both laboratory and field conditions using soils with different textures and natural or simulated rainfall. Brunton and Bryan (2000), for example, carried out simulated rainfall experiments on a Canadian silt loam soil in a flume. By adopting rill length and cross-sections as characterization parameters they studied the development of rill head morphology within an evolving rill system. Fujiwara and Fukada (1989) established a stochastic model based on the fractal geometry theory for the simulation of rill morphology evolution on hillslope, although the physical mechanism of rill formation and water and soil conditions were not taken into account, the simulation results were very similar to the actual situation. Many researchers have attempted to find relationships between rill morphology and erosion factors through laboratory experiments. The studies concentrated on the relationships between the changes in morphology parameters and topographic factors (Wang et al., 1988; Wright and Webster, 1991; Zhang and Yang, 2010) or the main hydraulic variables such as the flow discharge and velocity (Xue et al., 2008), volume of rill runoff, hydraulic slope (Bai, 1999), and rainfall intensity (Mortolock, 1998; Kong and Zhang, 2003). Different researchers choose different quantitative measurements to describe rill morphology, but few studies have focused on the effect of parameter choice. Quantitative measurements of rills include those of rill width, depth, density and the width-to-depth ratio as well as space filling tendencies of the networks (Raff et al., 2004; Wang and Fang, 1998; Zhang and Yang, 2010). Unfortunately, the different approaches to describe this phenomenon have had poor effectiveness in their application (Giménez and Govers, 2002; Govers et al., 2007; Merz and Bryan, 1993). The occurrence of rill is an irreversible nonlinear dynamic process that is controlled by a variety of dynamic conditions and boundary conditions. A single quantification method will directly affect the reliability and accuracy of prediction models. Other methods are needed to reveal the evolution of rill networks from the internal structure and soil loss.

The present study has three main objectives: 1) to gain a profound understanding of rill evolution by tracking development and sedimentation processes along a rill; 2) to build a quantification system for rill morphology by applying different theories of fractal geometry, topology, and entropy to rill erosion processes; and 3) to evaluate the various quantification methods via comparison with experimentally observed rill development.

2. Materials and methods

2.1. Experimental materials

In the present study, an indoor soil pan rainfall simulation was used to investigate the evolution of rill morphology. The experiments were carried out in the Key Laboratory of Soil and Water Loss Process and Control on the Loess Plateau of China's Ministry of Water Resources (MWR). The experiments were conducted in a slope adjustable pan, which was 5 m long, 1 m wide, 0.6 m deep, and were constructed from a galvanized iron sheet with a runoff funnel at the lower end. The slope gradient ranged from 0° to 30° with adjustment intervals of 5°. The soil used in this study was loessial soil which was collected in Gongyi, Henan Province, China from the surface layer (0 to 20 cm) in Loess Plateau areas of landform type V. The particle size of 0.05–0.01 mm particles accounted for 43.4%, 0.02–0.05 mm accounted for 35.45%, and other particles accounted for 21.15%. Rainfall intensity and duration settings reflected the Loess Plateau erosive rainfall characteristics. Artificial rainfall was produced from a rotating sprinkler rainfall simulator which was based on closed loop automatic control technology with uniformity of 92%. The rainfall simulator is made of pressure pipes attached to nozzles. The pressure pipes and nozzles are mounted on the ceiling of the laboratory at a height of 21 m from the plot bed. This height is sufficient to gain terminal velocity, so the force of raindrop impact is similar to natural rainfall. Water is supplied from a water tank connected to the water supply system. The water is pumped up through a main water pipe and then divided into four or five pipes depending on the number of nozzles used for spraying water over the plot (Fig. 1). At each pipe, nozzles are installed and pressure gauges are attached. Each group of nozzles has five different sizes. The rainfall simulator can simulate rainfall intensities ranging from 30 mm/h to 180 mm/h by adjusting the pipe pressure and the nozzle size. The rainfall simulator was used to produce a 52 min rainfall at an intensity of approximately 90 mm/h. The chosen rainfall intensity of 90 mm/h is typical of intense storms on the Chinese Loess Plateau (Fang et al., 2015). The soil pan was adjusted to a 20° slope gradient to correspond with the steep slope for cultivated land on the Chinese Loess Plateau. The soil samples were crushed and passed through a 10 mm sieve. The soil was packed to a density of approximately 1.25 g/cm^3 to achieve its natural bulk density (1.2 to 1.4 g/cm^3) (Fang et al., 2015).

2.2. Preparation of the soil pan

Permeable holes with diameters of 5 mm were drilled into the bottom of these sheets and adhesion sand was laid to facilitate infiltration. In a soil pan, a 0.5 m soil layer was placed over a 0.1 m layer of coarse sand that allowed free drainage of excess water. In the course of filling the plots, the soil was tamped layer by layer to ensure consistency, and the soil surface was raked between addition of layers in order to strengthen the combination. The soil amount of each layer was kept as constant as possible to maintain a homogeneous bulk density. The soil pan was filled with sieved soil and the soil surface was flattened using a board. Before the experiment, a pre-rainfall with 30 mm/h intensity was carried out until the slope started to produce runoff. This was done to ensure the consistency of the soil moisture and reduce the spatial variability of underlying surface conditions. After the pre-rainfall, the plot surface was covered with plastic sheeting to prevent evaporation. The plot was then left for 24 h. The rainfall