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An experimental study of rill erosion and morphology

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A B S T R A C T

Rill erosion is recognized as an important process of water erosion on agricultural land. The objectives of this study are to examine the effects of rainfall intensity on rill network development and to present some indicators for a quantitative description of rill morphology. A soil pan (10 m long, 3 m wide and 0.5 m deep and with an adjustable slope gradient from 0 to 30°) was subjected to three successive rains under rainfall intensities of 50 and 100 mm h^{-1}. The results showed that rainfall intensity significantly affected rill erosion, especially in the active period of rill network development. The magnitude of rill erosion was 28.5 and 33.1 kg m^{-2} and contributed 78.6% and 76.2% to the soil loss under rainfall intensities of 50 and 100 mm h^{-1}, respectively. The formation of rill network under the 50 mm h^{-1} intensity was more complex than that under the 100 mm h^{-1} intensity; for the latter rill networks developed fast and then varied slightly. The mean rill inclination angle (δ_{mean}), rill density (ρ), degree of rill dissection (μ) and mean rill tortuosity complexity (c_{mean}) increased with the increase of rains under the same rainfall intensity. The μ value was the optimal derivative morphological indicator to estimate rill erosion and morphology, which was followed in descending order by δ_{mean}, c_{mean} and ρ.

1. Introduction

Rill erosion is a major soil erosion process caused by water on sloping croplands and rangelands in many areas around the world and causes much soil loss (Cai et al., 2004; Kimaro et al., 2008). It is geomorphologically important because it produces erosion features and resultant rill transport materials supplied by interrill erosion (Bewket and Sterk, 2003). Many studies have focused on rill erosion processes (Bryan and Rockwell, 1998; Wirtz et al., 2012). However, there are some differences in results depending on specific experiments, soil types, rainfall conditions and spatial scales (Devente and Poesen, 2005; Govers et al., 2007). Therefore, rill erosion is still one of the current research hotspots.

Rill networks develop with varying complexity (Brunton and Bryan, 2000; Mancilla et al., 2005). Rill network development leads to an increase in runoff connectivity and concentration of water flow along the channeling network (Heras et al., 2011). Quantitative measurements of rills include those of rill width, depth, and the width-to-depth ratio, as well as space filling tendencies of the networks (Raff et al., 2004). A rill network tends to fill the drainage area more completely with time.

The existing results usually focus on main rills, which transport most surface runoff and sediment out of the plot and are usually larger than the rest of the finer channels. Most studies have generally ignored secondary rills, which are small channels that usually transport less surface runoff than main rills or dissipate before reaching the plot outlet (Mancilla et al., 2005). However, this exclusion of secondary rills neglects an important part of the rill network.

Rill morphology plays a significant role in determining surface runoff and soil loss from hillslopes (Govindaraju and Kavvas, 1994). Flows in rills have higher velocities and transport significantly more sediment downslope than overland flows (Gatto, 2000). Eroding rills evolve morphologically in time and space (Lei and Nearing, 1998), and it is necessary to consider temporal and spatial variations (Boardman, 2006). Microtopography caused by rill erosion is often complicated and irregular, and a rill-by-rill survey is difficult and especially impractical in the field. The stochastic method was adopted to characterize rill morphology at various cross-slope locations along a hillslope (Govindaraju and Kavvas, 1994). Experiments on rill morphology at the field scale are essentially limited to qualitative or semi-quantitative descriptions (Bewket and Sterk, 2003).

Rill length and cross-sections are employed as indicators of rill morphology, where rill length is usefully chosen to describe the rilling process (Bruno et al., 2008) and is also a major component of rill volume variability on a watershed scale (Ludwig et al., 1995). Rill width and

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depth are measured and interpolated along the incision network for calculation of the erosion rate (Cerdan et al., 2002).

Researchers have attempted to use rill density to characterize the erosion process (Gilley et al., 1990). However, there is an opposing view that rill density is insufficient to describe rill structure (Govindaraju and Kavvas, 1994). Rill horizon density (Wu et al., 1997) represents rill erosion intensity and morphology. Bewket and Sterk (2003) defined the area of actual damage as the surface area covered by rills.

To promote process studies of rill erosion, quantitative descriptions of rill morphology are useful. Therefore, a laboratory study with detailed measurements was conducted under controlled experimental conditions. Rill density (ρ) was used to characterize rill erosion; in addition, degree of rill dissection (μ), rill inclination angle (δ) and rill tortuosity complexity (c) were chosen to investigate characteristics of rill morphology and to quantify the evolution of rill networks on the hillslope. The objectives of this study are to investigate the effects of rainfall intensity on rill erosion and morphology, to present temporal and spatial variations of rill networks by using morphological indicators, analyze correlations between rill erosion and morphological indicators and propose the optimal indicator.

2. Materials and methods

2.1. Experimental materials

The simulated rainfall experiments were completed in the rainfall simulation laboratory of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling City, China. The experiments were conducted in a slope adjustable pan, which was 10 m long, 3 m wide, 0.5 m deep and with many holes (2 cm aperture) at the bottom to facilitate drainage. The slope gradient ranged from 0 to 30° with adjustment steps of 5°. In this study, the soil pan was set at a slope of 20°. A down sprinkler rainfall simulator system (Zheng and Zhao, 2004) was used to apply rainfall. The rainfall simulator, which includes three nozzles, can be set to any selected rainfall intensity ranging from 30 to 350 mm h^{-1} by adjusting the nozzle size and water pressure. The fall height of the raindrops is 18 m above the ground, which allows all raindrops to reach the terminal velocity prior to impact. The simulated raindrop diameter distribution was 0.2–3.1 mm, and >85% of raindrop diameters were <1.0 mm. According to Chen and Wang (1991), most raindrop diameters from natural rain were also <1.0 mm. Thus, the simulated raindrop size could successfully replicate the natural raindrop size.

The soil used in this study was the loessial soil with 28.3% sand (>50 μm), 58.1% silt (50–2 μm), 13.6% clay (<2 μm) and 5.9 g kg^{-1} soil organic matter. The methods used to analyze soil texture and soil organic matter were the pipette method and the potassium dichromate oxidation-external heating method, respectively (Liu, 1996). The tested soil was collected from 0 to 20 cm in the Ap horizon of a well-drained site in Ansai, Shaanxi Province, China. Impurities, such as organic matters and gravels, were removed from all the soil, but the soil was not passed through any sieve to keep the natural state of the soil.

2.2. Preparation of the soil pan

Before packing the soil pan, the soil water content of the tested soil was determined, which was used to calculate how much soil was needed for packing the soil pan to obtain target soil bulk densities for different layers. First, a 5-cm-thick layer of sand was packed at the bottom of the soil pan that allowed free drainage of excess water. Then, the layers over the sand layer were divided into the plow pan with a depth of 15 cm and the tilth layer with a depth of 20 cm to simulate local sloping croplands; the bulk densities for the plow pan and the tilth layer were 1.35 and 1.10 g cm^{-3}, respectively. During the packing process, both the plow pan and the tilth layer were packed in 5-cm increments, and each packed soil layer was raked lightly before the next layer was packed to ensure uniformity and continuity in the soil structure. The soil amount of each layer was kept as constant as possible to maintain similar bulk density and uniform spatial distribution of soil particles. After completion of packing the soil pan, a manual tillage on the soil pan was performed at an approximately 20 cm depth along the contour line, which is similar to the plowing depth of croplands. After plowing, the soil pan was allowed to settle for 48 h.

2.3. Experimental procedures

Before runs, the experimental soil pan was subjected to a pre-rain with the 30 mm h^{-1} rainfall intensity until surface flow occurred; the duration of this pre-rain was approximately 25 min. The purposes of the pre-rain were to maintain consistent soil moisture, consolidate loose soil particles by rainfall wetting, and reduce the spatial variability of surface conditions. The soil surface was covered with a plastic sheet after the pre-rain to prevent soil moisture evaporation and surface sealing, and allowed to stand for 24 h.

Prior to the experiment, rainfall intensity was calibrated to confirm the run-rainfall intensity reaching the target rainfall intensity and meeting experimental requirements; uniformity was >90%. The designed two rainfall intensities of 50 and 100 mm h^{-1} were used in this study, while a total rainfall of 50 mm was maintained during each treatment of both rainfall intensities; thus, rainfall durations were 60 min for 50 mm h^{-1} and 30 min for 100 mm h^{-1}. For better development of rill networks, each rainfall intensity experiment contained three successive rains (i.e., 1st to 3rd rains) with an interval of 24 h, respectively.

2.4. Experimental measurements

2.4.1. Runoff and soil loss

One day after the pre-rain, the designed rainfall intensity (50 or 100 mm h^{-1}) was applied to the soil pan. For each treatment, after runoff occurred, runoff samples were collected in 15-liter buckets, and the samples were measured in 1 or 2 min intervals for the whole rainfall durations, with 30 min for 100 mm h^{-1} and 60 min for 50 mm h^{-1}, respectively. These samples were weighed and then oven-dried at 105 °C to calculate sediment yield.

2.4.2. Rill development

Manual measurements of each rill's length, width, depth and locations (x, y) along with rainfall duration, were performed when rills were generated. To aid in recognizing these rills, photographs were taken of the soil pan surface at different times throughout each rain. After the completion of each rain, the rill network was mapped in detail. Rill width and depth measurements were conducted along each rill channel at intervals of 5 or 10 cm. Furthermore, these measurements were also performed once sudden changes in the rill pattern occurred (Øygarden, 2003).

2.5. Defining derivative morphological indicators

Rill length, width and depth are the basic morphological indicators, which are directly measured and used to calculate other derivative morphological indicators. In this study, four derivative morphological indicators were chosen and defined to describe rill morphology.

2.5.1. Rill inclination angle

The rill inclination angle along the hillslope (δ, in degrees) is an average angle between directions of a rill at measurement points and the vertical direction of the rill. It reflects the ductility of a rill in the horizontal and vertical directions. In general, if δ is larger, runoff and sediment have a stronger conductivity in the horizon direction. On the contrary, if δ is smaller, a greater degree of vertical extension of a rill