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Estimating rill erosion process from eroded morphology in flume experiments by volume replacement method

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ABSTRACT

Rills are commonly found on the sloped farm fields in the loess regions worldwide, especially on Chinese Loess Plateau. The erosion process along a rill provides information for understanding the rill erosion mechanism. This study uses a volume replacement method to estimate the rill erosion processes by refilling the eroded rill segments. The sediment concentration was calculated by summering the eroded soil mass and divided by the total water volume during the erosion period. A flume that was 0.6 wide and 12 m long was subdivided into strips of 0.1 m wide and 12 m long to imitate eroding rills. A typical silty-loam soil from the Loess Plateau of China was used for the experiments. The commutative eroded rill volumes along the rills under five slopes and three flow rates were measured at 11 rill segments. All the sediment-laden runoff was harvested at the rill outlet to measure the average sediment concentration. The sediment concentrations at locations higher than that at the outlet were caused by sediment deposition and removed from the data set. The computed sediment concentration processes increased with slope gradient and flow rate. They also increase with rill length exponentially, with all the coefficients of determination above 0.95. The results were about the same of the previous studies, with sampling method. This demonstrates that the proposed method is a feasible approach to estimate rill erosion distribution. The data set is applicable to the estimation of rill erosion model parameters. This study will provide a basis for estimating rill erosion model parameters.

1. Introduction

Extensive loess deposits are found in northwestern China, the Great Plains of North America, central Europe, and parts of Russia and Kazakhstan. The thickest loess deposits are near the Missouri River in the U.S. state of Iowa and along the Yellow River in China (Piest and Ziernnicki, 1979; Tang, 2002).

Loess soils are among the most fertile in the world, principally because the abundance of silt particles ensures a good supply of plant-available water, good soil aeration, extensive penetration by plant roots, and easy cultivation and seedbed preparation. Therefore, loess soils have long been used in agriculture. And rill erosion is commonly seen on the sloped loess farm field (Tang, 2002).

As an important component of soil erosion on cultivated slopes, rill erosion is an intermediate process between sheet and gully erosions (Jackson, 1997). Eroding rills are important sources of slope erosion and are the primary channels for sediment transportation. When an eroding rill is formed, the surface flow becomes a concentrated flow, such that the hydrodynamic characteristics of flow are significantly transformed. The scouring power of concentrated flow greatly increases, thus causing a significant increase in soil erosion.

Rill erosion has been considered as a serious problem and accounts for approximately 70% of upland erosion on Loess Plateau in China; this process delivers great quantities of sediments to river systems (Nearing et al., 1997; Zheng and Tang, 1997; Gyssels et al., 2002; Yang et al., 2003; Miao et al., 2010).

Eroding rills are commonly observed in cultivated field worldwide and can cause huge soil losses (Govers and Poesen, 1988; Poesen et al., 2003; De Santisteban et al., 2004; Miao et al., 2011). Given the importance of this erosion type, methods to estimate rill erosion process should be established. Three kinds of methods have generally been recommended by previous studies to quantify rill erosion process.

Casalí et al. (2006) advanced a volumetric method that measures and calculates a series of cross sectional area to estimate the volume and erosion process along the eroded rill attributed to the condition in which rill volume is equal to the eroded soil volume. They highlighted that rill size and morphology were important factors that cause measurement errors. Another method is to refill a rill with soil, tiny foam particles, rice grains, or other possible materials before its volume is measured to estimate erosion (Zheng, 1989). However, in these previous studies, the rills were not well confined, such that rills of various

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sizes were not easily identified to cause highly random and significant measurement errors.

Huo et al. (2011) and Yan et al. (2011) conducted their experiments by performing detailed scans of an eroded rill before and after soil erosion events by using a 3D laser scanner to estimate rill erosion. This method is usually time-consuming and needs high-cost equipment. Sometimes, when an eroded rill is deep, the laser beam cannot reach the bottom of the rill, thus causing a measurement error.

In addition, rare earth elements or radioelements were used to trace and estimate the erosion process along an eroding rill. Liu et al. (2011) used 7 Be to differentiate inter-rill and rill erosions. Similarly, Olson et al. (2013) conducted field experiments using 137 Cs to determine soil erosion and subsequently proved the feasibility of this approach. Tracer element method can be applied to both small- and large-scale experiments to acquire soil erosion dynamic data.

Erosion models can provide a quantitative approach to predict soil erosion under a wide range of conditions. Chen et al. (2003) used the Water Erosion Prediction Project (WEPP) to estimate purple soil erosion and considered WEPP as a rational model in purple soil areas.

Previous studies found that the random fluctuations of rill width were the primary deficiencies in the previous rill erosion experiments (Lei et al., 1998, 2001, 2008; Lei and Nearing, 1999; Yan et al., 2008). Lei et al. (2009) suggested an experimental method and procedures using a well-confined rill to simulate rill erosion processes and to estimate all the model parameters, such as detachment rate, erodibility, critical shear stress, and transport capacity. They suggested the use of well-confined rills in experiments to overcome the random fluctuations of rill width and rill flow hydrodynamics, which cause uncertainty in rill erosion processes and, consequently, in the rill erosion model parameters.

The aims of this study are as follows: 1) to develop a method for estimating the rill soil erosion process from the eroded morphology by refilling the lined eroded rill with water and to assess cumulative eroded mass; 2) to compute for the sediment concentration distribution and erosion process along rill length, as influenced by slope gradient and flow rate.

2. Methods and materials

A typical silt-loam soil from the Ansai Research Station of Soil and Water Conservation on the Loess Plateau of China (109° 19′ 23″ E, 36° 51′ 30″ N) was collected as the experimental soil in this study. The soil contents are 15.92% clay (<0.005 mm), 63.90% silt (0.005 to 0.05 mm), and 20.18% sand (>0.05 mm). The soil was air-dried before being crushed and passed through an 8 mm sieve.

A laboratory flume platform that is 3 m wide and 12 m long was used to build the experimental rills in six strips that were 0.1 m wide and 12 m long, as divided by upright PVC boards (Fig. 1), to imitate rills and/or to converge water flow to form the required concentrated flow. The experimental flume was placed at a horizontal position for soil packing. The same soil materials were glued onto both sides of the PVC boards to imitate the roughness of the soil surface, such that the boundary effect on the rill erosion process is minimized. The bottom 5 cm of the flume was densely packed with clay soil to a bulk density of approximately 1500 kg m^{-3} to imitate the plow pan layer. On top of this layer, 20 cm of flume was packed in layers of about 5 cm to a bulk density of approximately 1200 kg m^{-3} to simulate the cultivated layer. The soil near the flume walls was packed to be slightly higher than the middle to converge the water flow into the middle and to minimize the boundary effect further. Before the experimental runs, the prepared rills were saturated by using a rainfall simulator and allowed to set for 24 h to ensure even and homogeneous initial soil moisture conditions. The flume was then adjusted to the designed slope. Tap water was introduced into the rill from the upper end, through a water supply tank and a pump at the desired flow rate. Gauze was placed at the water inlet to avoid the direct flushing of the rill and to ensure a steady and evenly distributed water flow at the rill inlet. Each experiment was run for 3 min to 8 min. The experiments were conducted under five slope gradients of 5°, 10°, 15°, 20°, and 25° and three flow rates of 2, 4, and 8 L min^{-1} with two replicates.

Fig. 1. Experimental flume.

After the experiments, the eroded volumes were measured by using volume replacement method, which uses water to refill the eroded rill segments. After erosion, the flume was lowered to the horizontal position for the measurements of eroded rill volumes. Thin plastic sheets were used to line the eroded rill bottom before filling the rill segments with water. The volumes of water required to fill the eroded rill to the brim at each rill segment were recorded as the eroded volume. The first segment was between 0 and 0.5 m and sequentially between 0.5 and 1 m, 1 and 2 m, through 7 and 8 m, 8 and 10 m, as well as 10 and 12 m. The total transported sediments comprise the mass of eroded soil, which is equal to the eroded volume times the bulk density of the original rill bed at 1200 kg m^{-3}. The total runoff and sediments were measured by using a collecting tank at the outlet of the rill during the experiments to estimate the average sediment concentration, as the maximum sediment concentration during the experimental run.

3. Results and discussion

3.1. Eroded mass along the rill

The cumulative eroded volume along a rill was calculated by adding the eroded volumes from all rill segments at the upstream. The cumulative eroded masses were calculated by multiplying the eroded volume by the soil bulk density.

$$V_i = \sum_{j=1}^{i} v_j \qquad (i = 1 \cdots 10) \tag{1}$$