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Determining ephemeral gully erosion process with the volume replacement method

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ABSTRACT

Background: Ephemeral gully erosion is an important form of hillslope erosion all over the world. It is of high significance to understand its erosion mechanism.
Objective: A new volume replacement method is proposed to determine ephemeral gully erosion process. Styrofoam particles of hard granules were used to refill the eroded ephemeral gully sections lined with gauze sheet to the original elevation, before their volumes were measured for estimating sediment concentration distribution along the ephemeral gully. The measurement and the computational methodologies are illustrated in details.
Method: A series of flume experiments were conducted with a silt loam (loess) soil to study ephemeral gully erosion process under four slope gradients and three flow rates. The ephemeral gully was pre-formed before each experimental run. The volumes of the eroded ephemeral gully sections were measured and the distribution of sediment concentration along the gully was computed at 1 m intervals. For comparison purpose, the sediment concentration distribution along the eroded gully was also measured by manual sampling of the sediment-laden water flow with cups.
Results: The results showed that both the sediment processes estimated by the volume replacement and measured by the sampling method were very similar. The estimated and measured sediment concentrations increased with ephemeral gully length under a given flow rate. The increase rate decreased gradually as the sediment concentration gradually approached its limit.
Conclusions: Under different flow rates and slope gradients, the sediment concentrations at different distances, as estimated by the volume replacement method were about the same as those measured with the sampling method. The new method provides a useful and efficient way in determining the ephemeral gully erosion, and helps to understand ephemeral gully erosion process.

1. Introduction

Ephemeral gully erosion is an important form of hillslope erosion on the Chinese Loess Plateau (Cheng et al., 2007; Zhang et al., 1991), and the cultivated farmlands all over the world. Ephemeral gullies are temporary and continuous channels. According to a report by Soil Science Society of American (Soil Science Glossary Terms Committee, 2008), ephemeral gullies are small channels eroded by concentrated flow, which can be refilled by tillage and reformed again at the same location under additional runoff events.

Ephemeral gullies are commonly found in the cultivated farmlands in the world and potentially are the dominant sediment source in many cultivated loess belt (Casalí et al., 2006; Casali et al., 2000; Maugnard et al., 2014; Zhang, 1991b). In the European Loess belt and Southeastern United States, ephemeral gully erosion amounts to more than 30% of the overall soil loss, or even more than 40% in the intensively cultivated sloped cropland (Casali et al., 2000). And in the Northern Mississippi, ephemeral gully erosion amounts to more than 60% of the overall soil loss inform the watershed. The ephemeral gully erosion occurs widely in the sloped cropland that is steeper than gradient of 15°. Its soil loss amounts to 2–3 times of that without ephemeral gully erosion, and more than 70% of inter-gully area on the Loess Plateau of China (Zhang et al., 1991).

In fact, the initiation and development of ephemeral gullies are controlled by the concentrated flow of sufficient quantity (Vandaele et al., 1996). Poesen et al. (2003) distinguished ephemeral gullies from rills by a critical cross-sectional area of 929 cm^2 (1 ft^2), while others defined it with a critical width, such as 0.3 m (Brice, 1966) or 0.5 m (Imeson and Kwaad, 1980). Although numerous studies have mentioned the characteristics and developing conditions of ephemeral gully, the concept and the critical size of ephemeral erosion may vary. According to Zhang et al. (1991) and Vandaele et al. (1996), ephemeral gully erosion is caused by

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concentrated surface runoff, often with the interacting influences of subsurface piping or seepage processes. Ephemeral gullies usually occur in topographic depressions within tilled fields, and are small enough to be filled in with farming equipment and reformed at the same location. Ephemeral gullies may be connected to edge-of-field overfalls, or they may terminate within fields where slope gradients become low enough.

The measurement of the eroded gully or rill volume is typically made by measuring the eroded amount, and this is very important in soil erosion assessment. The instruments used on the volume measurement of eroded gully or rill include tape and ruler (Bennett et al., 2000; Casalí et al., 1999; Di Stefano et al., 2013; Ludwig et al., 1995; Nachtergaele et al., 2001a, 2001b; Smith, 1993; Spomer and Hjelmfelt, 1986), micro-topographic profiler (Casalí et al., 2006), laser scanner (P. Zhang et al., 2008, 2009), high accuracy GPS (Cheng et al., 2007; P. Zhang et al., 2008), stereoscopic photogrammetry (Xu and Zhou, 1988), photo-reconstruction methods (Alvaro et al., 2014) and so on. Typically, the cross sections of ephemeral gullies are in irregular shapes and are difficult to be measured precisely by a tape and a ruler, besides labor consuming. The measurement with micro-topographic profiler is more precise and less dependent on the distance between consecutive cross sections (Casalí et al., 2006). However, the computation for the area of the irregular cross section is strenuous and time-consuming. Laser scanner and high accuracy GPS are high in cost, and cumbersome. The scanning of the gully is of low time efficiency. The accurate measurement of the volume of ephemeral gullies remains an important problem to be solved.

A method that measures the volume of eroded gully or rill by refilling the eroded gully with soil was mentioned by Zheng (1989). With this method, the similar soil materials of the studied slope are used to refill the eroded gully. After the soil mass and water content are measured, the volume of the eroded gully can be estimated. In the method, soil in the same condition of the studied rill should be prepared, and the soil moisture content needs to be measured. When refilling the gully with soil materials, it is difficult to compact the soil material into the gully to exactly the same density of the gully banks, because the eroded ephemeral gullies were of such diverse shapes in cross sections and sometimes with great eroded depths. As a result, variations in the compaction processes make varied mass of the refilled soil and bring in high measurement errors. Thus, the application of this method is not frequently reported in the literature. More suitable material, which is not easily compacted and convenient to operate, should be used to replace the eroded volume.

The purposes of this study include: 1) to suggest a method and related procedures to measure the spatial distribution of eroded volume of ephemeral gully by refilling it to the original elevation with styrofoam particles; 2) to compute sediment concentrations at different positions along the ephemeral gully so as to quantify the erosion process, based on the discharge rate, and experimental duration and the eroded soil mass; and 3) to verify the method by comparing the two data sets of sediment concentration distribution as determined by this new method and those by the manual sampling method.

2. Methods and materials

2.1. The volume replacement method

In this method, the volumes of the eroded ephemeral gully at different sections were measured, which can represent the erosion. Sediment concentration was estimated by the dry sediment mass and the sediment-laden water volume. The water flow rate, the duration of the experiment and the soil bulk density were known, so the sediment concentration distribution along the ephemeral gully can be determined.

Light and handy material was used to refill the eroded ephemeral gully sections to the original elevation before the volume of the materials (eroded sediment) was measured. The styrofoam particles of hard granules in a diameter of 1–2 mm were used to refill the ephemeral gully sections to determine the eroded volumes. Unlike soil particles that contain moisture more or less, styrofoam particles of hard granules are elastic and their volumes do not vary much when being packed. So the use of styrofoam particles can reduce the error caused by compaction during the refilling process. Also, the styrofoam particles are of lower density with no cohesion which make them easier to be handled than soil materials. The eroded ephemeral gully sections of 1 m were covered with gauze (Fig. 1) before they were filled with styrofoam particles to the original elevation, to ensure that all the styrofoam particles can be easily taken out of the ephemeral gully. The refilled volumes were the eroded soil volumes of the ephemeral gully sections. The eroded soil volumes and the bulk density were used to compute the eroded soil masses. According to the known flow rates and the recorded experiment periods, the sediment concentrations were computed by Eq. (1):

$$c_m = \frac{\sum_{i=0}^{m} V_i \rho_b}{q \Delta t} (m = 1, \ldots, 12) \tag{1}$$

where c_m is the sediment concentration at point m along ephemeral gully, kg/m^3; m is the number of segment, dimensionless; ρ_b is the soil bulk density of the ephemeral gully, kg/m^3; V_i is the eroded soil volume within the segment between i-1th and ith coordinates (Fig. 1), m^3; q is the flow rate, m^3/min; Δt is the experimental duration, min.

2.2. Experiment design

The experiments were conducted in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, in Yangling, China. The platform was 12 m long and 3 m wide with an adjustable slope between 0° and 30°. On the platform, the 1 m wide, 0.5 m deep and 12 m long flume was subdivided into two 0.5 m wide strips to build imitated ephemeral gullies. Shutters were installed at the outlet of the flume to guarantee smooth runoff outflow.

Sufficient concentrated flow is important in the ephemeral gully erosion. The critical flow rate of concentrated flow depends on the critical catchment area, rainfall intensity and the runoff coefficient in the region where ephemeral gully erosion happens. According to the surveys of Qin et al. (2010) and Zhang et al. (1991), the average runoff area of ephemeral gully erosion is reported to be about 650 m^2. The critical rainfall intensity of rill and ephemeral erosion region on the Loess Plateau is 0.26–0.3 mm/min (Zhang, 1991a). According to the geomorphic threshold condition (a power function of critical slope gradient and drainage area) and the concept of drainage area (Vandaele et al.,

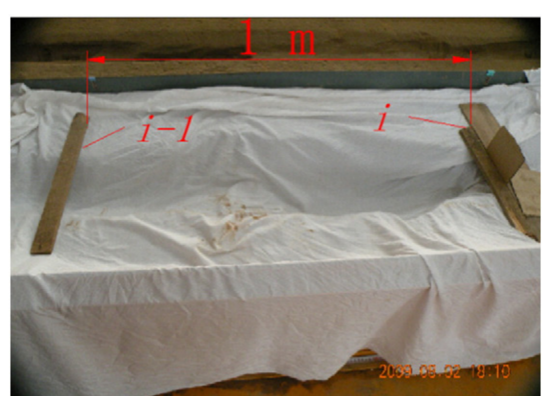

Fig. 1. Eroded ephemeral gully section to be measured.