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Spatial heterogeneity of soil detachment capacity by overland flow at a hillslope with ephemeral gullies on the Loess Plateau

Zhen-wei Li [a,b,c], Guang-hui Zhang [a,d,*], Ren Geng [d], Hao Wang [d]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China
[b] Key Laboratory for Agro-Ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha 410125, China
[c] Huanjiang Observation and Research Station for Karst Ecosystem, Chinese Academy of Sciences, Huanjiang 547100, China
[d] School of Geography, Beijing Normal University, Beijing 100875, China

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ABSTRACT

Ephemeral gullies are typical erosional landforms and widespread on the Chinese Loess Plateau. To better understand the spatial variability in soil detachment capacity (*DC*) by overland flow and its influence at a hillslope with an ephemeral gully, this study investigates a hillslope on the Loess Plateau using classical statistics, geostatistical analysis, and principal component analysis. Undisturbed soil samples were collected from 202 sites along nine 90 m transects in two completely developed ephemeral gullies, and were scoured in a laboratory flume under consistent hydraulic conditions. The results indicate that *DC* varied widely from 0.0004 to 1.25 kg m^{-2} s^{-1} with a mean of 0.22 kg m^{-2} s^{-1}. The coefficient of variation also shows a high variability in *DC*. The ephemeral gullies were divided into four sections (uppermost, upper, middle and lower slopes) and *DC* differed significantly among the four sections. A semivariogram of *DC* indicated a moderate spatial dependence. The sampling interval significantly affects the spatial pattern of *DC*. When the sampling interval decreased from 10 to 2 m, the nugget variance decreased, whereas structured variance, spatial dependence, and range increased. Distribution maps of *DC*, derived from kriging interpolation, showed that samples in the lower slope position have greater *DC* than the other positions. *DC* significantly correlates with clay content, sand content, median soil grain size, bulk density, cohesion, water stable aggregate, and litter mass density. Principal component analysis (PCA) and a minimum data set (MDS) method identified that the median soil grain size, bulk density, and litter mass density were the major factors affecting the spatial variability in *DC*.

1. Introduction

According to the Soil Science Society of America (2010), an ephemeral gully is defined as “small channels eroded by concentrated flow that can be easily filled by normal tillage, only to reform again in the same location by additional runoff events”. It acts as a principal source of eroded sediment and an effective link for transferring overland flow and sediment from hillslopes to channels or rivers (Vandaele et al., 1996; Capra et al., 2009). This results in on-site land degradation and off-site consequences such as sedimentation or nonpoint pollution in surface water bodies (Valentin et al., 2005; Maugnard et al., 2014; Shi et al., 2014). Furthermore, ephemeral gullies can accelerate interrill and rill erosions via increasing the local slope gradient after several void-filling cycles (Nachtergaele et al., 2002; Poesen et al., 2003). On the Chinese Loess Plateau, especially on steep slopes, ephemeral gullies approximately contribute to 35–70% of the slope soil loss (Cheng et al., 2007; Gong et al., 2011). A better understanding of ephemeral gully erosion processes and their potential effect is of paramount importance to identify the innate characteristics of soil erosion on the Loess Plateau.

Ephemeral gully erosion includes the processes of soil detachment, sediment transport, and deposition (Bryan, 2000; Ventura et al., 2002). Soil detachment is the removal of transportable materials from the soil mass by eroding agents, providing loose, non-cohesive sediment for subsequent transport and deposition (Zhang et al., 2003; Wang et al., 2013). Ephemeral gullies facilitate the transport of coarse particles, including soil aggregates, resulting in variable micro-topography and soil redistribution (Poesen et al., 2003; Zhang et al., 2007; Shi et al., 2012). Hence, most of soil properties exhibit considerable spatial variations in ephemeral gullies, which may cause spatial heterogeneity of soil detachment processes. Nevertheless, field investigation on the spatial variability in soil detachment is limited, although it is crucial to estimate soil loss by ephemeral gully erosion.

For a long hillslope on the Loess Plateau, soil erosion is characterized by evident vertical division. Soil erosion is limited at upper slopes and relatively serious at middle slopes, whereas more severe erosion or

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* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China.
E-mail address: ghzhang@bnu.edu.cn (G. Zhang).

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deposition occurs at lower slopes (Zheng et al., 2005). For other regions, Selby (1993) indicated that deposition can be present at both upper and lower slopes. These results indicate that a large fraction of eroded sediment was redistributed within a hillslope, particularly that with ephemeral gullies (Poesen et al., 2003; Fang et al., 2012). Soil redistribution is known to result in spatial variations in soil properties on hillslopes with ephemeral gullies. In a small watershed on the Loess Plateau, Hu et al. (2012a) found that the clay content had a stronger spatial variability than silt and sand contents in all transects, and the soil organic matter showed a moderate spatial variability for all landscapes. Lentz et al. (1993) demonstrated that ephemeral gully erosion has the greatest impact on sand content, bulk density, and organic matter at mid- and lower sections of a gully.

Plant litter can influence ephemeral gully development and erosion rate by disrupting the sediment-laden flow in the ephemeral gully. It often falls into the ephemeral gully and can form composite litter dams to reduce flow velocity (Pannkuk and Robichaud, 2003). These small dams can trap sediment when the sediment-laden flow is low and can break and release accumulated sediment when the sediment-laden flow increases (Geddes and Dunkerley, 1999). Hence, vegetation litter can be washed away or incorporated within the topsoil and exhibit spatial variations across the ephemeral gully. In well-developed ephemeral gullies, Gyssels et al. (2002) showed that some cereal crops were washed away, leading to spatial variation in the plant roots. De Baets et al. (2007) found that the spatial distributions of root properties (e.g., diameter, density, and length density) were highly variable in ephemeral gullies in the Mediterranean region. The spatial variation in roots depends on plant species, with grasses and reeds being the most effective species in reducing soil detachment capacity (*DC*) because of their high density of fine roots. Thus, specified plant species can be used to vegetate different positions of ephemeral gullies for preventing erosion by overland flow (De Baets et al., 2009).

DC by overland flow is defined as the maximum soil detachment rate when the flowing water is clear (Zhu et al., 2001; Zhang et al., 2009a). It is closely related to hydraulic conditions, such as flow discharge, slope gradient, flow depth, velocity, and sediment concentration. When the flow overcomes a threshold resistance of the soil, overland flow induces scouring, initiating macro channel formation (Nachtergaele and Poesen, 2002; Chaplot, 2013). *DC* increases with both flow discharge and slope gradient and can be well predicted by a power function (Zhang et al., 2003). The hydraulic parameters of shear stress, stream power, and unit stream power can also be used to estimate *DC* (Nearing et al., 1991).

DC is strongly influenced by soil properties, such as soil texture, bulk density, cohesion, and water stable aggregate (Knapen et al., 2007; Zhang et al., 2008). Clay partly determines the shear strength of the soil and thus enhances the soil resistance to detachment (Knapen et al., 2007). However, the effects of silt and sand particles on *DC* are ambiguous. Knapen et al. (2007) showed that *DC* was positively related to silt content and negatively related to sand content, whereas Sheridan et al. (2000) found that the particles larger than silt but less than 10 mm were easily eroded and associated with high erodibility. With an increase in bulk density and cohesion, the binding forces between soil particles are promoted and hence reduce the soil detachability to flowing water erosion (Zhang et al., 2009b; Wang et al., 2014a). Water stable aggregate, which express the soil structure stability, is generally recognized to have a negative effect on *DC* (Knapen et al., 2007; Li et al., 2015).

DC is also affected by plant properties, especially litter and root system. Plant litter has a significant effect on *DC* by overland flow (Smets et al., 2008). Knapen et al. (2008) found that litter incorporated into topsoil can decrease soil detachment by overland flow. The explanations for this decrease are two-fold: (1) litter increases the soil surface roughness, thereby increasing water ponding, decreasing runoff volume, and flow velocity, and (2) part of total flow shear stress is dissipated by litter and can no longer contribute to detach soil particles. Plant roots are another important factor affecting *DC* by overland flow (De Baets et al., 2006; De Baets and Poesen, 2010). The effectiveness of roots in reducing detachment to flowing water is closely related to its physically binding and chemically bonding effects (Prosser et al., 1995; Wang et al., 2014b).

At ephemeral gully developed hillslopes, soil and plant properties exhibit significant spatial variations that may lead to the spatial variability in *DC* by overland flow. Nevertheless, few studies have been conducted to detect the spatial variability in *DC* caused by ephemeral gully development, and its potential influencing factors remain unclear. Hence, the objectives of this study were to investigate the spatial variation in *DC* by overland flow using 606 undisturbed soil samples collected from nine transects at one typical ephemeral gully developed hillslope on the Loess Plateau and, further, to identify the dominant factors influencing the heterogeneity of *DC*.

2. Study site

The study was conducted in the Zhifanggou small watershed (36°46′28″–36°46′42″N, 109°13′46″–109°16′03″E) that belongs to the second Deputy District of the hilly Loess Plateau region. The watershed has a drainage area of 8.27 km^2 and an altitude ranging from 1010 to 1431 m. The climate is semi-arid, and the mean annual temperature and precipitation are 8.8 °C and 505 mm, respectively (Wang et al., 2013). The precipitation is highly variable within the year, with 70% of the rain occurring between July and September as short heavy storms (Li et al., 2015). The watershed features a typical mountainous topography with deeply incised and densely distributed gullies (gully density 8.06 km km^{-2}) (Li, 1995). The principal soil is loess with a silt loam texture and is easily eroded.

After detailed field surveys, a typical hillslope with ephemeral gullies covered with black locust (*Robinia pseudoacacia* L.) was selected for this study. The selected hillslope was originally used as farmland and has been forested for approximately 20 years (Fig. 1). The vegetation cover is approximately 80%, and there is some litter (leaves, beans, and dead wood) incorporated within the topsoil. The slope gradient of the selected hillslope varies from 30.9% to 50.0%, and the elevation ranges from 1207 to 1257 m. Two completely developed ephemeral gullies were selected for soil sampling. The length of the ephemeral gully is approximately 80 m, and the width is approximate 40 m. At the top of the hillslope, the 10-m-long original hillslope located just above the head of ephemeral gullies was also selected to compare *DC* between ephemeral-gully and non-ephemeral-gully developed areas. From top to bottom of the hillslope, the study area was categorized into four areas: uppermost, upper, middle and lower slopes, respectively (Fig. 1). There are some weeds (i.e., *Setaria viridis* (Linn.) Beauv.) in the uppermost slope, whereas there are few or none in the other three slopes.

3. Materials and methods

3.1. Soil sampling

3.1.1. Sampling sites

The topography of the studied hillslope was measured using a real-time differential Hi-Target V30 RTK GPS (with planimetric and altimetric precisions of 2 and 20 mm, respectively) (Cheng et al., 2007) after soil sampling was complete to avoid potential disturbance of top soil during the topography measurement. Measurements were taken at intervals of approximately 0.5 m. Altogether, 9707 points were measured and further used to build a DEM of the study area with ArcGIS software (Version 9.2).

All sampling sites were designed according to the topography of the ephemeral gully. For two adjacent ephemeral gullies, nine transects (named Ephemeral gully top 1, Ephemeral gully side 1, Ephemeral gully floor 1, Ephemeral gully side 2, Ephemeral gully top 2, Ephemeral gully side 3, Ephemeral gully floor 2, Ephemeral gully side 4, and Ephemeral gully top 3) were selected for soil sample collection (Fig. 1). To detect the spatial variation in *DC* at different scales, intensive