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Soil moisture variability along transects over a well-developed gully in the Loess Plateau, China

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ABSTRACT

Knowledge of soil moisture distributions in gullies, which are highly variable spatially and temporally, is important for both restoring vegetation and controlling erosion in them, but little attention has been paid to this spatio-temporal variability to date. Therefore, we examined soil moisture profiles and their variability along three transects traversing sidewalls of a well-developed gully with steep slopes in a hilly area of the Chinese Loess Plateau. We took intensive measurements at 20-cm intervals from 0 to 160 cm depth, using a portable time domain reflectometer, from September 3 to October 20 2009 and from April 5 to July 20 2010. The results indicate that the mean, standard deviation and coefficient of variation of moisture content vary with time, their responses to precipitation vary at different depths, and moisture content is most variable when mean values are moderate (15–20%). Revised fitting functions developed and introduced by Famiglietti et al. (2008) captured with confidence the relationship between spatial variability (SD and CV) and spatial mean of moisture content (RMSE ranging from 0.0015 to 0.0293). Soil moisture clearly varied along the transects, the vertical distribution of soil moisture differed in different seasons, and correlation analysis showed that soil texture influenced the variability of surface soil moisture more strongly than terrain attributes (except during distinct rainfall events, when this pattern reversed). The results presented here should improve understanding of spatio-temporal variations in soil moisture profiles in well-developed gullies in the Loess Plateau, and potentially elsewhere.

1. Introduction

Soil moisture is a limiting factor governing vegetation restoration in semiarid areas (Chen et al., 2007; Moreno-de las Heras et al., 2011) involving the Chinese Loess Plateau (Fu et al., 2003; Wu et al., 2003), and is critical to runoff generation and soil erosion by switching continuous hydrological pathways between source areas (Fitzjohn et al., 1998). The spatio-temporal variability of soil moisture strongly influences vegetation restoration (Chen et al., 2007; Fu et al., 2003; Tromp-van Meerveld and McDonnell, 2006; Rodriguez-Iturbe et al., 1995), and hydrological processes (Choi and Jacobs, 2007; Hupet and Vanclooster, 2002). Thus, its complex spatio-temporal patterns and variability have been widely investigated, at various scales, by hydrologists and ecologists in recent decades. However, few studies have focused on the spatio-temporal variability of soil moisture in gullies (e.g., Melliger and Niemann, 2010; van den Elsen et al., 2003). This is partly because it is difficult to sample soil moisture in gully areas where steep slopes are prevalent. Nevertheless, despite the inconvenience, knowledge of the variability of soil moisture in gullies is essential to advance our understanding of soil erosion processes and factors affecting vegetation restoration in gullies (Collins and Bras, 2008).

Gullying is an important form of land degradation (Melliger and Niemann, 2010), which is responsible for most of the sediment deposited in downstream pools (Krause et al., 2003; Li et al., 2003) and reduces the grazing value and agricultural potential in many regions of the world (Avni, 2005). In the Loess Plateau of China, gullies occupy approximately 42% of the total area, with a density of 1.5–4.0 $km \cdot km^{-2}$ (Zheng et al. 2006), rising to 50–60% and 3–8 $km \cdot km^{-2}$, respectively, in hilly loess regions (Huang and Ren, 2006). Gully erosion is also regarded as the main source of sediments in catchments in hilly loess areas (Huang and Ren, 2006; Li et al., 2003; Valentin et al., 2005;), contributing to 60–70% of total sediment production (Li et al., 2003; Zhu and Cai, 2004). Although soil moisture is not a key parameter for most quantitative models of gully evolution,

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it plays critical roles in gullying, for several reasons (Melliger and Niemann, 2010). First, abundant soil moisture can promote vegetation regrowth (Melliger and Niemann, 2010), while prolonged water deficiency promotes vegetation decay and gully incision (Rodriguez-Iturbe et al., 1999; Collins and Bras, 2008). Second, when soil moisture approximates saturation, the shear strength of soils becomes low, making soils prone to erosion (Istanbulluoglu et al., 2005; Moore et al., 1988), while drier soils retain more rainfall, reducing the probability of runoff generation. Third, gully sidewalls are highly susceptible to drying through evapotranspiration (van den Elsen et al., 2003), potentially enhancing water stresses, reducing vegetation cover and accelerating gullying processes, while moist sidewalls can enhance vegetation growth and gully stability, in uplands.

The relationship between mean moisture content and spatial variability has been intensively studied, and spatio-temporal correlations between soil moisture variability and mean moisture content have also been examined in various environmental contexts. However, as noted in a recent review by Vereecken et al. (2007), conflicting results have been reported; some studies have found increases in the standard deviation (SD, hereafter) of soil moisture with reductions in mean moisture content (Brocca et al., 2007; Famiglietti et al., 1999; Hupet and Vanclooster, 2002), while others have found the opposite (Famiglietti et al., 1998; Martinez-Fernandez and Ceballos, 2003). Furthermore, recent studies have found that SD and mean moisture content exhibit a convex upward relationship, i.e., SD initially increases with mean moisture content, peaks and then declines (Brocca et al., 2010; Famiglietti et al., 2008; Vereecken et al., 2007). Numerous factors influencing soil moisture variability have also been reported, for instance, topography, soil properties, vegetation and atmospheric forcing. It is worth noting that the dominant factor is expected to vary with different hydrological settings (Western et al., 2004). For example, Famiglietti et al. (1998) found soil texture than topography exhibited strong correlations with soil moisture along a transect with gentle slope. This has been demonstrated to be correct even in areas with steep slopes (Penna et al., 2009). Whereas, Grayson et al. (1997) argued that the dominating factors controlling soil moisture variability were dependent on soil moisture status. For instance, Bogena et al. (2010) found that terrain attributes showed the strongest correlations with soil moisture over dry periods, but not in the wet periods. Furthermore, Gómez-Plaza et al. (2001) found vegetation played a vital role in soil moisture variability in vegetated zone while soil texture and slope explained a large part of soil moisture distribution in non-vegetated zone. For gullies in the Loess Plateau, both steep slopes and complex micro-topography exist, so the relationship between soil moisture and topography warrants further attention.

To date, there have been few studies of the spatio-temporal variability of soil moisture in gullies, although a number of investigations have examined its variability in gully catchments (e.g., Fitzjohn et al., 1998; Fu et al., 2003; Qiu et al., 2010). These limited reports have shown that distributions and dynamics of soil moisture in gullies differ from those in slopelands. For instance, van den Elsen et al. (2003) found that the sidewalls of a hillslope gully located in the Loess Plateau had much lower water contents than the surrounding uplands, and received small amounts of infiltration from rain showers. They also found that soil moisture contents of the sidewalls decreased with increasing distance from the gully edge and that precipitation could supply water down to 70 cm in a wet year, but not to such depth in a dry year. Similarly, Melliger and Niemann (2010) found that the bottom of gullies they studied in Colorado tended to be wetter, and their sidewalls drier, than adjacent uplands, due to lower evapotranspiration and rapid drainage during and after storm events, respectively. They also argued that the occurrence of gullies promotes spatial variability of soil moisture, although little impact of gullies was found on the spatial mean soil moisture content in their field sites. Another important aspect to consider is that plant-accessible zones of soil moisture are generally deeper in arid and semiarid environments because of the hydrotropism of roots and usually low moisture contents in their shallow soil layers. In the Loess Plateau in particular, the depth of active zones often exceeds 1 m because of the thick loess (Yang and Shao, 2000). Thus, in vegetation-related contexts, especially, soil moisture should be studied throughout the whole soil profile (or at least over a depth of several decimeters) rather than just a thin layer at the soil surface (Blöschl and Sivapalan, 1995).

The objectives of the study presented here were to characterize: (i) spatio-temporal distributions of soil moisture, and their variation, in three soil layers (0–20, 0–80 and 80–160 cm; defined here as the surface soil, root zone and deep soil layers, respectively); and (ii) the relationships between mean moisture content and both terrain attributes and soil texture in a well-developed gully in a hilly area of the Loess Plateau, China.

2. Materials and methods

2.1. Site description

The study site was a well-developed gully of Yuanzegou catchment (37°15′N, 118°18′E) (Fig. 1), located in the north central part of the Loess Plateau in the northern Shaanxi province of China. The catchment covers an area of 0.58 km^2 with a gully area of 0.31 km^2. This area has a semiarid continental climate with (based on data for 1956–2006): mean annual precipitation of 505 mm, 70% of which falls during late summer and early autumn (August, September and October); a mean annual temperature of 8.6 °C, with mean monthly temperatures ranging from −6.5 °C in January to 22.8 °C in July; 157 frost-free days and 2720 h of sunshine on average each year (Weather Bureau of Qingjian county, Shaanxi province). The elevation of the Yuanzegou catchment ranges from 865 to 1105 m. The main gully stretches from south to north, with prevalent steep slopes, of 35–90°.

The gully sidewalls are weakly disturbed by human activity. Soils are primarily composed of loess with texture of fine silt and silt loam. Summary information on soil properties in 0–100 cm is shown in Table 1. Soil thickness ranges from less than 0.2 m on the gully floor to more than 15 m at gully edges. The soils are primarily vegetated with perennial grasses, including *Artemisia gmelinii*, *Bothriochloa ischemum* and *Lespedeza davurica*, with main rooting depths of 60–80 cm. The shrub *Caragana korshinskii*, is sparsely scattered over sidewalls, with a rooting depth of approximately 280 cm (Cheng et al., 2009).

2.2. Soil moisture sampling transects and soil moisture sampling

Three transects (A, B and C; Fig. 1), traversing the gully sidewalls were established, with lengths of approximately 50, 80 and 50 m, respectively, to sample soil moisture. The gully floor was ignored since much of it consists of exposed bedrock and the rest is covered with thin loess (<20 cm). There were nine sampling points along transect B, and five along both transects A and C, spaced ca. 10–15 m apart (Fig. 1). Soil moisture was sampled at these points at depths of 0–160 cm at 20 cm intervals during two periods: from September 3 to October 20 2009 and from April 5 to July 22 2010. During the two periods, soil moisture was sampled approximately weekly routinely, and 1 h after rainfall events. During the entire sampling periods there were 26 sampling occasions and 3853 measurements were taken in total. Note that soil moisture was only measured along transect A in April 5 and April 15 2010, and soil moisture was not measured along transect C in May 6 2010. On each sampling occasion, soil moisture was sampled within 4 min at each sampling point and all the soil moisture measurements were taken within 2 h. During such short times, the temporal variation of soil moisture was expected to be negligible.

A portable automatic weather station is located on the relatively planar gully upland, close to the sampling transects. In total 379.7 mm precipitation was observed during the study period. The precipitation and potential evapotranspiration (ET_0) recorded for each month during the study period are shown in Table 2. Soil moisture values for all depths were sampled using a portable time domain reflectometry (TDR)