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Profile distribution of soil moisture in the gully on the northern Loess Plateau, China

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ABSTRACT

Gully is a typical geographical unit and a key component of the slope–gully system on the northern Loess Plateau. Understanding the distribution of soil moisture in gullies aids water resource regulation and ecological restoration. To investigate temporal–spatial variability of soil moisture, we measured values of soil water content (SWC) within 0–500 cm by using a neutron probe on 19 occasions from October 2014 to July 2017 in the gully and bank of a developed gully in Liudaogou catchment of Shenmu County. Results showed that the values of space–averaged soil water storage (SWS) in the gully were significantly ($P < 0.01$) higher than those in the bank. Soil clay content (SCC) and topography (including site elevation and distance from the gully head) were the most important factors affecting SWS of 0–500 cm in the gully. Topography can indirectly control SWS by redistribution of rainfall and soil properties. SWS and SCC rose with increasing distance from the gully head to the outlet. SWS in the gully exhibited strong temporal stability, and two time–stable sites around the middle section can be used to represent mean SWS within 500 cm depth in the gully. The gully sidewall significantly ($P < 0.05$) aggravated drought of soils in the bank between 150 and 250 cm from the gully edge. Gullies make the temporal–spatial patterns of soil moisture complex in slope–gully system. These results were expected to improve understanding of soil moisture distribution in the gully region and aid vegetative restoration of the northern Loess Plateau.

1. Introduction

Soil moisture plays an important role in vegetative restoration of the Loess Plateau, China (Hu et al., 2009; Gao et al., 2011). Characterising soil water content (SWC) and soil water storage (SWS) can provide essential information on vegetation conservation and on sustainability of the environment. In recent years, many studies have focused on temporal–spatial dynamics of soil moisture on the Loess Plateau (Hu et al., 2009; Hu et al., 2010a; Hu et al., 2010b; Gao and Shao, 2012; Jia et al., 2013; Jia and Shao, 2013; Wang et al., 2012; Zhao et al., 2010). Soil moisture over different terrains, patterns of land use and soil types have been investigated. Soil moisture is highly variable over time and space because of soil heterogeneity, climatic forcing, vegetation and topography, but it also shows a spatial pattern with strong temporal stability (Vachaud et al., 1985; Zhao et al., 2010; Zhang and Shao, 2013). The concept of temporal stability has been broadly applied to identify representative locations for estimating mean soil moisture in various land types (Brocca et al., 2009; Coppola et al., 2011; Cosh et al., 2004, 2008; Guber et al., 2008; Lin, 2006; Schneider et al., 2008; Zhao et al., 2010; Martinez et al., 2014). Estimating mean soil moisture of large areas by monitoring representative locations can significantly reduce economic and labour costs. Special topography and spatial pattern of soil moisture allowed the use of temporal stability method to predict soil moisture in the gullies.

The Chinese Loess Plateau is one of typical regions with large gullies in the world. Gully areas in the Loess Plateau account for 42% of the whole land with gully density reaching 1.5–4.0 km km^{-2} (Zheng et al., 2006). Qiu et al. (2001) considered that topography and land use played controlling roles in the spatial distribution of soil moisture content in the regions with gully. Catchments on the Loess Plateau can be divided into hillslopes and gullies. With the water accumulating and intense erosion in the gully, the subsoil was exposed after a heavy rain. The exposed subsoil and topography significantly altered soil texture, organic matter, soil structure and vegetation (Famiglietti et al., 1998),

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which dominantly influence soil moisture variability. However, most studies on soil moisture in the Loess Plateau focused on the bank region. Insufficient attention was paid to soil moisture in the gully. This was because of the complex topography, steep slopes and difficulty while sampling soil moisture in gullies. In this regard, Gao et al. (2013) used data on soil moisture sampled from uplands to estimate mean soil moisture from 0 cm to 80 cm in gullies. However, more studies should be conducted to investigate the temporal–spatial dynamics and temporal stability of soil moisture in gullies to improve sampling strategies and predictive models for monitoring soil moisture.

To date, some studies have investigated soil moisture in gully regions, although there have been few studies about the soil moisture variation in gullies (Fu et al., 2003; Qiu et al., 2010; Gao et al., 2013). Given the highly variable soil, terrain and vegetation properties (Zhao et al., 2010), soil moisture in gullies highly differs from that in slopelands (Fu et al., 2003; Qiu et al., 2010). In a storm event, rapid drainage in gullies can significantly improve soil moisture at the gully outlet (Melliger and Niemann, 2010). Meanwhile, unequal supplement of rainfall along the gully increases variability of soil moisture over space. With 55–78% of the precipitation falling in June through September in the Loess Plateau, and mostly as high intensity rainstorm (Jia et al., 2017), elucidating the effects of topography on spatial pattern of soil moisture in the gully will add more significance in developing related strategies for monitoring. By contrast, the sidewalls of a hillslope gully contain much lower water contents than those at the bank. Soil moisture of the sidewalls also decreases with increasing distance from the gully edge (Van den Elsen et al., 2003; Melliger and Niemann, 2010). Scale, depth and shape of the gully and the local climate can affect the extent of side evaporation (Zheng et al., 2006). Huo et al. (2008) reported the effects of gully sidewalls on soil moisture of the shrubland on the bank within 400 cm in the horizontal direction in the Liudaogou catchment. However, the group did not account for soil texture, which varied remarkably over space in the Liudaogou catchment, while evaluating side evaporation.

In the Liudaogou watershed, where contained lots of gullies, an accessible gully was selected to explore soil moisture in areas with erosional gully and to extend application of temporal stability of SWS. We observed SWCs of the 0–500 cm soil profile in the gully and bank. Sampling was performed on 19 occasions from October 2014 to July 2017. The specific objectives of this study were as follows: (i) to compare characteristics of soil moisture in various soil layers between the gully and the bank, (ii) to analyse temporal–spatial dynamics of SWC profiles and to identify representative locations that can estimate mean SWS of the 0–500 cm layer in the gully and (iii) to evaluate side evaporation in both sides of the gully.

2. Materials and methods

2.1. Study area

The selected gully area for this study is located at the Liudaogou watershed of Shenmu County, Shaanxi Province, China (110° 22′ E, 38° 49′ N) (Fig. 1). The Liudaogou watershed has deep gullies and undulating slopes. This area is in the moderate–temperate and semi–arid zones, with a mean annual precipitation of 437 mm and a potential evapotranspiration of 785 mm. The elevations range from 1094 m to 1274 m above sea level. The study area is representative of the transitional belt subjected to both wind and water erosion. The soil type is a calcaric regosol (FAO–UNESCO) that developed from low–fertility loess. The soil exhibits weak cohesion, high infiltrability and low water retention, and is prone to erosion. The gully is 3–7 m deep, 8–30 m wide and approximately 240 m long, and its longitudinal cross is V–shaped. The average slope of this area is approximately 19°. In this area, trees and farmlands are absent. In the bank, degraded alfalfa (*Medicago sativa* L.) and bunge needlegrass (*Stipa bungeana* Trin.) are prevalent with sporadic grazing. Chinese pines (*Pinus tabuliformis*) were planted on the bank in August 2017. A transect in the middle part of gully was selected to assess the effects of side evaporation on soil moisture distribution (Fig.1). The depths of the gully sidewall are 360 cm and 300 cm for the northern and southern observational sites. The gully sidewall in the northern site is towards the south, and the gully sidewall in the southern site is towards the north. Sparse *Artemisia capillaris* are covered in the southern gully sidewall and the northern sidewall is almost bare.

2.2. Soil sampling and data collection

2.2.1. Measurement of SWC and SWS

Twelve 500 cm long aluminium neutron probe access tubes were installed from the top to the outlet of the gully with a mean interval of 20 m between two adjacent locations. Paralleled to the gully, seven aluminium neutron probe access tubes were installed in key locations on the bank 20 m away from the gully edge (Fig. 1). To preferably present SWC status of the bank near the gully edge, we equally divided 12 aluminium neutron probe access tubes into two groups and installed them separately in bank locations 50, 150, 250, 350, 450 and 550 cm from the gully edge in the northern and southern sites (Fig. 1). SWCs were measured using a neutron probe during growing seasons from October 2014 to July 2017. In total, 19 sampling occasions were recorded during the entire sampling period. Slow–neutron counts were obtained at 10 cm intervals to a depth of 100 cm and at 20 cm intervals from 100 cm to 500 cm. The volumetric soil water content θ at each depth was calculated from the slow–neutron counting rate (CR) using the following calibration curve:

0–10 cm depth: $\theta = 0.111 * \mathrm{CR} + 3.9565$ ($R^2 = 0.8996$, $P < 0.001$)

10–500 cm depth: $\theta = 0.091 * \mathrm{CR} + 1.8995$ ($R^2 = 0.7578$, $P < 0.001$).

The calibration curve was obtained in the same area and was considered valid for all soil depths. The SWS (mm) was calculated from the θ_k ($\mathrm{cm^3\,cm^{-3}}$) (k refers to different soil depths, cm). The SWS values of the 0–100 cm and 100–500 cm layers were calculated by the following trapezoidal rules:

$$\mathrm{SWS}\ (0\text{–}100\ \mathrm{cm}) = 100 * (\theta_{10} + \theta_{20} + \theta_{30} + \theta_{40} + \theta_{50} + \theta_{60} + \theta_{70} + \theta_{80} + \theta_{90} + \theta_{100})$$

$$\mathrm{SWS}\ (100\text{–}200\ \mathrm{cm}) = 200 * (\theta_{120} + \theta_{140} + \theta_{160} + \theta_{180} + \theta_{200})$$

$$\mathrm{SWS}\ (200\text{–}300\ \mathrm{cm}) = 200 * (\theta_{220} + \theta_{240} + \theta_{260} + \theta_{280} + \theta_{300})$$

$$\mathrm{SWS}\ (300\text{–}400\ \mathrm{cm}) = 200 * (\theta_{320} + \theta_{340} + \theta_{360} + \theta_{380} + \theta_{400})$$

$$\mathrm{SWS}\ (400\text{–}500\ \mathrm{cm}) = 200 * (\theta_{420} + \theta_{440} + \theta_{460} + \theta_{480} + \theta_{500}).$$

2.2.2. Measurement of other main characteristics

The disturbed soil samples from 0 cm to 500 cm for each observational point were collected and air–dried at 20 cm intervals. Their soil particle sizes were analysed by laser diffraction using a Mastersizer 2000 (Malvern Instruments, Malvern, England). To measure the saturated soil hydraulic conductivities (Ks, $\mathrm{mm\,min^{-1}}$) and soil bulk density (BD, $\mathrm{g\,cm^{-3}}$), a pit was excavated 50 cm away from the access tube to collect the undisturbed soil samples at 10 cm intervals to a depth of 30 cm. The Ks of the collected soil samples were measured using the constant–head method (Klute and Dirksen, 1986). AGB and Litter data were collected in July 2016 and 2017, and the details of the sampling method can be found in the study of Jia et al. (2013). The mean values of AGB and Litter in 2016 and 2017 were used to correlate with SWS values. An RTK–GPS receiver was used to locate the sampling sites and record the sea elevations (SE, m) and the distance from gully head (DGH). Using the selected variables, we investigated the effects of soil, topography and properties of vegetation (Table 1) on the SWS. A rain gauge was set in the Shenmu Erosion and Environment Research Station in the Liudaogou watershed to obtain the rainfall data.