Geoderma 261 (2016) 1–10

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Effects of large gullies on catchment-scale soil moisture spatial behaviors: A case study on the Loess Plateau of China

Xiaodong Gao [a,b], Xining Zhao [a,b,*], Pute Wu [a,b], Luca Brocca [c], Baoqing Zhang [d]

[a] Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, Shaanxi, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling 712100, Shaanxi, China
[c] Research Institute for Geo-Hydrological Protection, National Research Council, Via Madonna Alta 126, 06128 Perugia, Italy
[d] College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, Gansu, China

ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 30 June 2015
Accepted 2 July 2015
Available online 12 July 2015

Keywords:
Soil moisture
Spatial variability
Gully
Geostatistics
Sampling strategy
Loess Plateau

ABSTRACT

Large gullies which occur globally affect greatly ecohydrological processes in gullied landscape. However, the effects of large gullies on spatial behaviors of soil moisture, a critical ecohydrological variable, at catchment scale are poorly understood. To this end, we conducted spatially intensive soil moisture measurements in the 0–60 cm during the spring, summer and fall of 2010 in the Yuanzegou catchment on the Loess Plateau of China. Statistical and geostatistical analyses showed that the presence of gullies clearly increased the spatial variability in terms of standard deviation (by 26.4% on average), nugget (by several folds) and sill (by 41.3% on average), but had weak effects on spatial means. Particularly, the large gullies also markedly strengthened soil moisture spatial correlations. Slope aspect was shown to be a stronger topographic control than elevation and gradient on soil moisture spatial variability whether or not gully observations were included. The role of elevation in soil moisture variability depended on the presence of gullies. As gully observations were included, significant ($P < 0.01$) and stronger correlations were observed in summer; however, as gully observations were excluded, stronger correlations were found in spring and fall. The presence of gullies increased the required number of samples (N) by 33 to 100% to accurately represent spatial means. A random combination method showed that the effects of sample counts on soil moisture spatial variability were more dependent on gully observations and showed clear seasonality compared with spatial means. This means that both spatial means and spatial variability should be considered for optimizing sampling strategy for gullied topography.

1. Introduction

Large gullies, which occur globally, represent an important form of severe land degradation and affect greatly ecohydrological processes in gullied landscape (Melliger and Niemann, 2010). Soil moisture is an important ecohydrological variable in land-surface ecosystems (Rodriguez-Iturbe et al., 1999) and usually exhibits complex spatial patterns affected jointly by precipitation, topography, soil properties and vegetation (Vereecken et al., 2007). Consequently, the characterization of large gully's effects on soil moisture spatial behaviors is vital for improving predictions of hydrological and ecological processes in gullied environments (Gao et al., 2013a).

Spatial variability of soil moisture has been intensively probed across scales in the last three decades (Bell et al., 1980; Hawley et al., 1983; Famiglietti et al., 1998, 2008; Qiu et al., 2001; Cosh et al., 2004; Brocca et al., 2007, 2012; Penna et al., 2009; Hu et al., 2010, 2011; Gao et al., 2011; Rosenbaum et al., 2012; Biswas et al., 2014). However, only a few efforts have been done in gullied environments to understand soil moisture variability there, probably because of the difficulty of sampling (Gao et al., 2011). Melliger and Niemann (2010) characterized the effects of gullies with an average depth of 2.5 m on surface (0–10 cm) soil moisture variability in southeastern Colorado. They found that gullies increased soil moisture spatial variability but had no significant effects on spatial means. Van den Elsen et al. (2003) and Gao et al. (2013a) studied soil moisture spatial variations at much deeper (30–100 m) gullies on the Loess Plateau of China. They found that the uplands had higher soil moisture contents than the gullies; however, their sampling locations only distributed over gully sidewalls and they missed to examine the effect of gullies on soil moisture spatial variability. Furthermore, Hu (2009) characterized the effects of gullies on soil moisture spatial distribution on the Loess Plateau. They found that the presence of gullies increased clearly both spatial means and spatial variability of soil moisture, maybe because the majority of the locations in gullies were distributed in gully bottoms where soils should be wetter.

Despite the above efforts, the effects of large gullies on soil moisture spatial variation is still far beyond clear. Three particularly important questions relating to this topic are (1) do large gullies alter the spatial correlations of soil moisture fields; (2) how large gullies affect the

---

* Corresponding author at: No. 26, Xinong Road, Yangling, Shaanxi Province 712100, China.
E-mail address: xiningz@aliyun.com (X. Zhao).

http://dx.doi.org/10.1016/j.geoderma.2015.07.001
0016-7061/

relations of soil moisture with the complex topography; and (3) what is the optimal soil sampling strategy when working in areas with large gullies. For the third issue, earlier studies primarily focus on mean values and did not consider spatial variability for the design of optimal sampling strategies (Brocca et al., 2007, 2010, 2012; Zhou et al., 2007; Wang et al., 2008; Hu et al., 2010; Han et al., 2012; Heathman et al., 2012; Gao et al., 2013b; Sur et al., 2013). Here, this issue is addressed by investigating the effects of increasing sample counts on both spatial means and spatial variability.

The Chinese Loess Plateau is typical of regions with large gullies around the world. In general, catchments on the Loess Plateau can be divided into two parts: uplands, which are usually hillslopes, and gullies (Tang, 2004). Overall, gullies cover approximately 42% of the total area of the Loess Plateau, at a density of 1.5–4.0 $\mathrm{km \cdot km^{-2}}$. Gully coverage and density increase to around 50–60% and 3–8 $\mathrm{km \cdot km^{-2}}$, respectively, in the plateau's hilly regions (Huang and Ren, 2006). However, most investigations into catchment-scale soil moisture variability in this region have focused on soil moisture behavior in the uplands, where the topography is much flatter than in gullies, and used the results to draw conclusions about the catchment as a whole (Qiu et al., 2001; Fu et al., 2003; Hu et al., 2010; Gao et al., 2014). Consequently, the effects of large gullies on catchment-scale soil moisture variability on the Loess Plateau remain poorly understood.

Based on the above analyses, we hypothesize that the presence of large gullies has significant effects on the spatial behavior of soil moisture at catchment scale. To test this hypothesis, we analyzed spatial behaviors of soil moisture by examining a soil moisture dataset relating to a heavily gullied catchment on the Loess Plateau. The dataset contains soil moisture observations collected at 213 sampling locations with 42 out of them in gullies. Soil moisture was measured during three campaigns conducted in the spring, summer and fall of 2010. The effects of large gullies on the spatial behavior of soil moisture are investigated through statistical, geostatistical and numerical analyses.

2. Materials and methods

2.1. Site description

The study site, Yuanzegou catchment (37°14′N, 110°20′E, Fig. 1), is located in the northern part of Shaanxi province of China. This catchment is typical of heavily gullied catchments on the Loess Plateau with an area of 0.58 $\mathrm{km^2}$ wherein 53.4% of the total area is covered by gullies. Based on meteorological data from 1956 to 2006 provided by Weather Bureau of Shaanxi province, this region has a semiarid continental climate: annual average precipitation of 505 mm, 70% of which falls in 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. As indicated in Fig. 1, the elevation of the catchment rises from 865 to 1105 m. The uplands comprise hillslopes of tens to hundreds of meters, with relatively gentle gradients (<30°). The gullies have much steep slopes generally ranging from 30 to 90°. The main gully direction extends from south to north. Most of the gully bottom comprises exposed bedrock with only a thin soil layer (generally <20 cm). The whole catchment is covered by thick silt loam loess soils (Inceptisols, USDA) with 19.8% sand, 63.0% silt and 17.2% clay. The average field capacity and permanent wilting point are 25.6 and 6.5% in volume, respectively. There are mainly three land use types on uplands: croplands, abandoned croplands with different years, and jujube orchards. The gullies are covered by sparse annual and perennial grass. Please refer to Gao et al. (2011, 2014) for more details in soil properties, topography, and land use types in the catchment.

2.2. Soil moisture data

We selected three typical non-rainstorm periods in spring (April 10 and 11), summer (June 14 and 15) and fall (August 31 and September 1) in 2010 to collect soil moisture. The sampling locations were distributed in different spatial positions over the whole catchment (Fig. 1). There were in total 213 locations, of which 171 were over hillslopes and 42 over gullies. The reason of fewer sampling locations over gullies is because of the difficulty in collecting soil moisture over complex topography and steep slopes there. However, soil moisture collected from these locations is expected to represent reliably that of the whole gully because these locations covered different aspects and slope positions of gully sidewalls as well as gully bottoms where soil sampling is available. Soil moisture was sampled at the depths of 10, 20, 40 and 60 cm by hand augers (28 cm in diameter). These soil samples were taken to lab to measure gravimetric moisture content by using oven-dry method (For details, please refer to Penna et al. (2009)). The precipitation prior to the three sampling periods was 8.2 mm (April 3, 2010), 4.8 mm (Jun 8, 2010) and 58.9 mm (from August 18 to August 22, 2010). Note that this dataset includes only gravimetric moisture contents.

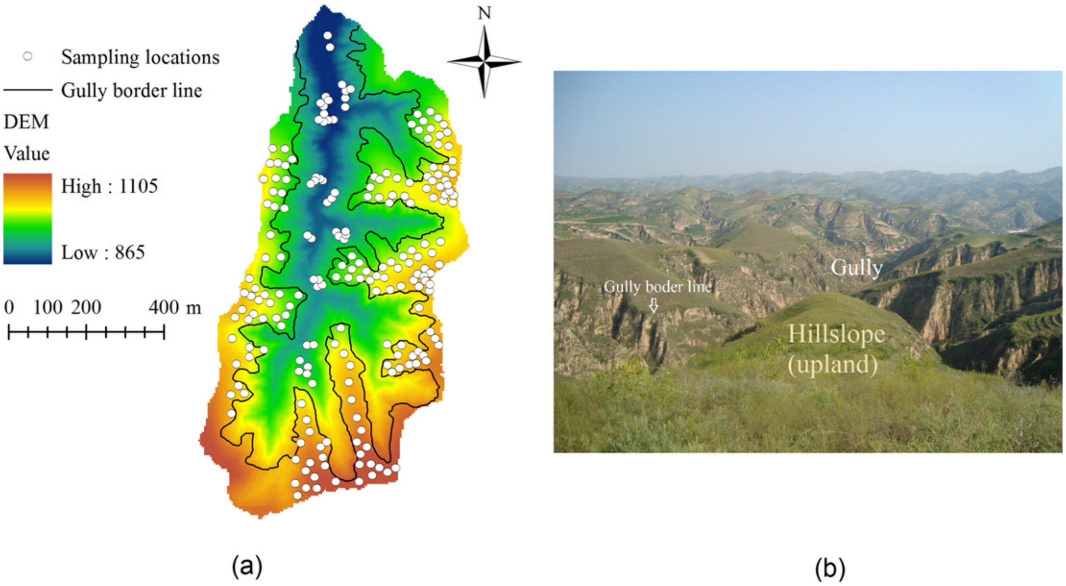

Fig. 1. Information of study site: DEM of the Yuanzegou catchment and distribution of sampling locations (a) and views of landscape for the catchment (b).