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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)

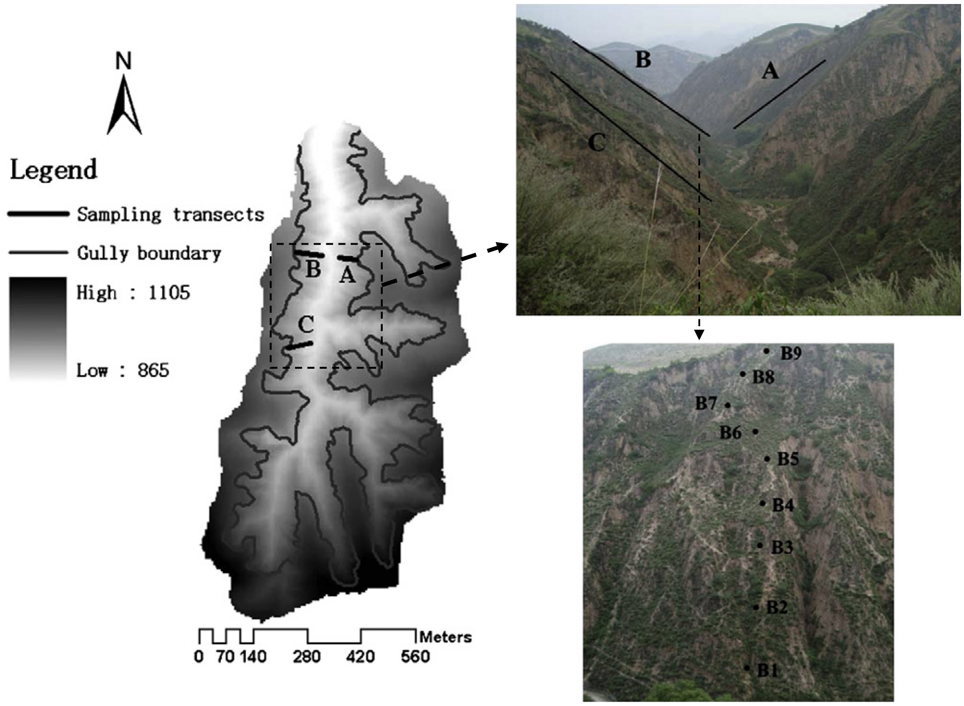

Fig. 1. Digital elevation model (a) and photograph (b) of Yuanzegou catchment and locations of the sampling transects (A, B and C) traversing the gully sidewalls.

system (TRIME-PICO IPH/T3; IMKO, Germany), consisting of a TRIME-IPH probe, a TRIME-DataPilot datalogger and fiberglass access tubes ($\phi=40$ mm). A hand auger ($\phi=45$ mm) was used to install fiberglass access tubes instead of the original accessories for installing tubes, which are difficult to operate over gully sidewalls. To facilitate installation of the tubes, the relief at some sampling points was disturbed slightly. The space between the tube and soil was filled with a mixture of the soil removed by the hand auger and water. The TRIME TDR system has been shown to provide accurate soil moisture measurements in the Loess Plateau region after local calibration (Li et al., 2005). Therefore, the system was gravimetrically calibrated for the specific local soils examined in this study, as follows. Soil moisture was measured using the TDR tool in five 20 cm intervals down to a depth of 100 cm. Meanwhile, a 1 m-deep pit was excavated 0.5 m from the access tubes to collect undisturbed soil samples from the corresponding depths in order to obtain measurements of the dry soil bulk density and gravimetrical soil moisture content (θ). Values of θ were then transformed to volumetric moisture contents (Hu et al., 2009), and a calibration curve was generated by plotting the measured TDR-derived moisture values (X,$cm^3 \cdot cm^{-3}$) against the volumetric moisture contents (Y,$cm^3 \cdot cm^{-3}$), and fitting a regression equation (Eq. 1).

$$Y = 0.9471X - 4.3796, \qquad R^2 = 0.904, \qquad RMSE = 2.68\% \qquad (1)$$

2.3. Terrain attributes and soil texture

The resolution of the only available digital elevation model (DEM) of the study site (5 m) is too low to characterize terrain attributes of the sampling points because of the steep slopes and complex micro-topography of the gully sidewalls (Fig. 2). Hence, a geological compass was used to determine the initial slope (before installing tubes), the disturbed slope (after installing tubes), and the aspect at each sampling

Table 1
Soil properties of 0–100 cm at the study site.

Soil layer	BD	Soil texture			K_{sat}	θ_s	$\theta_{33\ kPa}$	$\theta_{1500\ kPa}$
	g/cm^3	Sand% (2–0.02 mm)	Silt% (0.02–0.002 mm)	Clay% (<0.002 mm)	mm/min	cm^3/cm^3	cm^3/cm^3	cm^3/cm^3
0–20 cm	1.33	19.2	65.1	15.7	1.04	50.8	28.1	6.8
20–40 cm	1.38	18.8	65.2	16.0	1.11	53.8	28.7	7.7
40–60 cm	1.39	16.9	65.9	17.2	0.82	53.3	29.6	8.2
60–80 cm	1.46	16.2	63.7	20.1	–	54.6	30.5	9.4
80–100 cm	1.43	16.9	61.4	21.7	–	56.0	29.9	10.1

BD: bulk density; K_{sat}: saturated hydraulic conductivity; θ_s: saturated water content; $\theta_{33\ kPa}$: soil moisture content at 33 kPa; $\theta_{1500\ kPa}$: soil moisture content at 1500 kPa.

Table 2
Monthly precipitation and potential evapotranspiration (ET_0) during the study period.

Month	2009/9	2009/10	2010/4	2010/5	2010/6	2010/7	2010/8	2010/9
Precipitation	103.2	18.8	21.3	29.7	12.9	27.1	136.7	46.3
ET_0[a]	91.8	66.5	112.3	166.7	204.2	178.0	123.4	102.4

[a] ET_0 was calculated using Penman–Monteith equation.

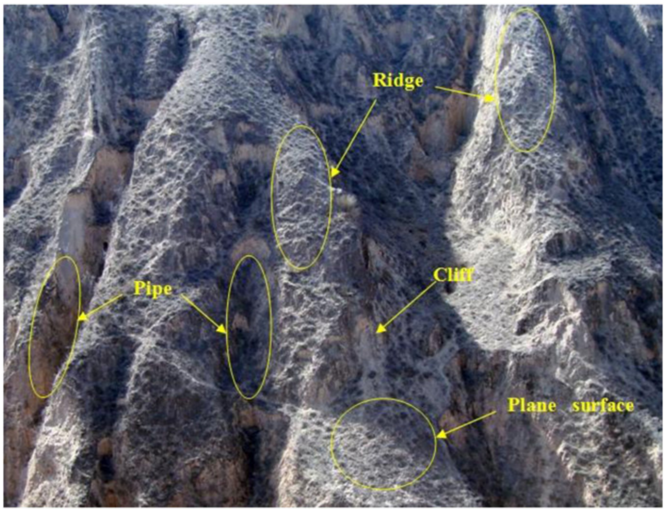

Fig. 2. Photo illustrating ridges, pipes, plane surfaces and cliffs in the gully sidewall.

point. In addition, a portable global positioning system (GPS) was employed to determine the elevation at all sampling points.

Due to the distinctive irregularities of gully sidewalls' relief, their terrain can be classified into four types — ridges, pipes, plane surfaces and cliffs (Fig. 2), all of which influence soil moisture distributions. Specifically, ridges refer to long narrow surfaces while plane surfaces refer to surfaces much wider than ridges. Pipes are defined as long narrow concaves where surface runoff concentrates and flows down. In fact, pipes usually exist in the form of small gullies.

Along each transect, disturbed soil in the 0–20 cm layer at each sampling point was sampled with a hand auger ($\phi=40$ mm) to determine the soil texture, in terms of the sand (0.02–2 mm), silt (0.002–0.02 mm) and clay (<0.002 mm) contents. Three soil samples were collected by each sampling point, and their texture was determined using an MS 2000 particle size analyzer (Malvern, Britain). Table 3 presents an overview of the terrain attributes and soil texture at all sampling points.

2.4. Calculation of variables

We denote the 0–20, 20–40… 140–160 cm layers as d1, d2… d8, respectively, and the soil moisture content in these layers is calculated as follows.

a) Soil moisture profiles at a given sampling occasion for the three considered depths:

$$\theta_{20,j,t} = \theta_{d_1,j,t}, \qquad \theta_{80,j,t} = \frac{1}{4}\sum_{i=1}^{4}\theta_{d_i,j,t}, \qquad \theta_{160,j,t} = \frac{1}{4}\sum_{i=5}^{8}\theta_{d_i,j,t} \tag{2}$$

where d_i denotes the soil layer, j the sampling point and t the sampling occasion.

Table 4
Summary statistics of soil moisture at indicated depths derived from all measurements.

Depth	Mean (%)	SD (%)	CV	Skewness	Kurtosis	Maximum value (%)	Minimum value (%)
0–20 cm	16.8	6.18	0.37	0.17	−0.89	31.6	6.5
0–80 cm	18.3	5.63	0.31	0.02	−1.04	30.8	8.6
8 0 – 160 cm	17.0	3.64	0.21	−0.09	−0.77	25.7	9.4

b) Mean moisture profiles for all locations at a given sampling occasion for the three considered layers:

$$\bar{\theta}_{20,t} = \frac{1}{19}\sum_{j=1}^{19}\theta_{20,j,t}, \qquad \bar{\theta}_{80,t} = \frac{1}{19}\sum_{j=1}^{19}\theta_{80,j,t}, \qquad \bar{\theta}_{160,t} = \frac{1}{19}\sum_{j=1}^{19}\theta_{160,j,t}. \tag{3}$$

c) Mean moisture profiles derived from the whole soil moisture datasets for the three considered layers:

$$\bar{\theta}_{20} = \frac{1}{T}\sum_{t=1}^{T}\bar{\theta}_{20,t}, \qquad \bar{\theta}_{80} = \frac{1}{T}\sum_{t=1}^{T}\bar{\theta}_{80,t}, \qquad \bar{\theta}_{160} = \frac{1}{T}\sum_{t=1}^{T}\theta_{160,t} \tag{4}$$

where T denotes the total number of soil moisture sampling occasions.

3. Results and discussion

3.1. Mean moisture content and spatial variability

3.1.1. Descriptive statistics of soil moisture in the considered layers obtained from all datasets

Table 4 shows summary statistics of soil moisture contents of the three considered layers derived from all measurements. Overall, the soil was driest in the 0–20 cm layer and wettest in the 0–80 cm layer. In addition, the soil moisture follows normal distributions in the 0–80 and 80–160 cm layers, but not the 0–20 cm layer. SD and CV are highly dependent on soil depth; both decreasing with increasing depth, suggesting that soil moisture is less variable in deeper soil layers. Skewness is also highly dependent on soil depth, decreasing with increasing depth. However, kurtosis displays no monotonous relationship with soil depth.

It should be noted that gully topography is rather complex in the Loess Plateau, some places are almost inaccessible and gullies with widely differing ages and forms co-exist in this area. Therefore, the three transects in this study reflect only a small part of the diversity of gullies in this area. Hence, the variability of soil moisture would probably be greater if the soil moisture sampling scale was increased in gullies. Nevertheless, the spatial and temporal characteristics of soil moisture in the 19 sampling points could represent to a large extent that of well-developed gullies, since the locations of these sampling points covered the main micro-topography (ridges, pipes, plane surfaces and cliffs) of well-developed gullies. To better understand soil moisture variability in gullies, further work is needed to sampling

Table 3
Overview of terrain attributes and soil texture at all sampling points.

ID of Points	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	C5
Original Slope (%)	64.9	70.0	90.0	83.9	55.4	160.0	142.8	103.6	32.5	64.9	72.7	72.7	70.0	60.1	180.4	103.6	51.0	60.1	67.5
Disturbed slope (%)	44.5	60.1	67.5	60.1	46.6	64.9	64.9	70.0	32.5	64.9	44.5	60.1	51.0	60.1	72.7	103.6	51.0	60.1	67.5
Cos (aspect)	0.14	0.05	0.10	0.10	0.26	0.09	−0.09	0	−0.09	0.42	0.5	−0.33	−0.42	−0.39	−0.53	−0.47	0.29	0.37	0.37
Elevation (m)	886	892	903	911	917	887	895	904	911	920	926	932	941	949	911	920	929	937	943
Location	PS	PS	R	R	PS	P	P	P	PS	PS	PS	R	R	R	P	P	PS	PS	PS
Clay (%)	20.5	13.4	14.7	15.2	12.9	19.1	21.1	16.5	11.5	18.9	19.4	10.2	12.7	13.1	–	–	–	–	–
Silt (%)	63.8	66.9	62.1	61.4	64.6	68.5	66.8	66.3	66.0	65.8	66.2	65.7	64.5	63.3	–	–	–	–	–
Sand (%)	15.7	19.7	23.2	23.4	22.5	12.4	12.1	17.2	22.5	15.3	14.4	24.1	22.8	23.6	–	–	–	–	–

Abbreviations: PS: plane surface; R: ridge; P: pipe.

soil moisture in younger gullies where different micro-topographies exist.

3.1.2. Temporal patterns of mean moisture content and spatial variability

Fig. 3 shows temporal dynamics of precipitation (a), and the mean, SD and CV of moisture content (b, c and d, respectively) at the three depths. Overall, mean moisture content responded positively to precipitation at all depths during the study period, although a noticeable lag was observed for 80–160 cm depth. However, the responses differed between seasons. In autumn, the mean moisture content increased comparably at all depths, following a continuous seven-day rainfall event during which there was 93.5 mm precipitation. In contrast, differing responses were observed at different depths during spring and summer, and the response weakened with increasing depth, as illustrated, for instance, by the 6.7% mean increase in the 0–20 cm layer following 16.7 mm precipitation in May 28, and the much more modest increases in mean moisture content in the 0–80 and 0–160 cm layers (1.3% and 1.0%, respectively) during the same period.

As illustrated by the time series shown in Fig. 3c and d, respectively (excluding values for 5 April and 15 April, because soil moisture data were only acquired from transect A during this period) the temporal dynamics of the SD and CV of soil moisture contents are more difficult to characterize. The response of SD to precipitation was observed at various depths during two distinct rainfall events, from September 3 to September 10 2009 and from August 6 to August 21 2010. Whereas, very small evolutions of SD following precipitation events were non-significant compared to larger evolutions in summer 2010. Moreover, SD at every depth peaked when the mean moisture content at the corresponding depth was moderate (15%–20%). Specifically, SD peaked during late May and early June in the 0–20 and 0–80 cm layers, but in late June in the 80–160 cm layer. Note that SD at 80–160 cm was lowest from April 4 to May 28 2010, and highest from June 23 to September 9 2010. CV showed similar temporal dynamics to SD at the monitored depths.

3.1.3. Relationship between spatial means and spatial variability of moisture content

The relationship between the mean and SD of moisture content, by depth, is shown in Fig. 4a–d (excluding SD data for April 5 and April 15 2010, for reasons mentioned above). Fig. 4a, which summarizes data from the whole soil moisture datasets, indicates that there is a convex upward relationship between these variables, i.e., SD peaks at a mean moisture content of 15.7%. When field conditions are drier than this, SD increases rapidly with mean moisture content, while it declines with mean moisture content when field conditions are wetter further. The result here corroborates findings of a number of numerical simulations (Teuling and Troch, 2005; Vereecken et al., 2007), and statistical analyses (Famiglietti et al., 2008; Western et al., 2003). Empirically, the resulting convex upward relationship may be because as soil dries, starting from saturation, a few sites (generally characterized by high clay content) initially remain wet, resulting in enhanced spatial variability (Penna et al., 2009), but when it dries beyond a specific moisture content at which SD is maximal, the remaining wet sites may gradually lose water via strong evapotranspiration, leading to decreasing spatial variability. Theoretically, based on stochastic theory, Vereecken et al. (2007) argued soil texture affected the relationship between spatial mean and spatial variability of moisture content. They found that SD peaked as mean moisture content was between 0.17 and 0.23 for silt loam and clay loam soils. However, SD increased with mean moisture content for sandy loam and loamy sand soils. The convex relationship between SD and mean

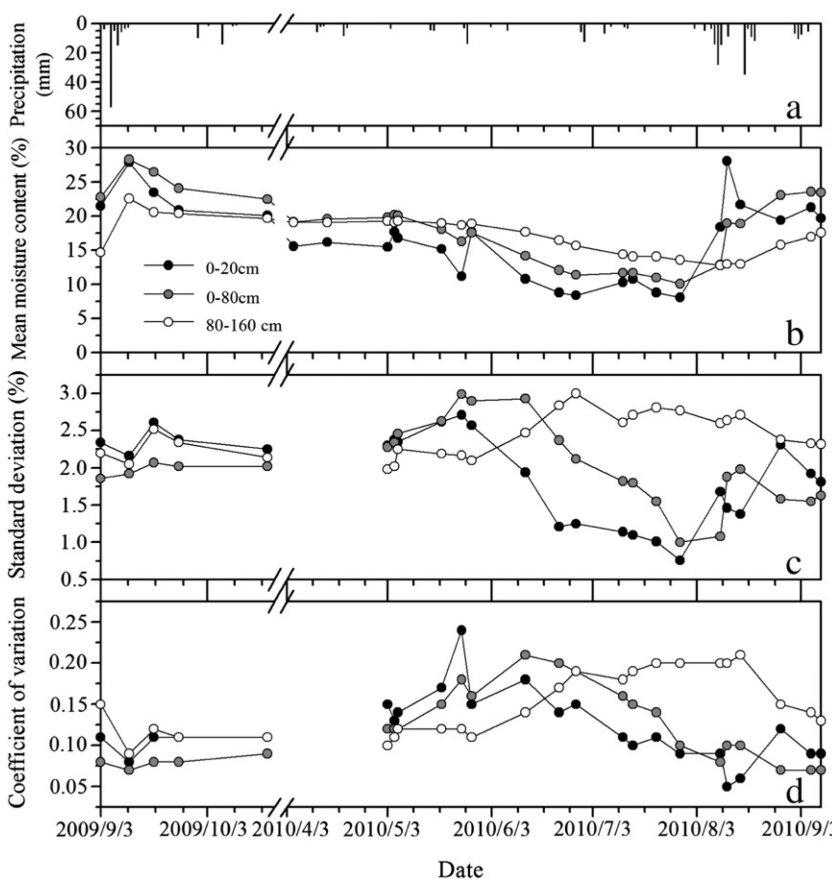

Fig. 3. Time series of daily precipitation (a), and the mean, standard deviation and coefficient of variation of moisture content (b, c and d, respectively) throughout the whole study period.

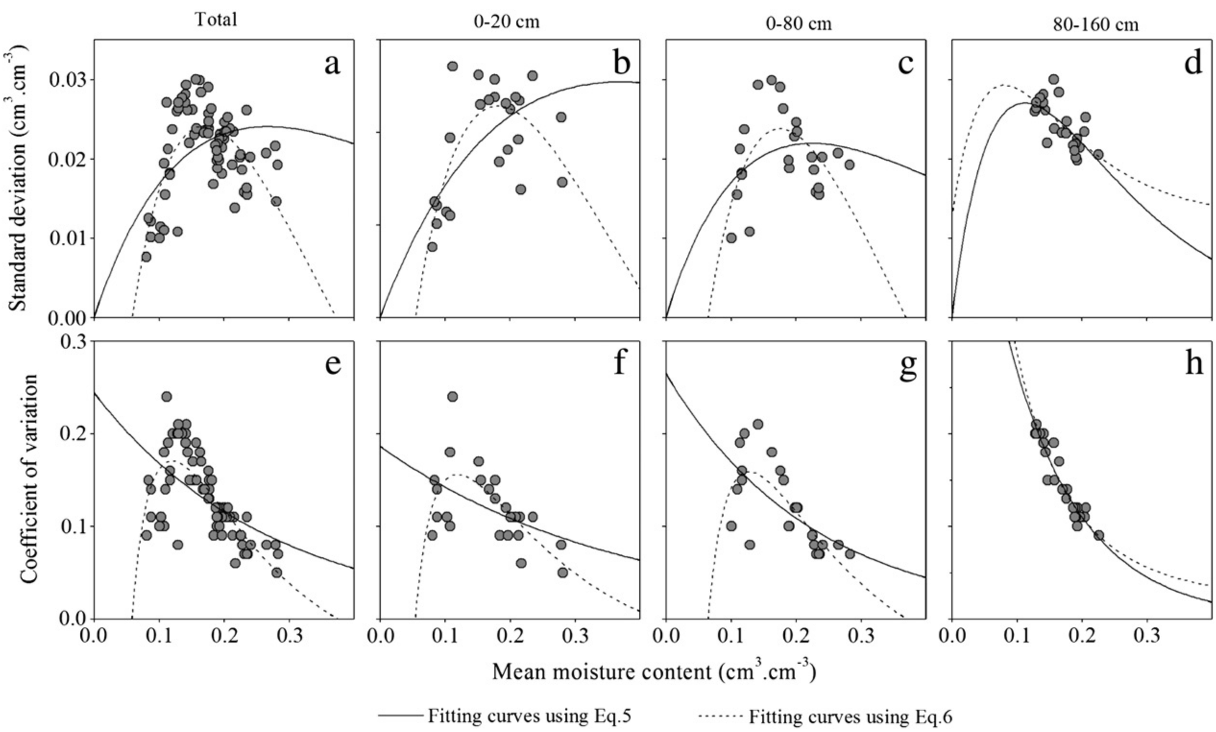

Fig. 4. Relationships between mean soil moisture and SD (a, b, c and d) and CV (e, f, h and g), overall (a and e), and for the 0–20 cm layer (b and f) 0–80 cm layer (c and h), and the 80–160 cm layer (d and g).

moisture content in this study is probably due to the silt loam soils in our test site. However, as shown in Fig. 4b–d, the relationship between the mean and SD of moisture content appears to vary with depth. In the 80–160 cm layer the SD decreased monotonously with increases in mean moisture content, while the relationships between the variables in the 0–20 and 0–80 cm layers were similar to those derived from the whole soil moisture datasets. This is probably because the mean soil moisture in the 80–160 cm layer was higher than in the other layers, and its range was relatively narrow.

The relationships between CV and mean moisture content by depth are shown in Fig. 4e–g (again, excluding CV data for April 5 and April 15 2010, for reasons mentioned above). Overall, the CV increases rapidly as mean moisture content increases from its lowest point, then peaks (at 0.24) at a mean moisture content of ca. 15.7% and declines with further increases of mean moisture content. However, as for the SD, the relationship between the CV and mean moisture content appears to vary with depth; the CV decreases monotonously with increasing mean moisture content in the 80–160 cm layer, but it shows similar patterns to the overall trends in the 0–20 and 0–80 cm layers. It is worth noting that since CV is calculated by dividing the SD by the mean moisture content, the rate of change in CV with increases in mean moisture content is amplified compared to that of SD.

Empirically fitted SD and CV versus mean moisture content curves are shown in Fig. 4 (panels a–d and e–g, respectively), using the fitting functions defined by Fimiglietti et al. (2008) as follows:

$$CV = A \cdot \exp(-B\,\overline{\theta}), \qquad SD = A\,\overline{\theta} \cdot \exp(-B\,\overline{\theta}) \tag{5}$$

where A and B are model parameters, and $\overline{\theta}$ is the mean moisture content. Note that the SD versus mean moisture content fitting function is derived from the corresponding CV function. Table 5 shows the fitting regression results using Eq. (5). Overall, the exponential decay function captures with confidence the relationship between CV and mean moisture content for the 80–160 cm layer ($R^2>0.9$), but not for the 0–20 cm and 0–80 cm layers ($R^2<0.5$). The RMSE is also lowest for the 80–160 cm layer. The exponential decay-based SD versus mean moisture content fitting function also does not capture the relationship between SD and mean moisture content robustly. Indeed, the SD versus mean moisture content curves has lower R^2 values and much larger RMSE values than the corresponding CV curves. These results are markedly in contrast to most previous studies (e.g., Choi and Jacobs, 2007; Famiglietti et al., 2008; Brocca et al., 2010) in which the exponential decay function in Eq. 5 clearly explained the relationship between CV and mean moisture content.

The unsatisfactory fitting results are possibly that the relationship between CV and mean moisture content may not follow the exponential function in Eq. (5). Whereas, the observed distribution (Fig. 4a) showed that the overall relationship between SD and mean moisture content (Fig. 4a–d) probably follows the latter function in Eq. (5). Therefore, revised fitting functions were developed to better fit the relationship between mean moisture content and SD as well as CV as follows:

$$SD = C + A\,\overline{\theta} \cdot \exp(-B\,\overline{\theta}), \qquad CV = C \cdot \frac{1}{\overline{\theta}} + A \cdot \exp(-B\,\overline{\theta}) \tag{6}$$

where C is a constant item. This constant item was added because the extension of the fitting curve between SD and mean moisture content is expected to intersect the vertical coordinate axis at some non-zero

Table 5
CV and SD versus mean moisture contents fitting results using Eq. (5) and Eq. (6), respectively.

Soil depth	A	B	C	R^2(CV)	R^2(SD)	RMSE(CV)	RMSE(SD)
Fitting results using Eq. (5)							
Total	0.245	0.037	–	0.339	0.127	0.0347	0.4986
0–20 cm	0.187	0.027	–	0.214	0.321	0.0349	0.4874
0–80 cm	0.265	0.044	–	0.421	0.096	0.0329	0.4880
80–160 cm	0.656	0.089	–	0.902	0.491	0.0116	0.2050
Fitting results using Eq. (6)							
Total	1.155	5.872	−0.048	0.600	0.425	0.0273	0.0039
0–20 cm	0.872	5.517	−0.035	0.474	0.493	0.0293	0.0015
0–80 cm	1.213	5.701	−0.055	0.588	0.259	0.0284	0.0042
80–160 cm	0.562	12.405	0.013	0.904	0.451	0.0118	0.0020

value when mean moisture content approaches zero (Fig. 4a). Fitting results showed that the revised fitting functions can capture the relationship between mean moisture content and SD as well as CV much better, for all depths except for 80–160 cm where similar performances existed, than that in Eq. (5) in terms of either R^2 or RMSE (Table 5).

3.2. Downslope soil moisture profiles and vertical patterns

Fig. 5a and b shows mean moisture profiles obtained for transects A and B, and the corresponding standard deviations for the three depths, derived from all soil moisture data obtained from all sampling occasions from those transects (selected because they traversed on opposite sides of the gully, thus allowing us to observe moisture behavior across the whole gully). Mean moisture content at each considered depth generally increased (but highly irregularly) down the transects toward the gully bottom. In addition, the standard deviation in the 80–160 cm layer decreased downslope along transect B, but there was no obvious change in the 0–20 and 0–80 cm layers along either transect.

To illustrate the trends in the downslope soil moisture profiles in different seasons, transect B profiles obtained for the three considered depths on 3 September 2009 (autumn), 25 May 2010 (spring) and 12 July 2010 (summer) are shown in Fig. 6. Soil moisture profiles along transect B were selected because there are more sampling points along this transect, and it showed a clearer downslope increase than along transect A (Fig. 5a). Overall, the profiles show increases, but far from regular increases, along the transect, and the fluctuations were greatest (with the highest standard deviation) in the 0–20 and 0–80 cm layers on May 25 2010, and lowest (with the lowest standard deviation) in the 80–160 cm layer on that date. This is probably because the mean moisture content was moderate in the 0–20 and 0–80 cm layers (12.4% and 18.0%, respectively) on May 25 2010, but peaked (at 19.5%) in the 80–160 cm layer.

The same three sampling occasions were selected to examine variations in the vertical distribution of soil moisture (Fig. 7a–c). Overall, distinct variations with depth were observed, which were greatest on 3 September and smallest on 12 July. As expected, soil moisture content fluctuated with depth on 3 September and 25 May, being highest in the rooting depth zone. In contrast, soil moisture content decreased continuously with depth on 12 July and was highest at 140–160 cm depth. Note that soil moisture content was roughly constant at all depths from 100 to 160 cm depth on 3 September, suggesting that vertical flow was in dynamic equilibrium at this depth. This phenomenon was also observed in other dates. In fact, this is a common phenomenon which was named the moisture-stability depth (Yang and Shao, 2000) in the Loess Plateau when soil moisture is at moderate level.

To illustrate the effects of precipitation on soil moisture, the vertical distribution of soil moisture content on three dates (18 September 2009, 28 May 2010 and 15 July 2010) are also shown, in Fig. 7a–c, respectively, since precipitation occurred during the periods between these dates and the dates in the corresponding seasons mentioned in the former paragraph. Note that 18 September 2009 rather than 11 September 2009 was selected in order to allow seeing the effect of deeper infiltration, although a rainfall event stopped on 10 September. Strikingly, the infiltration front reached 140–160 cm depth following 93.5 mm precipitation during the period between 3 September and 18 September 2009, resulting in the disappearance of the stable-moisture layer. However, less than 20 cm infiltration occurred during the other two periods (16.7 and 5.6 mm, respectively). This finding is inconsistent with van den Elsen et al. (2003) who found that rainfall could supply soil moisture down to 70 cm over gully sidewalls in Ansai county of the Loess Plateau in a wet year. The deeper infiltration we observed could have been due to the large amount of rainfall. However, in most years vertical percolation is not expected to reach this depth because analysis of a 40-year daily precipitation data set for some counties in the Loess Plateau (results not showed here) indicates that rainfall events in the region are usually more dispersed.

3.3. Relation of soil moisture to terrain attributes and soil texture

In this section, the contributions of terrain attributes and soil texture to the variability of soil moisture at different depths are analyzed by examining the correlation coefficients between mean moisture contents and both terrain attributes and soil texture observed at various times. We first analyze the relationships between

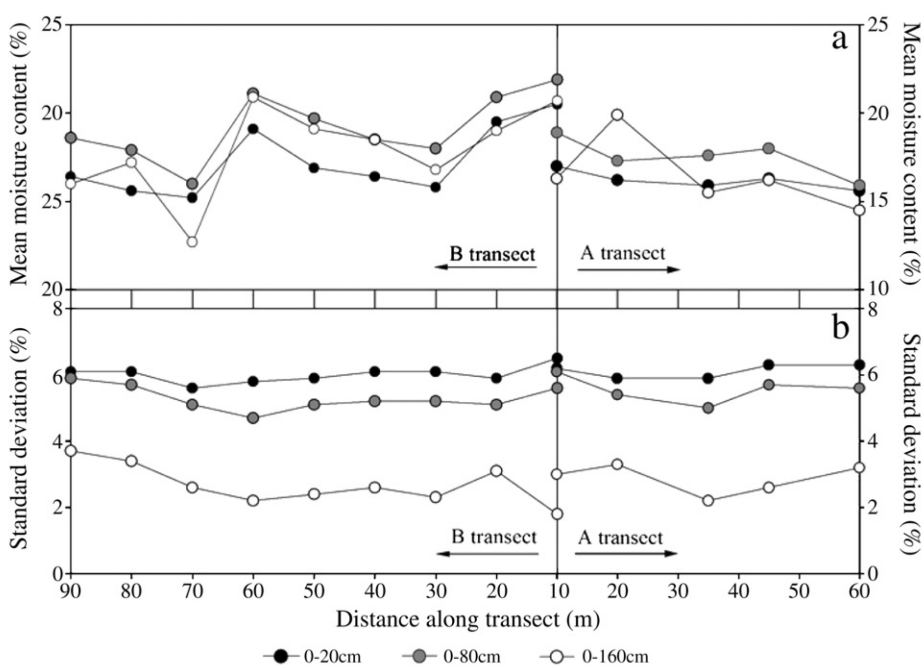

Fig. 5. Variations in the mean and standard deviation of moisture contents at 0–20, 0–80 and 80–160 cm depths along transects A and B, derived from data obtained on all sampling occasions.

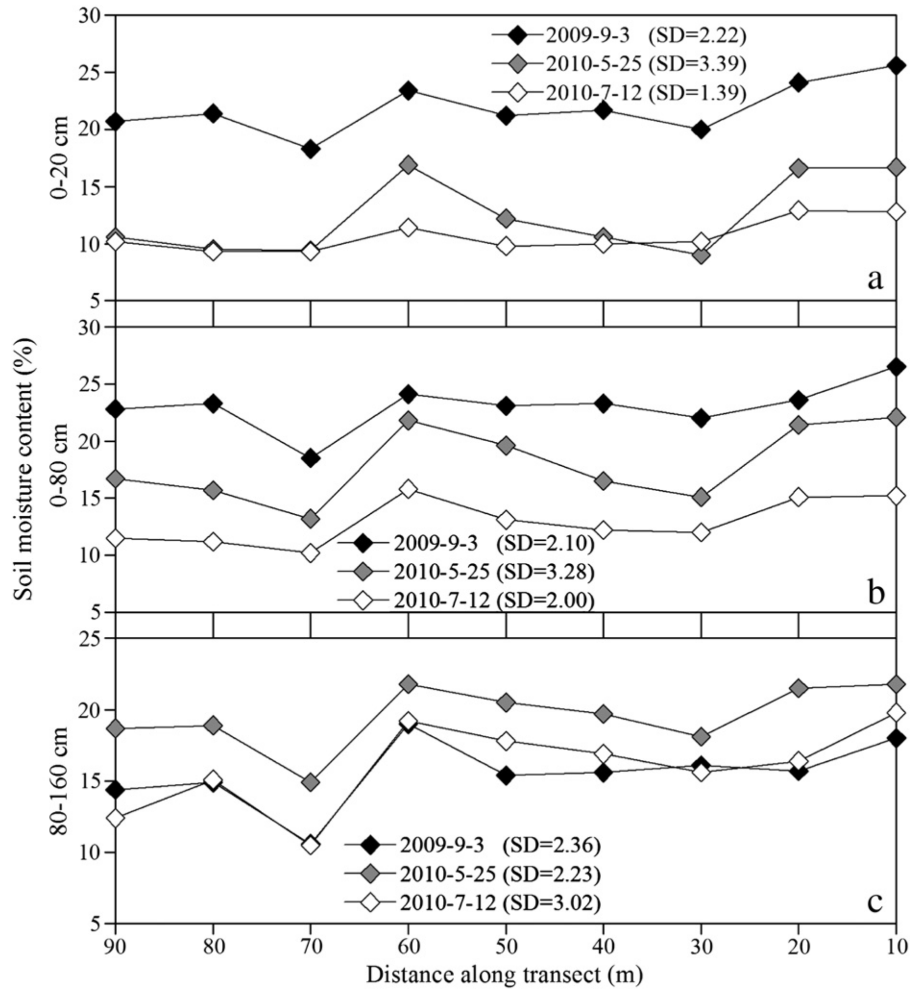

Fig. 6. Downslope moisture content along transect B on three sampling occasions at: a) 0–20 cm, b) 0–80 cm and c) 80–160 cm.

mean moisture content and controlling factors in terms of terrain attributes and soil texture, then present time-series of correlation coefficients for the relationships. Six terrain attributes, listed in Table 3, were selected for the correlation analysis. The original slope was chosen because it represents the mean slope around sampling points. Table 6 shows the correlation coefficients for mean moisture content versus terrain attributes (except for locations) and mean moisture content versus soil texture based on datasets obtained for the 0–20 cm layer along transects A and B. Overall, weak correlations (correlation coefficients ranging from 0.096 to 0.449) were found between mean moisture content and terrain attributes, except between mean moisture content in the 0–20 cm layer and original slope, but moderate or strong relationships (correlation coefficients ranging from 0.540 to 0.837) between mean moisture content and soil

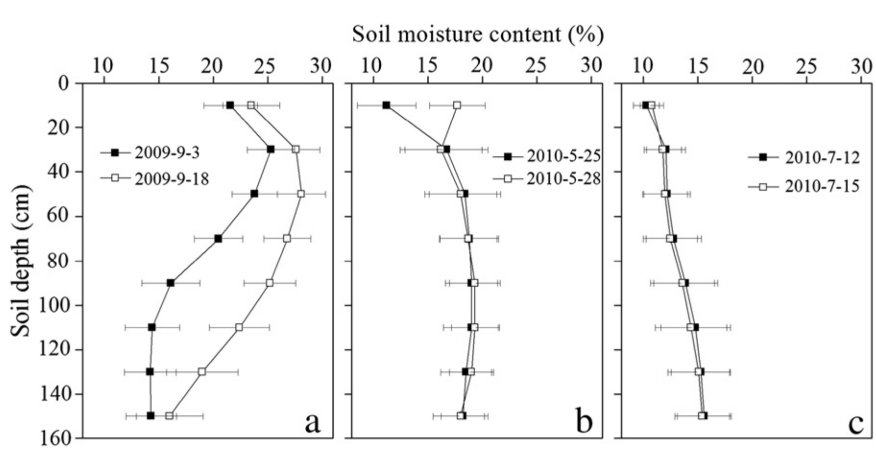

Fig. 7. Vertical distribution of soil moisture at A2 and A5 sampling points during pairs of sampling occasions before and after precipitation events: (a) Sept. 3 and Sept. 18 2009, (b) May 25 and May 28 2010, and (c) July 12 and July 15 2010. Error bar represents standard deviation.

Table 6
Correlation coefficients between mean moisture content and both terrain attributes and soil texture. Significant correlations ($P<0.05$) are shown in italics and significant correlations ($P<0.01$) in bold.

Soil depth	Original slope	Disturbed slope	Cos(aspect)	Elevation	Sand	Silt	Clay
0–20 cm	*0.560*	−0.152	0.152	−0.438	**−0.837**	*0.540*	**0.756**
0–80 cm	0.411	−0.225	0.195	−0.398	–	–	–
80–160 cm	0.224	−0.217	0.263	−0.449	–	–	–

texture. This is unexpected, since the gully sidewalls have steep slopes and complex micro-topography. The findings also suggest that soil texture rather than terrain attributes predominantly influence the variability of surface soil moisture in gullies in this area. This agrees with Famiglietti et al. (1998), but inconsistent with Bogena et al. (2010) who found that topography exhibited strong correlations with soil moisture over dry periods in a forest catchment. Note that the correlation coefficient between the original slope and mean moisture content is positive, while that for the disturbed slope is negative. This is probably because the original slope shares a similar increasing trend, downslope, with clay content (Table 3). Table 7 indicates the differences between mean moisture content and types of location in the gully sidewalls according to ANOVA. Significant differences ($P<0.05$) were detected among location types in mean moisture contents at 0–20 cm, but not in the 0–80 and 80–160 cm layers. Furthermore, multiple comparisons of the mean moisture content in the 0–20 cm layer show that there were no significant differences in mean moisture content between plane surfaces and ridges, while there were significant differences in this respect between pipes and both plane surfaces and ridges. Whereas, the higher moisture contents in pipes is probably because of the higher clay contents there (Table 3). ANOVA analysis showed that clay contents in pipes were significantly larger ($P<0.05$) than that in ridges (results not shown here). Pearson correlation coefficients between topographic features and clay content also indicated that significant correlations ($P<0.05$) existed between them (results not shown here). This implies that topography may control soil moisture variability indirectly via redistributing soil properties.

Fig. 8a–d presents time-series of correlation coefficients between soil moisture and the selected terrain attributes at the three considered depths (excluding coefficients between soil moisture and original slope, since the disturbed slope may reflect the true topography of sampling points better than the original slope). Overall, the correlations were strongly affected by depth and precipitation, for all terrain attributes but elevation. For disturbed slope, the coefficients obtained for the correlation in the 0–20 and 0–80 cm layers fluctuated, while those for the 80–160 cm layer were relatively stable, with time indicating that soil moisture is more strongly affected by precipitation in the 0–20 and 0–80 cm layers than at 80–160 cm. Clearly, the correlation coefficients for the 0–20 and 0–80 cm layers were small and negative during periods when the soil was drying and the moisture content was low (Fig. 3b). However, a transition to positive correlation occurred during a distinct rainfall event (in mid-August 2010), possibly because the sampling points with steeper disturbed slopes are more abundant in the lower parts of transects, where soil moisture was higher after precipitation (Figs. 5a and 6a and b). The time series of correlation coefficient for cos(aspect) shows sharply contrasting patterns to those for disturbed slope; displaying weak but positive correlation with soil moisture in the 0–20 and 0–80 cm layers during drying and a shift to negative correlation during distinct rainfall events. This implies that cos(aspect) plays a very different (even opposite) role in controlling soil moisture distributions in our site, comparing to disturbed slope. Soil moisture and elevation always exhibit negative correlations in gully sidewalls, and generally, the negative correlation increases during drying and decreases during rainfall events.

Table 7
Mean moisture contents at 0–20, 0–80 and 80–160 cm, at the indicated types of location and the significance of differences between pipes and the other types in this respect.

Soil depth	0–20 cm	0–80 cm	80–160 cm
Inside slopeland	16.5 a	18.0	17.2
Ridge	15.9 a	17.7	15.6
Pipe	18.5 b	19.9	18.3
P value	0.023	0.104	0.180

Note: The letter after the number indicates the significance. Numbers with the same small letter within a column are not significantly different.

Fig. 8e shows the time series of correlation coefficients between soil moisture and soil texture. Clay content and silt content were both positively correlated with soil moisture during drying, but their correlation coefficients generally declined to zero during distinct rainfall events. The correlation coefficient trends for sand content almost mirror those of clay content, possibly because the clay content tends to increase with decreasing sand content in the soils at this study site, while the silt content is relatively stable (Table 3). Moreover, soil texture consistently exhibited much stronger correlations than terrain attributes with soil moisture in the 0–20 cm layer, except during distinct rainfall events, when the pattern reversed. This suggests that soil texture is the dominant influence on soil moisture variability in gullies over drying periods while topography exhibits greater influence than soil texture during distinct rainfall events.

4. Conclusions

We have studied the spatio-temporal variability of soil moisture profiles in 0–20, 0–80 and 80–160 cm layers in a well-developed gully, located in the north central part of the Chinese Loess Plateau. During two periods, from 3 September to 20 October 2009 and from 5 April to 20 July 2010, soil moisture was sampled approximately weekly along three transects traversing the sidewalls of a gully using a portable TDR system.

The mean, SD and CV of moisture content along the three transects were all highly dependent on soil depth. The mean moisture content was lowest in the 0–20 cm layer and highest in the 0–80 cm layer. The results indicate that both SD and CV decrease with increasing soil depth. In addition, the mean moisture content increases during and after rainfall events, but decreases during drying. Moreover, the mean moisture content responds to precipitation most quickly in the 0–20 cm layer, and least sensitively at 80–160 cm.

A convex upward relationship was observed between mean moisture content and SD, i.e., SD appears to increase with mean moisture content in relatively dry field conditions (<15.7%), but decrease with mean moisture content in relatively wet field conditions (>15.7%), and the relationship between the CV and mean moisture content shows similar trends. Empirical fitting analysis indicates that an exponential decay function fits the relationship between CV and mean moisture content well for the 80–160 cm layer ($R^2=0.902$), but not for the other two layers (R^2, 0.214 to 0.421). Thus, soil depth affects the relationship between mean moisture content and CV as well as SD. However, the revised fitting functions can capture the relationship between mean moisture content and CV as well as SD much better.

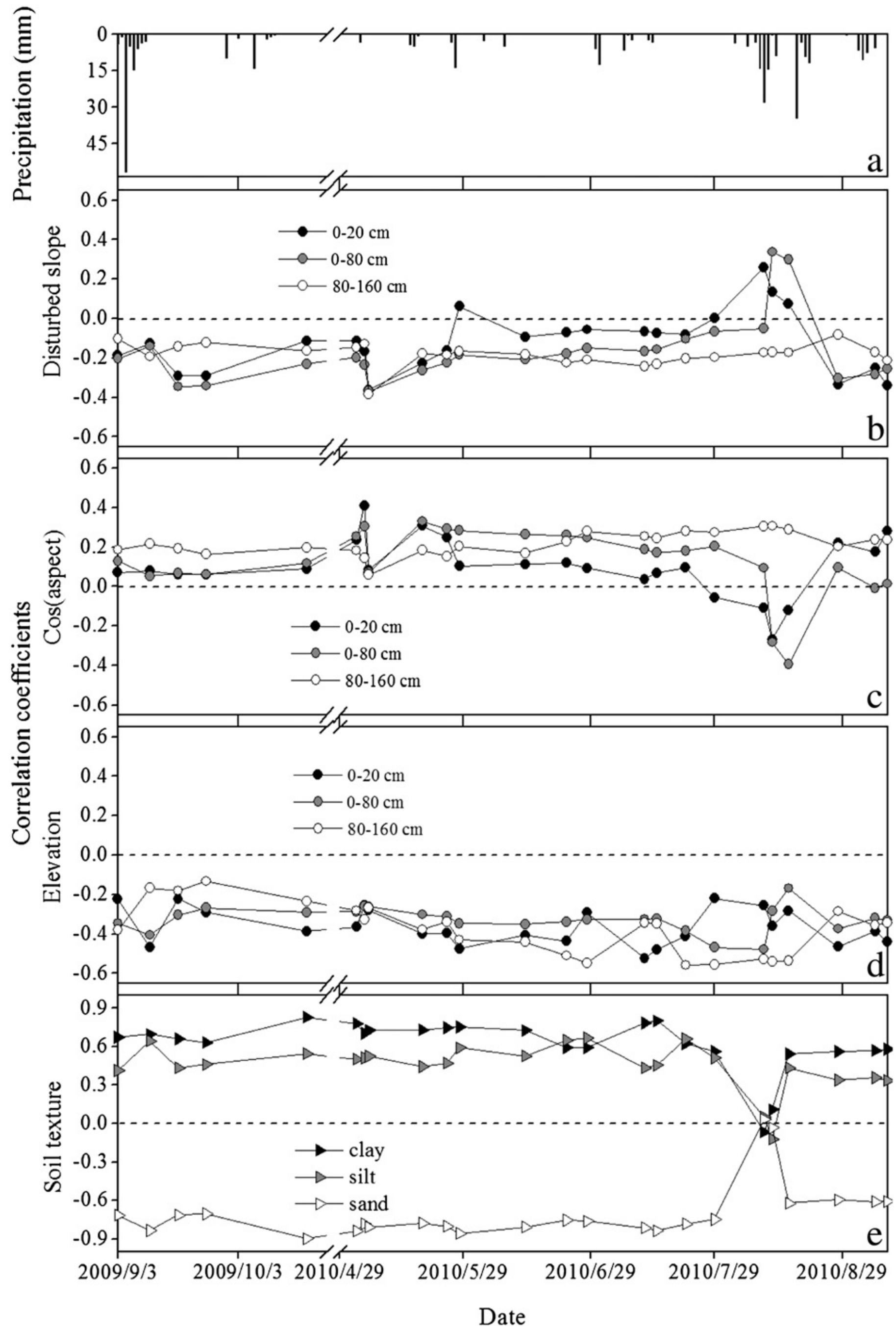

Fig. 8. Time series of correlation coefficients between soil moisture (at 0–20, 0–80 and 80–160 cm depths) and terrain attributes b) disturbed slope; c) cos(aspect); d) elevation; and e) soil texture. Panel a indicates rainfall events during the study period.

Soil moisture in different depths wavily increases downslope along transects. In autumn, moisture-stability layer (100–160 cm) exists and maximum soil moisture content is apparent at 20–40 cm, while soil moisture content decreases with depth in summer, suggesting strong evapotranspiration. Infiltration could reach depths of 140–160 cm when continuous, heavy rainfall occurs. However, during dry periods only very shallow infiltration occurs, owing to small precipitation as well as strong evapotranspiration probably.

Soil moisture exhibits almost negligible correlations with most terrain attributes (correlation coefficients ranging from 0.152 to 0.560) but moderate to strong correlations with soil texture (correlation coefficients ranging from 0.540 to 0.837). However, correlations between soil texture and surface soil moisture decline to near-zero during distinct rainfall events, while those for terrain attributes rise to relatively high levels.

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