

Responses of soil moisture and thermal conductivity to precipitation in the mesa of the Loess Plateau

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Abstract Regional precipitation is important due to its impact on potential feedback to hydrologic and climate change. In this study, we analyzed the responses of thermal conductivity and soil moisture to precipitation using soil moisture, precipitation and soil temperature datasets in the mesa of the Loess Plateau, which located in Baimiao village, Pingliang City, China. The temporal variations of soil water content (at depths of 5, 10, 20, and 40 cm) and the response of soil moisture at a depth of 20 cm to total antecedent precipitation are two topics of this investigation. The following results are obtained: (1) the temporal trends of soil moisture variation at different depths are similar in the study areas. Simultaneously, the positive responses of soil moisture to local precipitation at 5 cm are significant. (2) Two peaks (from March to May and from July to November) are observed for annual soil moisture variation at depths of 10 and 40 cm. (3) By analyzing the relationship between local precipitation and soil moisture at 5, 10, 20 and 40 cm depths, it is found to be possibly relevant to local effective antecedent precipitation. This finding implies that the response of soil moisture at a depth of 20 cm to effective antecedent precipitation is the most significant. (4) The simulated soil moisture at each layer shows the same trend with the observation data. Simulated results well depict the impacts of antecedent precipitation

on soil moisture. (5) The soil thermal conductivity exhibits somewhat responses to soil moisture variation, but the variation is irrelevant during the observational period.

Keywords Correlation analysis · Loess Plateau · Antecedent precipitation · Soil moisture

Introduction

Nearly half of the lands in China are semi-arid or arid areas. Most of these areas are located in the northwest of China (Ma et al. 2005). The main part of Loess Plateau is located in semi-arid and arid areas. In hydrological model, soil moisture plays an important role, which controls the surface runoff and drainage (Li et al. 2014b). The variability and distribution of soil moisture are influenced by topography, soil properties, vegetation, water routing processes, depth to water table, and meteorological conditions (Liu et al. 2007; Western et al. 1999). Furthermore, soil moisture can significantly alter land surface albedo and soil variables (such as soil temperature). Therefore, soil moisture variation influences surface energy as well as the partition of sensible heat and latent heat from the net radiation, which further affects regional climate change (Ma et al. 2000; Wen et al. 2003; Shi et al. 2010; Wang et al. 2012a). Soil moisture variation is mainly controlled by local evapotranspiration and precipitation.

Precipitation is the main factor that regulates soil moisture variation during periods when precipitation continually exceeds evapotranspiration (Beven and Kirkby 1979). In the arid and semi-arid areas of the Loess Plateau, uneven spatial-temporal distributions of precipitation as well as the large amount of land evapotranspiration significantly change the distribution of soil moisture. This

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condition results in a good relationship between local precipitation and top-layer soil moisture.

Although considerable studies have characterized the temporal variation of soil moisture and its causes on the Loess Plateau (Li et al. 2014b; Jinbai et al. 2014), a few have shown the relationship between the effective precipitation and the soil moisture. These aforementioned studies have mainly focused on the mechanism of soil moisture estimate and its cover or runoff impacts on regional climate change (Jiang et al. 2013; Beven and Kirkby 1979; Gupta et al. 2014), the direct positive forcing of precipitation on soil moisture variation has not been considered. However, in others places, the relationship between the precipitation and soil moisture have been studied. Chandra et al. (2008), Stolte et al. (2003), Koster et al. (2003) and Liu et al. (2009) investigated the precipitation and the impact on soil moisture. Nevertheless, they did not study the effective precipitation. Effective precipitation means the part of precipitation which can be used by plant root, including the antecedent precipitation and current effective precipitation (Wei et al. 2005; Liu et al. 2009). All of them focused on the daily precipitation and its influence on soil moisture. Therefore, the effective antecedent precipitation is used in accurately explaining the relationship between soil moisture and precipitation. However, the similar studies mentioned above are mainly conducted in the eastern or northeastern parts of China (Chen et al. 2005; Jinbai et al. 2014), there are few studies on the links between soil moisture and local precipitation in the Loess Plateau (Zhang et al. 2013), particularly on the effect of total effective antecedent precipitation on soil moisture variation during the early stage. Because the Loess Plateau is located in the arid, semi-arid, and semi-humid areas, most soil moisture variation processes are “non-shower” (the phenomenon in which soil is not completely wet, with rainfall reaching only a certain depth, groundwater is not involved in the water cycle within the soil layer) (Liu et al. 2007). The water holding capacity of soil is very little. So, the effective antecedent precipitation makes a great contribution to the soil moisture. As soil thermal conductivity is an essential factor in parameterizing the soil heat transfer process, the soil moisture has considerable contribution on its magnitude. And then, does the local rainfall influence the soil thermal conductivity variation?

Based on the preceding discussion collected in the Loess Plateau, the objectives of this research are to (1) to better understand the links between soil moisture and local antecedent precipitation, (2) to build a formula to calculate the soil moisture using total effective antecedent precipitation, and (3) to analyze the influence of local precipitation on thermal conductivity, thus improving understanding on the relationship between effective precipitation and soil moisture in the Loess Plateau as well as annual soil moisture variation.

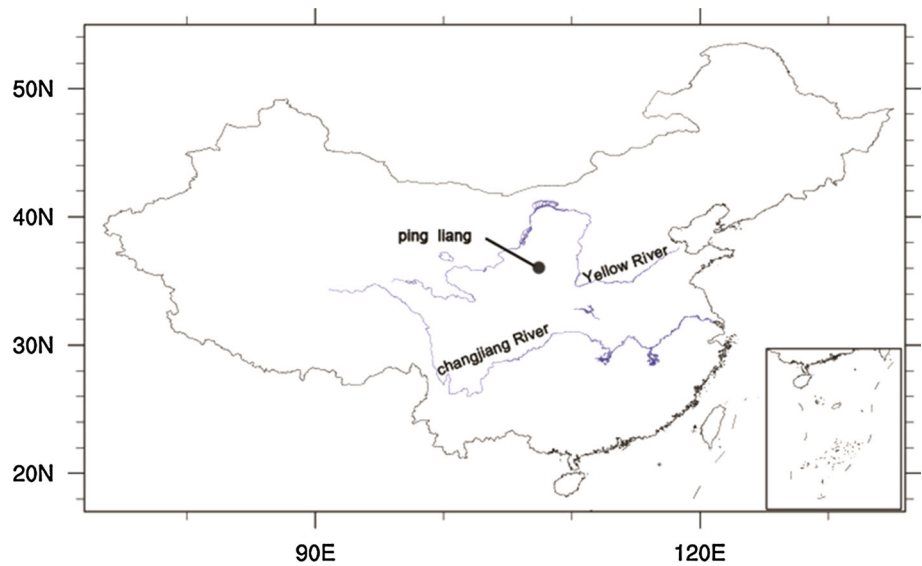
The descriptions of study area and datasets are presented in second section, the methodology is followed subsequently; the results are given in the fourth section, and the conclusions of this study will be drawn in the last section.

Study area and datasets

The Loess Plateau is located in the upper and middle reaches of the Yellow River; its average altitude is about 1000 m above sea level (Li et al. 2014a). As the Loess Plateau suffers from severe soil and water loss area in the world, over 60 % of the land has been subjected to soil and water loss, with an average loss of 2000–2500 t km⁻² each year (Li and Shao 2006). Most land is arid or semi-arid and it is one of the most environmentally sensitive regions in China (Zhang et al. 2006). The study was conducted in the Pingliang Lightning and Hail Storm Experimental Station of the Chinese Academy of Sciences, located in the Baimiao Mesa of the Loess Plateau, Pingliang City, Gansu Province, China (Fig. 1). The Baimiao Mesa is the main part of the Pingliang Northern Mesa, which is approximately 5 km away from the city. The Baimiao Mesa is a typical loess mesa, and is distributed across the northwest to the southeast. The width of this mesa ranges from a few kilometers to ten of kilometers. Its length is over 40 km. The Baimiao Mesa is a sub-region of the Liupan Mountain and is located upstream of the Jing River. Its mean elevation is approximately 1630 m above sea level. The climate in this region is mainly controlled by the west wind circulation. The region experiences southeast or east winds during spring and summer, and northwest wind during autumn and winter. It is a typical continental semi-humid and semi-arid climatological zone. Annual mean temperature is approximately 6 °C, whereas annual mean precipitation is approximately 510 mm (Wei et al. 2005). Given the unevenly distributed and concentrated rainfall from June to September, this region suffers from spring drought, landslides, and debris flow disasters. The cropland is the dominant land cover type with loamy clay, and rooting depth about 0.5–1.5 m, the soil field capacity is around 300.0–400.0 mm over the study area.

The precipitation datasets used in this study are collected from the site of the Pingliang Lightning and Hail Storm Experimental Station of the Chinese Academy of Sciences. The underlying surface is bare soil (106°42'24.93" E, 35°34'34.89" N), at an altitude of 1480 m above sea level. To explore the relationship between soil thermal conductivity and soil moisture during a precipitation event, Adding Water to Soil EXperiment (AWSEX) was conducted in the observation site from July 22 to August 17, 2012, and then the observation was continued to November 1, 2012 under the natural precipitation condition. The

Fig. 1 The geographic location of Pingliang observation station in China



liquid water was added to top soil layer during the observation period, two (soil moisture and temperature) sensors were buried at depths of 20 and 40 cm, a heat flux sensor was set at a depth of 30 cm during the experiment period. The collected datasets include soil temperature, soil water content (volumetric percent) at depths of 10, 20, 40, and 60 cm; and soil heat flux data, which are collected every 5 min. Moreover, the datasets, including soil temperature and soil water content at depths of 5, 10, 20, and 40 cm, are collected every 10 min, as well as daily precipitation data from 2005 to 2010. The specifications of the observation instruments used in this research are listed in Table 1.

Methodology

Precipitation affects land surface energy partition by infiltration and runoff. It also influences the energy and mass exchange process between land surface and the atmosphere. Land surface energy balance is one of the important aspects in studying. According to soil water

balance equation, precipitation has four destinations after a rainfall event: (1) interception of canopy leaves, (2) surface runoff, (3) infiltration, and (4) effective antecedent precipitation. Canopy interception could be neglected because of high precipitation intensity, short duration, and low vegetation cover in the study area. Moreover, the effective antecedent precipitation has received considerable attention.

According to the relationship between soil water balance and soil moisture variation, the following equation is obtained (Liu et al. 2009; Wei et al. 2005; Wang et al. 2012a):

$$\Delta W = P - O \tag{1}$$

where *P* is precipitation, *O* is surface runoff, and ΔW is the change in soil moisture.

Irrigation is not applied in the Loess Plateau. Therefore, the causes of soil moisture variation are mainly from precipitation. However, the surface runoff, underground infiltration, and evapotranspiration affect soil moisture. After these processes, the remaining water in the soil becomes the available soil water content. So the each layer

Table 1 Specifications of all sensors deployed in this study

Observation items	Instrument	Main specification
Soil heat flow	HFP01 heat flux sensor made by Hukseflux (The Netherlands)	Range is from -2000 to 2000 W m^{-2} . Nominal resistance is 2Ω . Sensitivity is $50 \text{ m}\mu\text{V W}^{-1} \text{ m}^{-2}$. Working temperature ranges from -30 to $70 \text{ }^\circ\text{C}$. Accuracy is -15 – 5%
Soil water content	CS616 moisture sensors made by Campbell (USA)	Accuracy is 2.5% . Resolution is 0.1% . Dry soil is $\pm 0.5 \%$. Saturated soil is $\pm 1.5 \%$
Soil temperature	107 type thermal temperature sensor made by Campbell (USA)	Range is -50 to $70 \text{ }^\circ\text{C}$. Interchangeability error is $\pm 0.2 \text{ }^\circ\text{C}$ (0 – $70 \text{ }^\circ\text{C}$, ± 0.5 – $50 \text{ }^\circ\text{C}$)

soil moisture dynamic equation can be shorthanded as below:

$$W_i - W_{i-1} = f(TEAP_i) \quad (2)$$

where W_i refers to the 1, 2, 3, ..., i days of the soil moisture data; W_{i-1} refers to the previous day; $TEAP_i$ refers to the 1, 2, 3, ..., i days of the total effective antecedent precipitation. Defining a function representing effective contribution of precipitation to soil moisture is possible. By analyzing precipitation and soil moisture data from 2007 to 2009 in the mesa of the Loess Plateau, soil moisture is implied to increase in July and commonly associated with precipitation during the same day (unless precipitation is over 10 mm in 2 days during a continuous rainfall event. These 2 days are regarded as a continuous rainfall event).

Soil water content under a no-rainfall scenario is little affected by the external environment, and is mainly affected by terrain and evapotranspiration. Based on the preceding discussion, an attenuation function is defined as

$$\delta_k = \left(\frac{270}{T_{k-1}}\right)^b \quad (3)$$

where T is soil surface temperature (K), b is affected by topography, soil condition, and other parameters. k refers to 1, 2, 3, ..., k days of the observation data.

By analyzing the field observed data in the mesa of the Loess Plateau and using the least square method (Liu et al. 2009), the results show that $b = 36.59$, and it passes through the 95 % significant test. Thus, effective precipitation (Koster et al. 2003; Chen et al. 2005) of the current day is as follows:

$$AP_k = P_k \times \delta_k \quad (4)$$

where P_k is the total precipitation (mm) in the current day.

Evapotranspiration is high in July and August over the mesa of the Loess Plateau. When precipitation is less than 1 mm, soil water content at a depth of 5 cm is not influenced by precipitation in the mesa of the plateau. When precipitation is over 10 mm, precipitation during the same day is to be regarded as a continuous rainfall event. Simultaneously, the contribution ratio of effective rainfall to soil water content from the previous 20 days is close to $0.00001 \text{ m}^3 \text{ m}^{-3}$. At the same time, the contribution of the total effective precipitation at 20 days ago to soil moisture variation is reaching zero. Therefore, the sum of effective precipitation for the previous 20 days is defined as the total effective antecedent precipitation.

Therefore, total effective antecedent precipitation is to be expressed as follows:

$$TEAP_{i+20} = \sum_{k=1}^{20} P_k \times \left(\frac{270}{T_k}\right)^{k+63.283} \quad (5)$$

where i refers to 1, 2, 3, ..., 20, which is day number after the TEAP data; k refers to 1, 2, 3, ..., 20, which is day number prior to the taken data.

Total effective antecedent precipitation can be calculated according to Formula (3) because the currently measured soil moisture and total effective antecedent precipitation are closely correlated. This study focuses on analyzing the relationship between soil moisture and total effective antecedent precipitation over the mesa of the Loess Plateau.

The soil temperature gradient indicates the strength of heat transfer in soil, the expression of soil heat flux is as follows:

$$G = -\lambda \frac{\partial T}{\partial Z} \quad (6)$$

where G is soil heat flux (unit: W m^{-2}), λ is soil thermal conductivity (unit: $\text{W m}^{-1} \text{K}^{-1}$), and $\frac{\partial T}{\partial Z}$ is the soil temperature gradient (unit: $^{\circ}\text{C m}^{-1}$). Soil thermal conductivity can be expressed as follows:

$$\lambda = -G \left(\frac{\partial T}{\partial Z}\right) \quad (7)$$

where G is the heat flux at a depth of 30 cm, and is the temperature gradient from 20 to 30 cm.

Results

Monthly soil moisture and precipitation

Precipitation significantly influences soil moisture temporal variation, which responds to precipitation. Using the collected datasets, the correlation between soil water content at different depths and precipitation can be explored. The monthly variations of the observed soil moisture and precipitation in 2009 are shown in Fig. 1. The minimal values of soil moisture at four layers all occur from December to January. The soil is frozen in the Loess Plateau during the period. Soil water content at a depth of 5 cm is approximately $0.05 \text{ m}^3 \text{ m}^{-3}$. Precipitation increases slightly from February to March, thus slightly increasing soil moisture because of melting snow, ice, etc. During the entire year, the maximal soil moisture occurred in August or September 2009. Meanwhile, soil water content at a depth of 10 cm reaches $0.30 \text{ m}^3 \text{ m}^{-3}$. In addition, the increased value at a depth of 10 cm is $0.18 \text{ m}^3 \text{ m}^{-3}$, which is higher than those at the other layers. During the aforementioned period, the trends of soil moisture variation are similar but slightly different upon reaching the peak. The peak value at depths of 40 cm is

approximately 1 month later than those at other depths because of soil water infiltration.

Because land evapotranspiration is very strong and it depletes soil moisture in the mesa of the Loess Plateau, the top-layer soil water content is easy to be dried out even after a rainfall event. Therefore, the soil water content at 5 cm depth is the smallest one among all layers. The water accumulates at the 40 cm depth, while the layer below is seldom ploughed in the mesa of the Loess Plateau, the soil density is large and the soil layer is hard, the rainfall water is not easy to infiltrate down. Therefore, the top-layer keeps a large soil water content compared the other layers. This conclusion is similar to that of a previous study in the Loess Plateau (Chen et al. 2008).

The precipitation amounts received by soil layers at different depths are dissimilar. The correlations between precipitation and soil moisture depend on depths. Soil moisture at a depth of 5 cm exhibits the maximal correlation coefficient with precipitation, which is approximately 0.545. The correlation coefficient between soil water content at a depth of 10 cm and precipitation is less, i.e., 0.455. This conclusion is different from that of a previous study in central Northeastern China (Zhang et al. 2008), which emphasized that soil moisture at a depth of 10 cm exhibited the highest correlation with precipitation during the same period because of the following reasons. (1) Solar radiation in the mesa of the Loess Plateau is strong in June and July (Lu and An 1998). Consequently, land surface is rapidly heated. Simultaneously, a part of precipitated water is evaporated into atmosphere before it penetrates the top soil layer. In this scenario, the relationship between precipitation and deep soil moisture is weak. (2) Differences in soil texture and vegetation cover result in the accumulation of soil water content.

Soil moisture variation at different depths

Soil moisture datasets are collected from the experimental site, which belongs to the Pingliang Lightning and Hail Storm Experimental Station of the Chinese Academy of Sciences. The terrain in the site is flat; consequently, topographic factors have minimal influence on soil moisture. Soil moisture fluctuation is mainly controlled by local precipitation. Because of precipitation intensity, the responses of precipitation to soil moisture at each layer exhibit significant differences. Figure 2 presents the soil moisture profile of the experimental site in the Loess Plateau.

Figure 3 indicates that soil moisture variation is significantly different at each layer from January to March because of snow or permafrost melting. Soil water content decreases from April to June. Soil moisture rises rapidly from July to November with the increase in precipitation. Moreover, soil moisture at different depths reaches its peak in September. With the influence of decreasing precipitation and land evapotranspiration, soil water content at different layers decreases dramatically. Soil moisture is at its minimum in December.

Soil moisture at depths of 40 and 10 cm has two peaks (from March to May and from July to November) in 2009 in the mesa of the Loess Plateau. Meanwhile, soil moisture reaches approximately $0.29 \text{ m}^3 \text{ m}^{-3}$ at a depth of 10 cm, and approximately $0.25 \text{ m}^3 \text{ m}^{-3}$ at a depth of 40 cm in late August. This result is consistent with that of a previous investigation in the Loess Plateau (Li et al. 2003). The period for accumulating water from precipitation has been obviously extended in the mesa of the Loess plateau. Figure 3 shows that soil moisture is relevant during the rainy season in the Loess Plateau. Soil water content at a

Fig. 2 Variations of monthly soil moisture and precipitation in the mesa of the Loess Plateau during 2009 (rectangle precipitation; dashed line soil moisture at a depth of 5 cm; solid line soil moisture at a depth of 10 cm; solid line with string soil moisture at 20 cm; and solid line with triangle soil moisture at 40 cm; units: $\text{m}^3 \text{ m}^{-3}$)

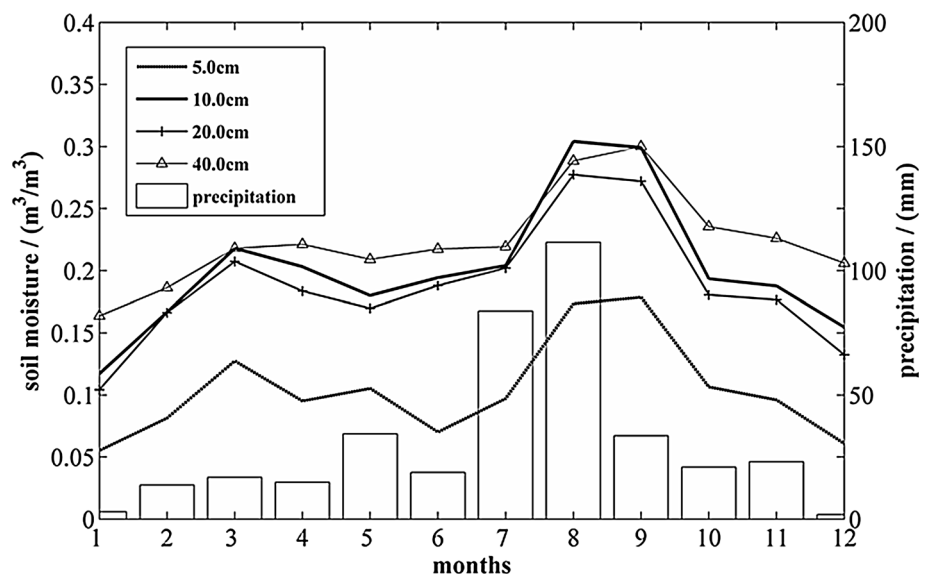


Fig. 3 The temporal variation of mean soil moisture profiles in the Loess Plateau from 2005 to 2010 (units: $\text{m}^3 \text{m}^{-3}$)

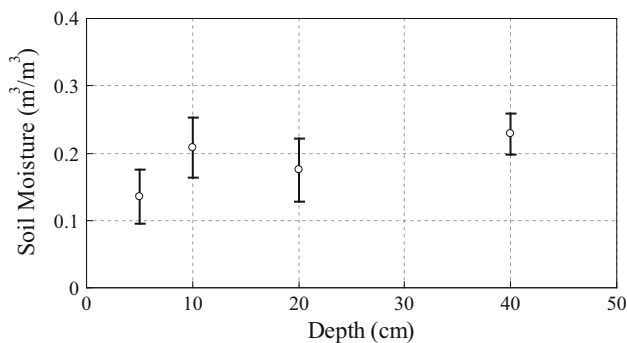
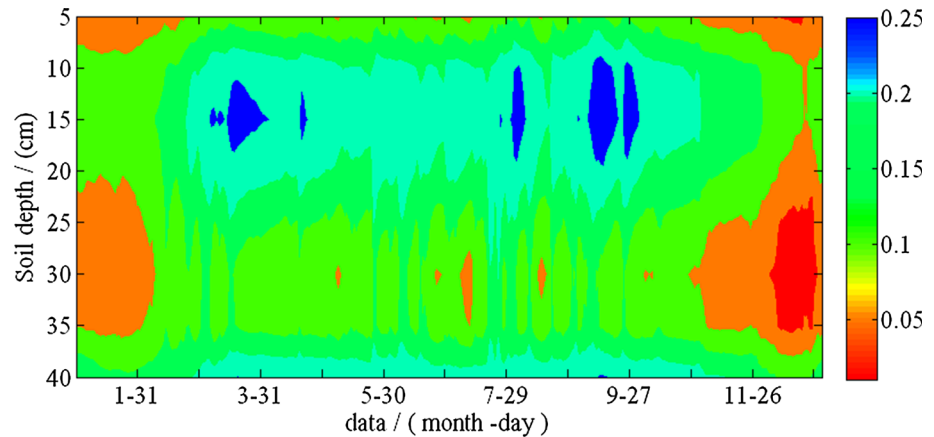


Fig. 4 The mean and standard deviations of the measured soil moisture at different depths in the mesa of the Loess Plateau from 2005 to 2010 (units: $\text{m}^3 \text{m}^{-3}$)

depth of 20 cm is significantly less than those at the upper and lower layers, which is particularly obvious from March to June. When moisture travels downward, soil moisture at a depth of 20 cm also exhibits an obvious increase during a year. Consequently, soil water content at the middle layer exhibits good correlation with that at the top layer. This result is similar to those of previous studies (Wang et al. 2009).

Soil moisture may be influenced by many aspects, such as air temperature, wind speed, etc. To get the accurate span of soil moisture change at different layer, this study uses the average of 5 years soil moisture at different depth. As the figure shown below (Fig. 4).

As shown in the figure, the change range of soil moisture for each layer varies. The depth of 5 cm changes from 0.05 to $0.18 \text{ m}^3 \text{m}^{-3}$, which experienced the widest range. It means the top layer is sensitive to the boundary environment or air temperature change. The deepest layer (40 cm) experiences the narrowest range, which between 0.17 and $0.23 \text{ m}^3 \text{m}^{-3}$. However, it is interesting to find that the changing range of 20 cm is a little wider than 10 cm. Compared with the Fig. 1, it seems has the same trend.

As shown in the preceding discussion, soil moisture in the mesa of the Loess Plateau is mainly influenced by local precipitation. Soil moisture variations are mainly associated with precipitation during the rainy season. However, monthly variation of soil moisture at different depths is obvious. The cause of such result is to be explored further.

Total antecedent precipitation and soil water content

The effective precipitation refers to precipitation water which is available to the root layer (Wei et al. 2005). However, the most important aspect is the indirect use of soil moisture of plants when precipitation flows into soil. Soil moisture variation is related to instantaneous precipitation and the accumulation of prophase effective precipitation. In order to find out the total effective antecedent precipitation has closer relationship with soil moisture than precipitation or not. The Fig. 5 adds all the relevant variables, as showing below.

Figure 5 shows that the total effective antecedent precipitation, comparing with precipitation, can better draw the trend of soil moisture change. Especially in the August of 2007, continuous precipitation leads to the increasing of soil moisture. Compared with precipitation, the total effective antecedent precipitation experiences a similar change with soil moisture. Not only the continuous precipitation, total effective antecedent precipitation also can show the soil moisture change after a single rainfall. Although the precipitation in 2009 not continuous, the trends of soil moisture and total effective antecedent precipitation are almost same. So as showing above, there is a strong correlation between total effective antecedent precipitation and soil moisture.

To explore the mathematic relationship between total effective antecedent precipitation and soil moisture, Fig. 6 presents the curve fitting and the correlation between them:

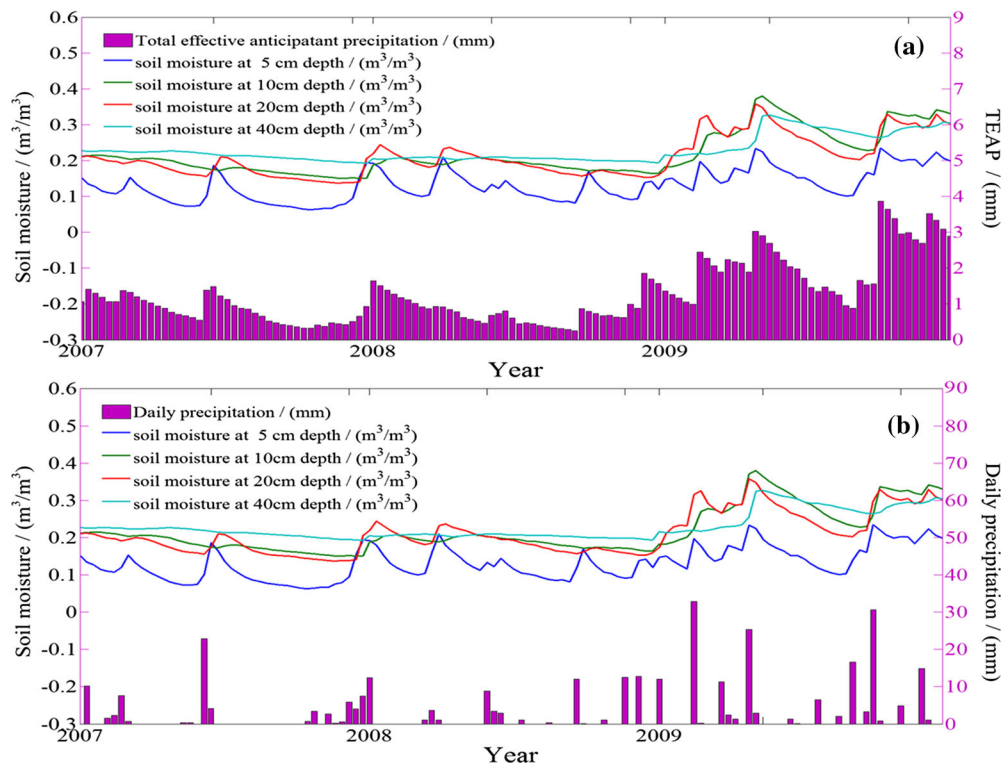


Fig. 5 Total effective antecedent precipitation and daily precipitation compared to soil moisture at four depths from 2007 to 2009 July to August. **a** Soil moisture and total effective antecedent precipitation. **b** Soil moisture and daily precipitation

An analysis between soil moisture and total effective antecedent precipitation for various depth showed that the correlation coefficients between them are all larger than 0.7. All the coefficients pass the significant test of 0.05.

Although the trends of soil moisture and the total antecedent precipitation are generally similar, all trends have a positive correlation at four depths. The dependence levels of soil moisture variation magnitude on total antecedent precipitation are slightly different. The curve at a depth of 10 cm exhibits the biggest slope. However, total effective precipitation at a depth of 10 cm presents the strongest effect on soil moisture. This conclusion is consistent with the results of previous studies (Liu et al. 2009; Wei et al. 2005). The correlation coefficient between soil moisture at a depth of 20 cm and the total antecedent precipitation is 0.873, which is the best fit. When total antecedent precipitation increases from 0 to 30 mm, soil moisture at a depth of 10 cm increases to 230 % of the initial value, which is the biggest amplitude. For deep soil, the force relationship between total antecedent precipitation and soil moisture decreases with depth. When total antecedent precipitation reaches approximately 30 mm, soil moisture increases to 155 % of the initial value at depth of 40 cm.

Compare with the former study by Liu and Wei (Liu et al. 2009; Wei et al. 2005), which using the liner fitting,

the quadratic equation proves to be better. Because the soil moisture would not increase dramatically when the precipitation is over the soil water-holding capacity. When total antecedent precipitation is close to 0 mm, soil water content is unaffected by early stage precipitation. Soil moisture is the initial soil water content during this period. Initial soil moisture contents at different depths (total antecedent precipitation at 0 mm in Fig. 6). The entire trend increases from shallow to deep. However, initial soil water content at a depth of 20 cm is slightly less than 10 cm, which agrees with actual observation results.

The highest storage capacity of soil water is related to porosity values of soil layer (Warrick 2003). Similar to initial soil water content, soil water content in the saturated layer varies slightly at different depths. From the quadratic fitting curve in Fig. 6, soil moisture values at different depths are to remain stable when total antecedent precipitation increases to approximately 40 mm. However, various peaks of soil water content appear at different depths. Water content at a depth of 10 cm is approximately 0.36 m³ m⁻³, which is the highest. Soil moisture decreases at a depth of 10–40 cm at the peak value. Moreover, the maximal saturation water content at a depth of 5 cm is less than that at 10 cm. The result is related to pore size and density of soil layer.

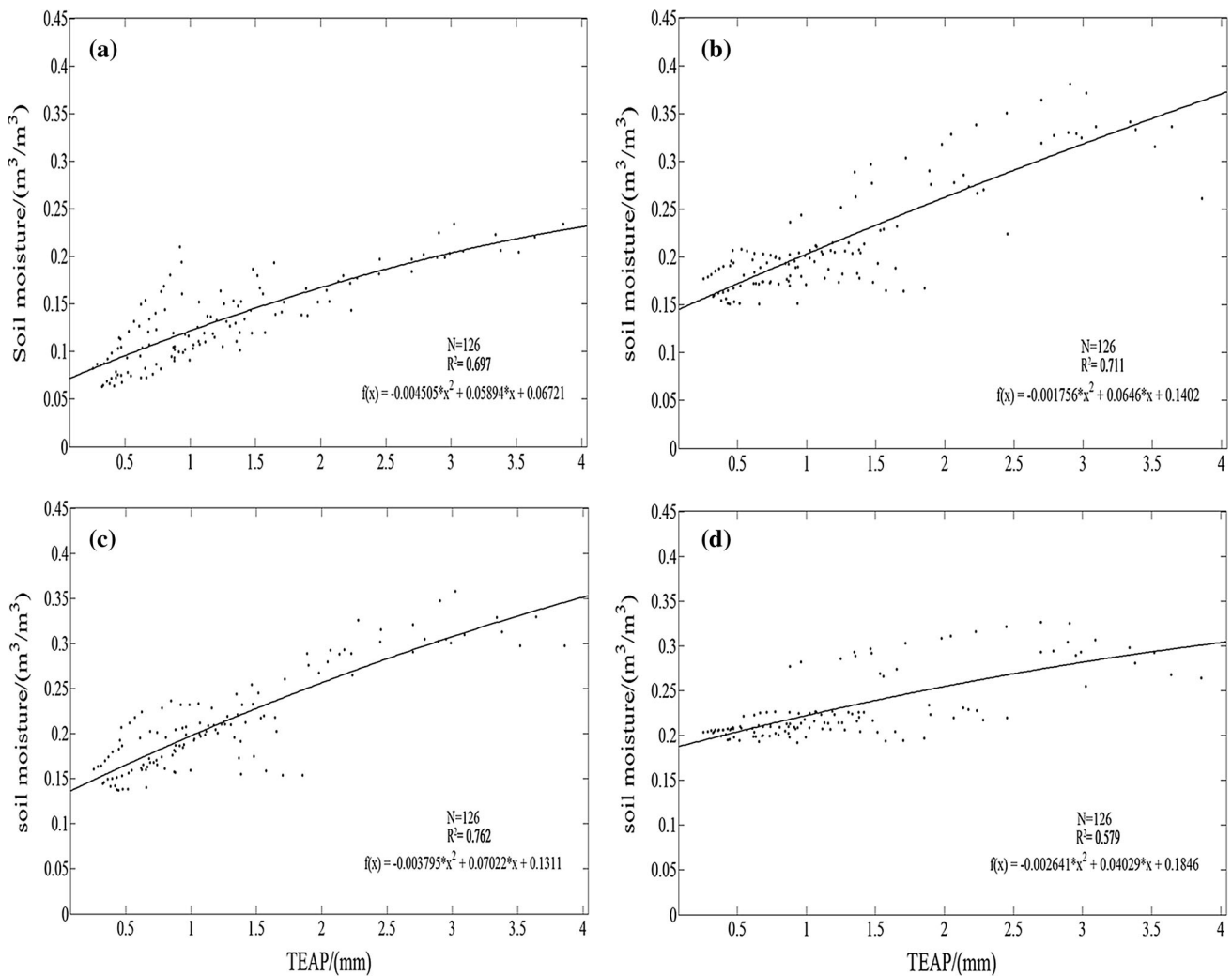


Fig. 6 The relationship between total effective antecedent precipitation (TEAP) and soil moisture: **a** 5 cm, **b** 10 cm, **c** 20 cm and **d** 40 cm

Model test

As mentioned above, the soil moisture during the summer can be calculated, based on the TEAP (total antecedent precipitation), using the equation below:

The simulation result and observation data are shown in Fig. 7.

Using the simulation data, which is calculated from the 1st June to 19th July 2010, compares with the observation soil moisture. As shown in the figure, the simulation soil

$$\begin{cases}
 SM_{5\text{ cm}} = -0.004505 \times TEAP^2 + 0.05894 \times TEAP + 0.06721 \\
 SM_{10\text{ cm}} = -0.001756 \times TEAP^2 + 0.06460 \times TEAP + 0.1402 \\
 SM_{20\text{ cm}} = -0.003795 \times TEAP^2 + 0.07022 \times TEAP + 0.1311 \\
 SM_{40\text{ cm}} = -0.002641 \times TEAP^2 + 0.04029 \times TEAP + 0.1846
 \end{cases} \tag{8}$$

In order to evaluate the simulation effect of the formula (8), in this paper, we select the data from 1st June to 19th July in 2010 to take an independent sample test.

moisture of each layer shows the same trend with the observation soil moisture. Simulation data can well depict the influence of anticipation on soil moisture.

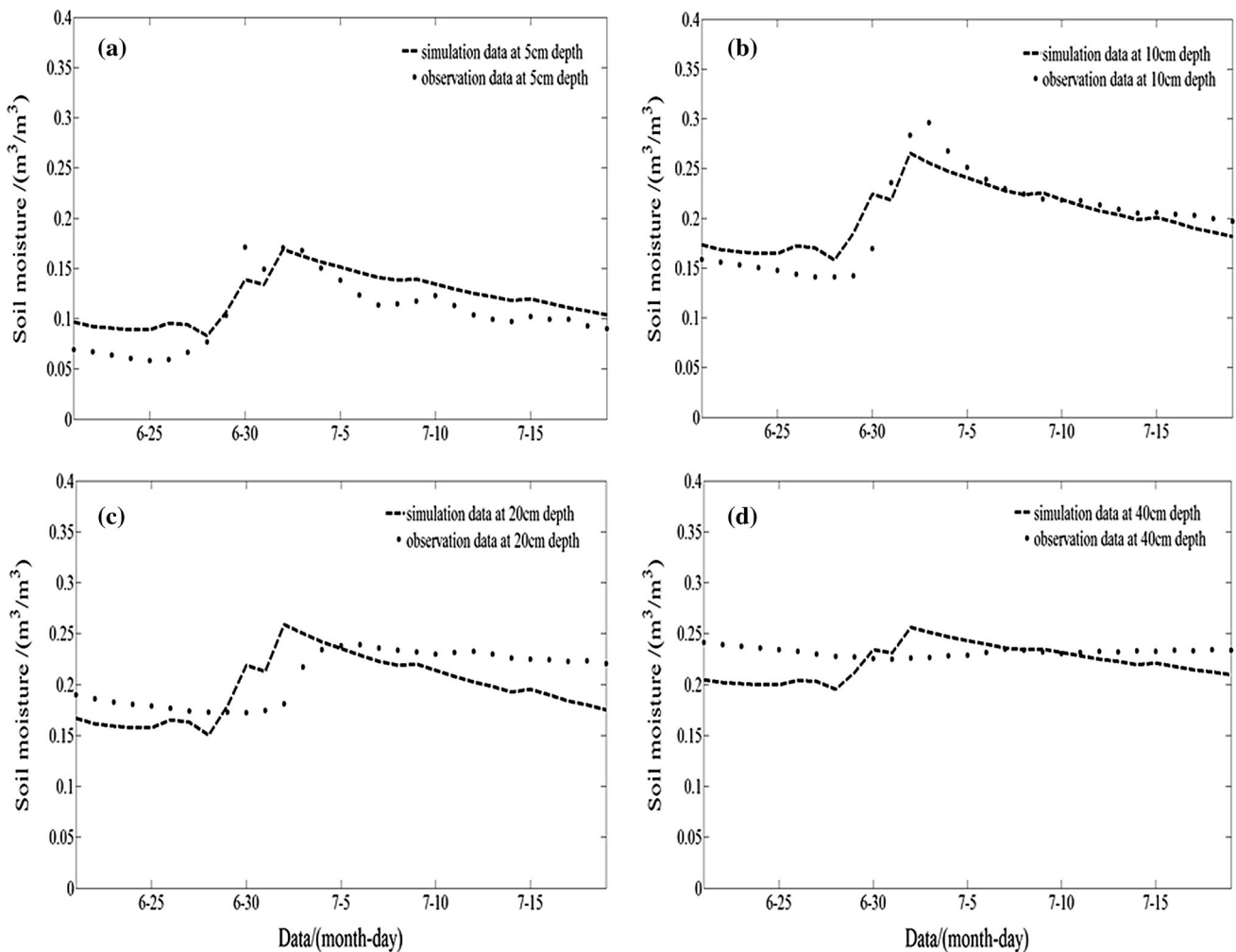


Fig. 7 The temporal variation of the observed and simulated soil moisture at four depths in from 1st June to 19th July, 2010. **a** 5 cm, **b** 10 cm, **c** 20 cm and **d** 40 cm

Table 2 Sample data fitting evaluation and the model calculation data evaluation (mean absolute error and mean relative error) (%)

	5 cm		10 cm		20 cm		40 cm	
	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE
Sample data fitting	1.827	15.452	2.314	10.723	2.015	10.164	1.870	7.756
Experiments verify	1.891	21.590	1.532	8.498	2.589	12.771	1.814	7.796

Table 2 reveals that the simulation result and observation data, MAE and MRE showed significant relationship in Loess Plateau. The mean absolute error of sample data fitting at each layer is below 2.4 %. At the same time, the simulation result is the worst at 5 cm, which experiences the maximum mean relative error. What’s more, the simulation result is better at 20 and 40 cm than the surface layer and deep layer. Compare with the former study by Liu et al. (2009), the simulation result at surface layer is both the worst. Because

the soil moisture at surface layer can be influenced by many other factors, such as wind speed or surface evaporation.

Test results show that, no matter the former fitting test or independence test, the simulation results are reached high precision. In the meantime, the precision rate of 5 cm is 88 %. At the same time, the precision rate of 10 cm is a little higher than 88 %, which better than some former study (Liu et al. 2009; Zhang et al. 2006; Wei et al. 2005). So the simulation effect is best at 10 cm.

Soil thermal conductive in the mesa of the Loess Plateau and its relationship with soil moisture

Soil temperature influences soil water content by changing soil diffusion and viscous coefficient, it also affects land surface evapotranspiration rate (Wang et al. 2012b). Given that water is a high thermal conductivity material, moisture content causes changes under different soil temperature conditions. The soil thermal conductivity is essential in determining soil heat flux using the measurement data of soil temperature gradient. Therefore, determining how soil thermal conductivity changes with soil moisture during a rainfall event has been a research hot spot in recent years.

By taking the layer between 20 and 40 cm as a whole, the soil temperature gradient at a depth of 30 cm can represent the temperature gradient of the layer as the soil temperature gradient is assumed negligible across this layer.

Figure 8 shows the temporal variation of soil moisture and thermal conductivity during AWSEX period. The trends of soil moisture variation at depths of 20 and 40 cm are similar during the entire observation period. This implies that the trends of soil moisture change at the 20–30 and 30–40 cm layers are similar. The soil water content in the 20–40 cm layer could be represented by mean soil moisture at depths of 20 and 40 cm.

The similarity among soil moisture variation trends provides available soil moisture datasets for the relationship between soil moisture and soil thermal conductivity at a depth of 30 cm. Figure 4 indicates that soil thermal conductivity is linked to the variation of soil moisture during AWSEX period. The maximal soil thermal conductivity is $1.7015 \text{ W m}^{-1} \text{ k}^{-1}$, whereas the minimum is $0.7754 \text{ W m}^{-1} \text{ k}^{-1}$ with a mean of $1.1037 \text{ W m}^{-1} \text{ k}^{-1}$ and standard deviation $0.1480 \text{ W m}^{-1} \text{ k}^{-1}$ during the observation period. The variation of soil thermal conductivity during an actual precipitation period is different from that during AWSEX period. The value of soil thermal

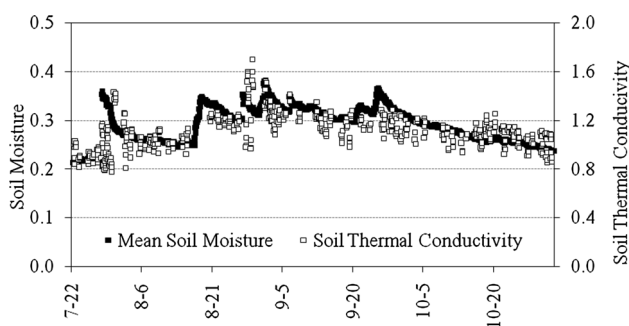


Fig. 8 The temporal variation of soil thermal conductivity and soil moisture in the mesa of the Loess Plateau

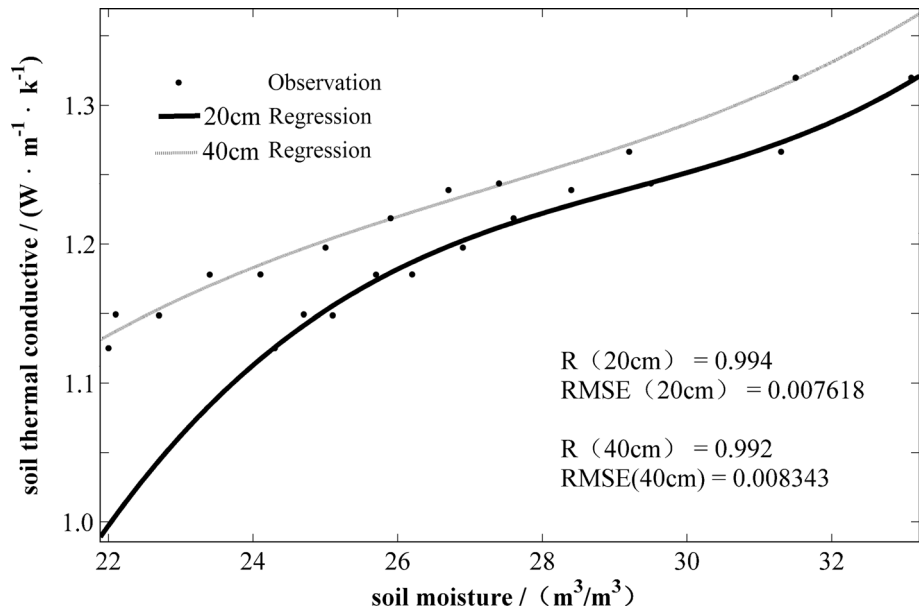
conductivity increased very fast at the beginning of AWSEX, whereas the value fluctuated according to soil moisture or local rainfall during the actual observation period (from August 18 to November 1).

The reasons for the aforementioned variation are as follows. (1) The thermal conductivity of water is 20 times that of air (Campbell 1985). When the added water completely fills in soil porosity, the soil reaches oversaturation and there is liquid water in soil layer. The measured thermal conductivity is contributed partially by liquid water. (2) The experiment shows that soil layer between the depths of 20 and 40 cm is not to be oversaturated during an actual rainfall event, this phenomenon also occurred during the experiments. Therefore, no liquid water accumulated within this layer. Soil thermal conductivity is therefore around a constant value in this case. The main factors that influence the soil thermal conductivity are soil water content, density, and porosity (Clothier 1985). During rainfall events, the relationship between soil moisture and soil thermal conductivity shows as follows:

Figure 9 shows that the relationship between soil moisture (the mean depths of 20 and 40 cm) and soil thermal conductivity (depth: 30 cm) is inconsistent. The fitting curve at a depth of 20 cm obviously increases with soil water content, whereas the fitting curve at a depth of 40 cm depth is not too steep. The increase rate at a depth of 40 cm is less than that at a depth of 20 cm. When soil moisture at different depths reaches $0.30 \text{ m}^3 \text{ m}^{-3}$, the increase in soil thermal conductivity at a depth of 30 cm begins to slow down. When soil at both depths are saturated and filled liquid water, the tendencies of soil thermal conductivity in both cases are approximately the same, and a significant increase trend is observed. In contrast to Fig. 6, the fitting effect of soil moisture increases (at depths of 20 and 40 cm) and thermal conductivity at a depth of 30 cm is obvious. R at a depth of 20 cm (40 cm) is 0.994 (0.992).

The causes of the aforementioned results are as follows. (1) During the initial stage, thermal conductivity and soil moisture in the lower layer have a significantly positive correlation at a depth of 30 cm with increasing soil water content. However, the amplitude of increase slow down as the soil moisture get to be saturated. These results are similar to those of the study of Wang et al. (2012b). (2) After the soil layer reaching oversaturation, soil thermal conductivity and soil water content in the lower layer experience a significant increase. As shown in the previous conclusion, liquid water fills top-layer soil. Moreover, the thermal conductivity of water is higher than that of soil. (3) The temporal variation of soil moisture at a depth of 40 cm is obviously later than that at a depth of 20 cm because when soil is deep, soil porosity and density are high.

Fig. 9 The fitting curves of soil thermal conductivity and soil moisture in the mesa of the Loess Plateau at 20 and 40 cm depths (*solid line* soil thermal conductivity and soil moisture change at 20 cm depth; *dashed line* soil thermal conductivity and soil moisture change at 40 cm depth)



Conclusions

Soil moisture plays an important role in controlling the surface runoff and drainage (Li et al. 2014b). Also it is one of the crucial variables in hydrological progress, which influence the energy fluxes and water exchange at the land surface-atmosphere interface (Wang and Qu 2009). To the author’s knowledge, however, the main factor which have the most significant influence on soil moisture has not be deeper studies on the Loess Plateau. Furthermore, the estimating of the soil moisture during summer is not well understood. So it is high time to build a method.

Based on the soil temperature, soil moisture and precipitation datasets collected in the mesa of the Loess Plateau from 2005 to 2010, July 22 to November 1, 2012, this research explored the links between soil moisture and total antecedent precipitation. Simultaneously, monthly variations of soil moisture at different depths, and the influence of local precipitation on soil thermal conductivity are analyzed. The following conclusions are drawn.

1. The maximal soil moisture at each layer occurs from August to September 2009 in the mesa of the Loess Plateau. The maximal value at a depth of 10 cm is larger than those at the rest of the layers, which is approximately $0.32 \text{ m}^3 \text{ m}^{-3}$. The minimal soil moisture values in four layers all appear from December to January. Meanwhile, the minimal soil water content at a depth of 5 cm is approximately $0.05 \text{ m}^3 \text{ m}^{-3}$. This implies that soil moisture variations are mainly controlled by local precipitation over the Loess Plateau. Although soil water contents in each layer have approximately the same variation trends, peak times

are slightly different. Peak time at depths of 5 and 40 cm lags at approximately 1 month compared with those at depths of 10 and 20 cm. The correlation coefficient between soil moisture and precipitation at a depth of 5 cm is approximately 0.545 within a year, which is the largest value. The correlation coefficient between soil moisture at a depth of 10 cm and precipitation is the lowest, which is approximately 0.455. There are temporal lags for responses of soil moisture to local precipitation. The deeper soil layer is less sensitive to local precipitation.

2. Monthly mean soil moisture variations at different depths from 2005 to 2010 are as follows. Soil moisture values in each layer obviously increase from January to March, and decreases from April to June, which corresponded the freezing and thawing process of the loess. As precipitation increases, soil moisture rises rapidly from July to November. Soil moisture at different depths reaches its peak in September. Simultaneously, two peaks (from March to May and from July to November) appear for soil moisture at depths of 10 and 40 cm. The accumulation time of soil water content in the study area is significantly longer than those in other Chinese areas. The depth of 5 cm soil moisture changes from 0.05 to $0.18 \text{ m}^3 \text{ m}^{-3}$, which experienced the widest range. It means the top layer is sensitive to the boundary environment or air temperature change. The deepest layer (40 cm) experiences the narrowest range, which between 0.17 and $0.23 \text{ m}^3 \text{ m}^{-3}$.
3. In the Loess Plateau, the correlation coefficient between soil moisture at a depth of 20 cm and total antecedent precipitation is highest of the four

observation levels, which is approximately 0.873. By contrast, the coefficient at a depth of 40 cm is minimal, i.e., only approximately 0.761. During the early stage, when effective precipitation increases to nearly 40 mm, soil water content at different depths remains unchanged. However, soil water content measured at each depth reaches its peak at different times. The value at a depth of 10 cm achieves the highest water content, which is approximately $0.37 \text{ m}^3 \text{ m}^{-3}$. The peak values of moisture content at depths ranging from 10 to 40 cm decrease, but all values remain approximately $0.30 \text{ m}^3 \text{ m}^{-3}$. There are links between soil moisture variation at certain depths and local antecedent precipitation.

4. No matter the former fitting test or independence test, the simulation results are reached high precision. In the meantime, the precision rate of 5 cm is 88 %. At the same time, the precision rate of 10 cm is a little higher than 88 %, which better than some former study. The simulation soil moisture of each layer shows the same trend with the observation data. Simulation data can well depict the influence of anticipation on soil moisture.
5. When soil moisture increases during the experimental period, soil thermal conductivity at a depth of 30 cm rises rapidly. Under the condition of natural precipitation, although precipitation causes soil thermal conductivity to fluctuate, the value remains significantly different from those under Adding Water to soil layer EXperiment period. Natural precipitation cannot increase soil thermal conductivity significantly. Simultaneously, correlation is poor. However, under the condition of soil unsaturation, the correlation between soil moisture and thermal conductivity is improved and presents obvious positive correlation. Meanwhile, thermal conductivity at a depth of 30 cm is approximately $1.1037 \text{ W m}^{-1} \text{ K}^{-1}$. These give evidence that water content of deeper soil layer is not seriously influenced by a moderate rainfall event in the mesa of the Loess Plateau, the soil thermal conductivity exhibit less sensitive to the local precipitation.

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References

- Beven KJ, Kirkby M (1979) A physically based, variable contributing area model of basin hydrology. *Hydrol Sci Bull* 24:43–69
- Campbell GS (1985) *Soil physics with basic transport models for soil-plant systems*[M]. Elsevier, Amsterdam
- Chandra SK, Sai MVR, Dwivedi RS (2008) Surface soil moisture changes during 2007 summer monsoon season derived from AMSR-E Land3 product. *Curr Sci* 95:1731–1738
- Chen B, Ding YG, Liu JM (2005) The soil humidity prediction model experiment research of the climatic humid zone. *Sci Meteorol Sin* 25:231–237 (in Chinese with English abstract)
- Chen SY, Guo KZ, Dong AX (2008) Research of variety rule of soil humidity in Loess Plateau of China. *Plateau Meteorol* 27:30–537 (in Chinese with English abstract)
- Clothier B (1985) *Soil physics with BASIC*. Elsevier, Amsterdam, pp 120–145
- Gupta M, Prashant S, Tanvir I (2014) Evaluation of TRMM rainfall for soil moisture prediction in a subtropical climate. *Environ Earth Sci* 71(10):4421–4431
- Jiang N, Shao M, Hu W et al (2013) Characteristics of water circulation and balance of typical vegetations at plot scale on the Loess plateau of China [J]. *Environ Earth Sci* 70(1):157–166
- Jinbai H, Jiawei W et al (2014) Runoff and water budget of the Liudaogou Catchment at the wind–water erosion crisscross region on the Loess Plateau of China [J]. *Environ Earth Sci* 72(9):3623–3633
- Koster RD, Suarez MJ, Higgins RW (2003) Observational evidence that soil moisture variations affect precipitation. *Geophys Res Lett* 30:1241. doi:10.1029/2002GL016571
- Li YY, Shao MA (2006) Change of soil physical properties under long-term natural vegetation restoration in the Loess Plateau of China. *J Arid Environ* 64:77–96
- Li HJ, Wang MB, Chai BF (2003) Spatial and temporal characteristics of soil moisture dynamics in Loess Plateau. *Chin J Appl Ecol* 14:515–519 (in Chinese with English abstract)
- Li X, Liu L, Duan Z et al (2014a) Spatio-temporal variability in remotely sensed surface soil moisture and its relationship with precipitation and evapotranspiration during the growing season in the Loess Plateau, China [J]. *Environ Earth Sci* 71(4):1809–1820
- Li Xiaoying, Liu Lichen et al (2014b) Spatio-temporal variability in remotely sensed surface soil moisture and its relationship with precipitation and evapotranspiration during the growing season in the Loess Plateau, China [J]. *Environ Earth Sci* 71:1809–1820
- Liu SL, Guo XD, Fu BJ (2007) The effect of environmental variables on soil characteristics at different scales in the transition zone of the Loess Plateau in China. *Soil Use Manag* 23:92–99
- Liu KQ, Liu ZX, Liang YT, Fang SQ, Tang YX (2009) Method for soil moisture calculation in plough layer based on antecedent effective rainfall. *Chin J Agrometeorol* 30(3):365–369 (in Chinese with English abstract)
- Lu H, An Z (1998) Paleoclimatic significance of grain size of loess-palaeosol deposit in Chinese Loess Plateau. *Sci China* 41(6):626–631
- Ma ZG, Wei HL, Fu CB (2000) Relationship between regional soil moisture variation and climatic variability over east China. *Acta Meteorol Sin* 58:278–287 (in Chinese with English abstract)
- Ma JZ, Wang XS, Edmunds WM (2005) The characteristics of ground-water resources and their changes under the impacts of human activity in the arid Northwest China—a case study of the Shiyang River Basin. *J Arid Environ* 61:277–295
- Shi XK, Wen J, Lei Wang (2010) Regional soil moisture retrievals and simulations from assimilation of satellite microwave brightness temperature observations. *Environ Earth Sci* 61(6):1289–1299
- Stolte J, van Venrooij B, Zhang G (2003) Land-use induced spatial heterogeneity of soil hydraulic properties on the Loess Plateau in China. *Catena* 54:59–75

- Wang LL, Qu JJ (2009) Satellite remote sensing applications for surface soil moisture monitoring: a review. *Front Earth Sci China* 3(2):237–247
- Wang R, Li WP, Liu X, Wang LN (2009) Simulation of the impacts of spring soil moisture over the Tibetan Plateau on summer precipitation in China Plateau Meteorol 28:1233–1241 **(in Chinese with English abstract)**
- Wang LQ, Liang T, Wang WL (2012a) Effects of antecedent soil moisture on losses of rare earth elements and phosphorus in runoff. *Environ Earth Sci* 66(8):2379–2385
- Wang S, Wang QJ, Fan J (2012b) Soil thermal properties determination and prediction model comparison. *Trans Chin Soc Agric Eng* 28:78–84 **(in Chinese with English abstract)**
- Warrick AW (2003) *Soil water dynamics*. Oxford University Press, New York, pp 95–245
- Wei ZG, Wen J, Lv SH (2005) A Primary field experiment of land-atmosphere interaction over the Loess Plateau and its ground surface energy in clear day. *Plateau Meteorol* 24:545–555 **(in Chinese with English abstract)**
- Wen J, Su ZB, Ma YM (2003) Determination of land surface temperature and soil moisture from tropical rainfall measuring Mission/Microwave imager remote sensing data. *J Geophys Res* 108(D2):4038. doi:[10.1029/2002JD002176](https://doi.org/10.1029/2002JD002176)
- Western AW, Grayson RB, Blöschl G, Willgoose GR, McMahon TA (1999) Observed spatial organization of soil moisture and its relation to terrain indices. *Water Resour Res* 35:797–810
- Zhang JT, Ru WM, Li B et al (2006) Relationships between vegetation and climate on the Loess Plateau in China. *Folia Geobot* 41(2):151–163
- Zhang WJ, Zhou TJ, Yu RC (2008) Spatial distribution and temporal variation of soil moisture over China Part I: multi-data inter-comparison. *Chin J Atmos Sci* 32:581–597
- Zhang B, Wu P, Zhao X et al (2013) Changes in vegetation condition in areas with different gradients (1980–2010) on the Loess Plateau, China [J]. *Environ Earth Sci* 68(8):2427–2438