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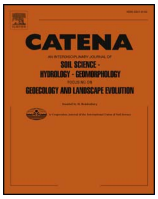

The spatial variability of soil water storage and its controlling factors during dry and wet periods on loess hillslopes

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ABSTRACT

Soil water storage (SWS), a critical parameter in hydrological processes, is an effective water source for vegetation growth in the semi-arid Loess Plateau of China. Its spatial pattern at various soil depths along transects and temporal changes in the dominant environmental factors that affect SWS are essential to ensure the sustainability of vegetation restoration efforts and achieve an accurate understanding of hydrological processes on the Loess hillslope. In this study, we investigated SWS at depths of 0–4 m at a total of 54 points on three hillslopes covered with artificial forest, natural forest and natural grass during four observation periods. The results reflected clear seasonal trends in SWS. A substantial water deficit occurred during the severe drought year of 2015. SWS at depths of 0–1 m increased and SWS at depths of 1–4 m decreased from after the rainy season of 2015 to before the rainy season of 2016 (a near-normal drought year), and SWS at depths of 0–4 m maintained its resemblance to conditions that occurred during the rainy season of 2016. These results may indicate that drought conditions affect variations in SWS. In addition, topography and vegetation type were the dominant factors controlling SWS in the different soil layers. SWS at shallow soil depths was mainly affected by topography, while SWS at deep soil depths was mainly controlled by vegetation type. During the dry season, slope aspect was the most important factor controlling SWS at shallow soil depths due to the effects of slope aspect on snowmelt and wind evaporation. On the other hand, during the wet season, the slope gradient was more important in terms of its effect on SWS than slope aspect at shallow soil depths due to the effects of slope gradient on infiltration and runoff.

1. Introduction

In semiarid areas, soil water storage (SWS) is a critical parameter in hydrological processes that is connected to precipitation, runoff and groundwater (Gao and Shao, 2012a; Li et al., 2016; Penna et al., 2013). It is a critical water resource for vegetation growth (Hu et al., 2009) and agricultural development (Li et al., 2016). Generally, a substantial portion of rainfall is intercepted by the plant canopy. The rain that reaches the soil surface forms runoff, and any remainder infiltrates into the soil. Soil water is greatly influenced by rainfall amount and intensity (Liu et al., 2015), vegetation type (Fang et al., 2016), topography (slope gradient, slope aspect, slope position, and relative elevation) (Yang et al., 2015), soil properties (bulk density, soil organic content, clay, silt and sand) (Fang et al., 2016), and other factors. Combinations of these controlling factors cause SWS to vary spatially and temporally (Li et al., 2015a, 2015b).

The spatial distribution and temporal dynamics of soil water at shallow depths on the Loess Plateau have been studied by many scholars (Huang et al., 2012; Jia et al., 2013a, 2013b; Wang et al., 2013; Zhu et al., 2014; Zhu et al., 2009). Soil water quantity has been shown to be closely related to soil depth, especially at the soil depths investigated (Jia and Shao, 2014). On the Loess Plateau, precipitation is the only source of soil water and recharge for the surface soil layers. Therefore, the soil water in deep soil layers cannot be replenished by contributions from rainfall and groundwater. In fact, the growth of perennial plants depends to a large extent on deep SWS. Perennial plants, especially introduced vegetation, cause deficits in deep SWS because they consume large amounts of soil water, exacerbating problems involving dry soil and leading to the degradation of land and vegetation cover (Fang et al., 2016; Yang et al., 2012). Deep SWS plays a relatively important role in vegetation restoration and ecosystem development (Wang et al., 2010 and 2011). However, high cost of labor and time is the limited factors making researches on deep SWS ignored. Therefore, few studies focused on spatial distribution and temporal dynamics of deep SWS which can clearly reveal the sustainability needs for vegetation restoration.

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Many studies have been carried out on the factors that affect spatial variations in SWS, such as precipitation, terrain attributes, soil properties and vegetation type. Famiglietti et al. (1998) found that precipitation variability is directly related to soil water variability. Huang et al. (2016) verified that antecedent precipitation is the main factor controlling soil water in the top layer of soils (0–10 cm). Terrain attributes are critical factors that influence soil water. Previous studies have indicated that the toes of slopes and gentle slopes contain larger amounts of soil water than the upper parts of slopes and steep slopes within shallow soil layers (Ali et al., 2010; Qiu et al., 2001; Western et al., 2004). Yang et al. (2015) found that the effects of terrain attributes on variations in soil water differ between surface soil layers and deep soil layers. Other studies have indicated that terrain attributes become increasingly important during wet periods; however, during dry periods, soil properties have a greater influence on the distribution of soil water (Grayson et al., 2002; Western et al., 1999). Vegetation type is a key factor contributing to soil water variation, especially introduced vegetation (Yang et al., 2014; Yang et al., 2012). The factors that control soil water have been investigated on scales corresponding to individual farms (Zhu and Lin, 2011), catchments (Huang et al., 2016; Huang et al., 2012; Takagi and Lin, 2012; Zhu et al., 2014), and hillslopes (Tromp-van Meerveld and Mcdonnell, 2006; Yang et al., 2015). Due to the difficulties involved in obtaining measurements from deep soil layers and the high cost of such measurements in terms of labor and time, few studies have considered the properties of deep soil layers. Instead, many studies have focused solely on the properties of surface soils (Takagi and Lin, 2012) or have neglected soil properties (Yang et al., 2015). Takagi and Lin (2012) determined the relationships between soil water in shallow (0–1.1 m) soil layers and soil-terrain attributes within a forested catchment in central Pennsylvania, USA. Yang et al. (2015) compared the correlation of the spatial patterns of soil water in the surface soil layer (0–1 m) and the deep soil layer (1–6 m) with topographic properties and vegetation attributes. Soil attributes were not considered in this study. Soil properties are critical variables that regulate soil water. Variations in soil properties depend considerably on soil depth; in particular, the properties of deep soil layers often differ substantially from those of the surface soil layer. Thus, determining the main environmental factors that consist of soil properties at various depths is necessary. It can clearly reveal effect of soil properties on SWS among several factors at wet or dry conditions. In addition, most previous studies have focused on more than one environmental factor that affects soil water, but few studies have examined the effect of multiple environmental factors on variations in SWS in different soil layers. In our study, considering multiple environmental factors consisting of soil properties at soil depths of 0–4 m can clearly determine the dominant factors controlling SWS and temporal changes in the dominant factors controlling SWS in different periods.

The study investigated the spatial distribution of SWS at four soil depths in the soil profile(0–1, 1–2, 2–3 and 3–4 m) on three hillslopes covered with artificial forest, natural forest and natural grass during dry and wet seasons. This study aimed to (1) compare SWS at various soil depths along three gradient-parallel transects on a hillslope and (2) identify the main factors affecting SWS in shallow and deep soil layers in different periods from a list of 10 environmental factors, and determine temporal changes in the dominant environmental factors that affect SWS.

2. Materials and methods

2.1. Study area

The study area is located in Caijiachuan Catchment on the Loess Plateau (110°40′-110°48′ E, 36°14′-36°18′ N). This catchment covers 39.33 km^2 and is located in Shanxi province (Fig. 1(a)). It experiences a semiarid continental climate and has received an average annual precipitation of 494.7 mm during 1985–2016. Approximately 85% of this precipitation falls during May to October. In addition, the annual precipitation varies greatly; the maximum recorded annual precipitation is 922.5 mm, whereas the minimum value is only 277.7 mm. The annual average evaporation is 1723.9 mm, more than half of which occurs from April to July (Bi et al., 2006).

The major soil type is classified as Alfisol according to the USDA classification system. The *Robinia pseudoacacia* was widely planted since implementation of the "Grain for Green" Project. Natural forest and natural grass are also dominant vegetation types on the Loess hillslope. The basic description of the experimental site is provided in Table 1.

2.2. Experimental setting and data collection

Three hillslopes covered with artificial forestland, natural forestland and natural grassland were chosen to investigate SWS variations. Three transects were located on each hillslope; these transects are labeled AF1, AF2, and AF3; NF1, NF2, and NF3; and NG1, NG2, and NG3. Within each transect, six slope positions were located at distances of 0 m, 20 m, 40 m, 60 m, 80 m and 100 m, respectively, from bottom to top along each transect. The individual stations are labeled AF11 to AF16, AF21 to AF26, AF31 to AF36, NF11 to NF16, NF21 to NF26, NF31 to NF36, NG11 to NG16, NG21 to NG26, and NG31 to NG36 (Fig. 1(b), (c) and (d)). All of the sampling sites belonging to a single transect have similar slope aspect. The experiment was carried out during two periods in 2015, May 02–12 (before the rainy season) and October 18–25 (after the rainy season) and two periods in 2016, May 04–12 and October 16–23. No precipitation fell during these periods or during the week preceding each experimental period. In this study, the period from November to April is defined as the dry season (i.e., the non-growing season), and the period from May to October was defined as the wet season (i.e., the growing season). Thus, the SWS values measured in May (before the rainy season) and October (after the rainy season) were considered to correspond to the dry season and the wet season, respectively. Soil samples were collected at depths of 0–400 cm at 20 cm intervals using an auger. Twenty soil samples were collected at each sampling site. The layer-cumulative SWS was divided into SWS0-1, SWS1-2, SWS2-3, and SWS3-4, which correspond to SWS at depths of 0–1 m, 1–2 m, 2–3 m, and 3–4 m, respectively. The layer-cumulative SWS was calculated as follows (Jia and Shao, 2013),

$$SWS = \sum \frac{10\theta_i d_i h}{\rho} \tag{1}$$

where *SWS* indicates layer-cumulative soil water storage (mm), θ_i indicates the gravimetric soil water content (%) in the soil layer, d_i indicates the soil bulk density (g/cm^3), h represents the soil layer thickness ($h = 20$ cm in our study). ρ is the density of water (1 g/cm^3), and i indicates the soil layer in question.

θ_i was obtained by the oven-drying method (105 °C, 24 h). During the experimental periods, the land cover type found at each site and the slope position of each site were recorded. Artificial forestland, natural forestland and natural grassland were coded as 1, 2, and 3, respectively. Slope position corresponds to the distance along the transect, as measured from the toe to the crest of each hillslope. A compass was used to determine slope gradients and the slope aspect of each site during the field investigations. Slope gradient was determined using a compass and was measured in degrees. With the compass, slope aspect was recorded in degrees clockwise from north and then transformed into its cosine. In the laboratory, soil sample was air-dried and passed through a 0.25-mm sieve after rocks and roots removed. Soil organic carbon (SOC) content was measured using the dichromate oxidation method (Feng et al., 2014). The air-dried soil sample passed through a 2 mm sieve after which clay (< 0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm) were measured using a Malvern Mastersizer 2000 laser diffraction device (Malvern Instruments Ltd., Malvern, UK). At each