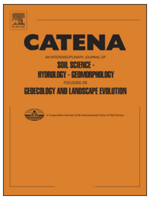
Catena 137 (2016) 563–571

Contents lists available at ScienceDirect

Catena

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



Use of a state-space approach to predict soil water storage at the hillslope scale on the Loess Plateau, China

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ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form 6 September 2015
Accepted 5 November 2015
Available online xxxx

Keywords:
Spatial pattern
Linear regression
Soil texture
Transect

ABSTRACT

Soil water storage is a critical variable controlling hydrological and biological processes. The precise estimation of soil water storage in diverse soil layers is fundamental to understanding hydro-biological processes and efficiently managing water resources. The objectives of this study were to evaluate the effects of topography (elevation) and soil properties (clay, silt, sand content, median grain size, and fractal dimension) on soil water storage and then to estimate soil water storage using a state-space approach. The soil water storage values of three soil layers (0–1, 1–2, and 2–3 m) were measured from May to December 2014 at 70 locations along two 187 m long transects on a hillslope of the Loess Plateau, China. Samples from various depths were also collected to determine soil properties. The best state-space approach explained 98.8% of the total variation in soil water storage, while the best classical linear regression equation only explained 64.2%. The state-space approach using any combination of variables described the spatial pattern of soil water storage much better than equivalent linear regression equations. Elevation and clay content were identified as the most effective combination for soil water storage estimation in the state-space approach, and were used to effectively predict the soil water storage spatial pattern along the second transect. The state-space approach is thus a useful tool that is recommended for predicting soil water storage spatial patterns at the hillslope scale using topography and soil properties.

1. Introduction

Soil water storage is a key state variable for understanding hydrologic and climatic processes, such as partitioning of precipitation and snowmelt water into infiltration and runoff, percolation, and evapotranspiration (Famiglietti et al., 1998; Hu et al., 2010b; Western et al., 2004). It also has an important role in maintaining ecosystem health by regulating the transport of sediment and chemicals to environmentally sensitive areas (e.g., surface water and groundwater) (Biswas and Si, 2011a; Sun, 1986). Additionally, soil water storage is the principal limiting factor in arid and semiarid ecosystems because it controls the transpiration demand of the plant community (Gao et al., 2013a; Hu et al., 2009; Hu et al., 2010a). Therefore, understanding soil water storage and its spatial patterns is a prerequisite for improving hydrologic and climatic models (Biswas, 2014; Western et al., 2002). Furthermore, accurate estimation of soil water storage can provide essential information for the rational management of water resources and the successful restoration of vegetation on the Loess Plateau, China (Gao et al., 2013b).

Soil water storage is well recognized as being spatially variable (Jia et al., 2013) and influenced by many factors, such as topography, soil properties, vegetation, and meteorological conditions (Biswas, 2014; Brocca et al., 2010; Gómez-Plaza et al., 2001; Western et al., 1999). In particular, soil water storage is greatly affected by topography, e.g., elevation, slope, and curvature. Work at the field scale by Charpentier and Groffman (1992) revealed that the spatial variation in soil water content increased with increasing topographic heterogeneity. Tomer and Anderson (1995) demonstrated that topography was the major controlling factor and that combinations of elevation, slope, and curvature could explain 51–77% of the variability in soil water storage across a sand plain hillslope. Penna et al. (2009) reported that slope and topographic wetness index were the best univariate spatial predictors of soil moisture at a hillslope scale.

Soil texture, which determines the water-holding capacity, is another important factor affecting soil water storage. Vachaud et al. (1985) indicated that the spatial patterns of soil moisture at the field scale could in large part be explained by variability in soil texture. da Silva et al. (2001) identified soil texture as a major factor controlling soil moisture, with clay content positively correlated with soil moisture. Mohanty and Skaggs (2001) demonstrated that fields with sandy loam soils had better soil moisture stability over time than those containing silt loam soils. Soil fractal dimension, reflecting the soil structure and particle-size distribution, also likely affects soil water storage (Arya and Paris, 1981; Tyler and Wheatcraft, 1992). In addition, soil water storage is closely related to vegetation and precipitation. Canopy cover, root characteristics, and litter depth can influence runoff, interception, evapotranspiration,

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http://dx.doi.org/10.1016/j.catena.2015.11.003
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and deep percolation, and thus affect soil moisture dynamics (Gómez-Plaza et al., 2001; Jacobs et al., 2004). Soil moisture is highly correlated with precipitation, increasing sharply following rainfall events and decreasing slowly over periods without rainfall (Gao et al., 2013a). Although precipitation exerts an extensive effect on soil moisture, especially during storms, soil texture is more important than precipitation in quantifying this influence (Yoo et al., 1998).

Heterogeneity in controlling factors and their combinations can create high spatial variability in soil water storage. To better understand this spatial variability, quantifying the relationships between soil water storage and its potential influencing factors is very important. Therefore, a large volume of research has been done to estimate soil water storage based on easily measured variables at various scales (Gao et al., 2013b; Penna et al., 2009; Qiu et al., 2003; Tomer and Anderson, 1995; Western et al., 1999). However, the analytical approach used in such studies is based on classical statistics. Such methods consider variables to be spatially independent of each other, with no spatial structure, and thus can generate erroneous or misleading results (Nielsen and Alemi, 1989). In contrast, the autoregressive state-space approach, by means of the Kalman filter, provides opportunities for suitable identification of the spatial process of a variable by taking into account spatial associations (Timm et al., 2003a; Wendroth et al., 2003). The state-space approach has proven more effective than classical statistical methods for identifying localized variation (Stevenson et al., 2001; Timm et al., 2004), and has been widely applied to estimate soil properties and vegetation yield and generate reliable predictions (Cassel et al., 2000; Li et al., 2001; Nielsen and Alemi, 1989; Stevenson et al., 2001; Timm et al., 2003a; Wendroth et al., 1992; Wendroth et al., 1999; Wendroth et al., 2003). The state-space approach has received increasing attention in the past ten years. For example, Joschko et al. (2006) successfully estimated earthworm biodiversity based on pH and total nitrogen values along a regional scale transect. Jia et al. (2011) described the spatial distribution of total net primary productivity of managed grasslands in a small catchment. Liu et al. (2012) and She et al. (2014) both reported that the state-space approach described spatial variation in soil organic carbon much better than the equivalent linear regression equation. Aquino et al. (2015) reported on the effect of land leveling on the spatial relationships of soil properties in a 1 ha lowland area. However, few studies have quantitatively predicted soil water storage using a state-space approach and previous state-space approaches have not been validated. Although Morkoc et al. (1985) studied the spatial association of soil moisture using a state-space approach, they only focused on the uppermost 5 cm. Thus, there is a strong need to identify the spatial variability of soil water storage in diverse soil layers in the profile from 0 to 3 m using a state-space approach.

The Loess Plateau, a severely eroded area, has received considerable and extended attention in China. Afforestation was a useful way to prevent soil erosion and hence the “Grain for Green” project was implemented in 1999 to plant trees and convert slope cropland to forest, shrub, and grassland (Fu et al., 2006). Black locust (*Robinia pseudoacacia* L.) is a promising tree for reforestation due to its fast growth, superior drought tolerance, and extensive cover area in the Loess Plateau as a non-native tree species (Qiu et al., 2010). However, afforestation of the area has produced some negative effects, such as the emergence of a dry soil layer that limits growth of black locust (Wang et al., 2011). Consequently, soil moisture has become a limiting factor governing vegetation restoration in the Loess Plateau (Hu et al., 2009; Jia et al., 2013). Precise prediction of soil water storage is critical for forest management with sustainable production. Thus, soil water storage in diverse soil layers (0–1, 1–2, and 2–3 m) was observed at 70 locations along two 187 m long transects at the hillslope scale. Because the distribution of black locust and precipitation on the hillslope were relative homogeneous, these two factors were not used to characterize the variability of soil water storage in this study. The objectives of this study were to: (1) quantify the spatial relationships between soil water storage and its potential influencing factors, such as topography (elevation) and soil texture in diverse soil layers, measured along one of transects; (2) compare the performance of the state-space approach with classical linear regression for estimating soil water storage; and (3) use the state-space approach to predict soil water storage spatial distribution in diverse soil layers along the second transect.

2. Materials and methods

2.1. Study area

The study was conducted in the Wangdonggou watershed (35°12′–35°16′N, 107°40′–107°42′E; elevation 946 to 1226 m above sea level, area 8.3 km^2), located in Changwu County, Shaanxi Province, China. The prevailing landform is loessial tableland and gullyland, covering 35 and 65% of the watershed, respectively. This area is characterized by a continental monsoon climate with a mean temperature of 9.2 °C. The mean annual precipitation is 582.3 mm, more than 58.2% of which falls between July and September. The groundwater table is about 50–80 m below surface and agricultural production on the tableland mainly relies on natural rainfall (no irrigation). The soil, derived from wind-deposited loess, belongs to the loessial soil group according to the FAO-UNESCO soil classification system. Dominant plant species in this region include wheatgrass (*Agropyron cristatum* L.), green bristlegrass (*Setaria viridis* L.), black locust (*R. pseudoacacia* L.), and Chinese arborvitae (*Platycladus orientalis* L.).

2.2. Experimental design

After a detailed field survey, one typical hillslope covered with black locust was selected as the study site. Two 187 m long transects were laid out along the hillslope with a mean slope of 36.4%. A total of 35 locations were selected for the installation of access tubes for soil water measurements and sampling along each of two transects (A and B) (Fig. 1). The distance between sampling locations was 5.5 m, while the distance between the two transects was 10 m. The elevation of each location was measured using differential kinematic GPS. Because the state-space approach is designed for variables taken in one dimension, observations for each transect were conducted starting from the 0–1 m soil layer at the first location and ending in the 2–3 m soil layer at the 35th location (Fig. 1) (Wendroth et al., 2003). Transects A and B both had 105 monitoring positions. The variables obtained from transect A were used to establish the state-space approach, and observations from transect B were used to validate the state-space approach.

2.3. Soil sampling and measurements

One 3-m soil core per location along both transects was taken using a soil auger (5 cm in diameter). Fifteen distributed samples were collected at 0.2 m increments from each soil core for soil particle analysis. Each soil sample was air-dried and passed through a 2-mm sieve. Soil particle sizes were measured using a Mastersizer 2000 (Malvern Instruments, Malvern, England) with three replicates. An access tube was installed at each location to measure soil water content to a depth of 3.0 m with a neutron probe (CNC-503B DR, ChaoNeng, China) calibrated using standard methods (Hauser, 1984; Huang and Gallichand, 2006). Soil water measurements were conducted nine times from May to December 2014 at each location, at increments of 0.1 and 0.2 m in the 0–1 and 1–3 m soil layers, respectively. If rainfall event happened, the measurement was conducted on the fourth day after rainfall event. The values of soil water storage (mm) for the 0–1, 1–2, and 2–3 m soil layers were calculated from the measured soil water content. To better apply the state-space approach, the mean soil water storage value of all nine measurements was used for analyses at each location.

The mean soil properties (e.g., clay, silt, sand content, soil median grain size, and fractal dimension) in the three soil layers were calculated to identify the spatial variability of soil water storage in diverse soil