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Land use dependent variation of soil water infiltration characteristics and their scale-specific controls

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A R T I C L E I N F O

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A B S T R A C T

Land use change has remarkable impact on hydrological processes. However, little is known on the land use dependent variation of soil water infiltration characteristics. This study aims to investigate the effects of land use type on the spatial variation of infiltration characteristics and to identify their scale-specific controls. A total of 132 in-situ infiltration measurements were conducted using a disc infiltrometer along four 96-m transects under different land use types (forestland, shrubland, cropland with tillage, and cropland without tillage) in a typical agricultural region in north China. Classical statistics and multivariate empirical mode decomposition (MEMD) were used to explore the features of the overall and scale-specific spatial variation of four infiltration characteristics, i.e., cumulative infiltration over 30 min (I_{30}), sorptivity (S), unsaturated hydraulic conductivity (K_0, h_0 = −2 cm) and saturated hydraulic conductivity (K_s). Besides, the scale-specific correlations between the infiltration characteristics and selected environmental factors, i.e., bulk density (BD), soil organic matter (SOM), initial soil water content (IWC) and water temperature (T) were investigated. The results indicated that land use type significantly affected not only the values of the infiltration characteristics but also their overall and scale-specific spatial variability. Tillage was found to have great impact on these infiltration characteristics. Generally, cropland with tillage revealed significantly higher values and weaker overall spatial variation of I_{30} and S; while its K_0 and K_s were significantly lower. Four major common spatial scales, i.e., 8–9 m, 13–16 m, 28–34 m and 47–94 m, were identified for the infiltration characteristics under different land use types using MEMD. The spatial variation of infiltration characteristics in forestland and shrubland were decomposed into larger common scales than that in croplands. Furthermore, the dominating factors of infiltration characteristics were scale-specific and also varied with land use type. Generally, SOM and BD were considered as important controls in smaller scales in croplands and the impacts of IWC and T were more effective in larger scales in forestland and shrubland.

1. Introduction

Infiltration, the process by which water on the ground surface enters the soil, is one of the most important earth surface processes. It controls the water cycles among surface-water, groundwater, and soil water reservoir (Horton, 1933), as well as substantially affects a series of ecological processes including water supply for plant growth (Ludwig et al., 2005), solute transport to deep soil and groundwater (Jarvis, 2007), and the development of surface runoff and soil erosion (De Roo et al., 1992).

At a given initial soil water content and water supply condition, the infiltration process is dictated by soil hydraulic properties, such as sorptivity (S), saturated and unsaturated hydraulic conductivity (K_s or K_θ). Under natural conditions, soil hydraulic properties vary spatially at different scales and are affected by a range of soil properties and environmental factors related to the development of soil structure, pore space and geometry, such as soil texture, organic matter, microbial activity, plant root development, drying-wetting and freezing-thawing alternations, and soil tillage and management (Loague and Gander, 1990). Moreover, the spatial heterogeneity of initial soil water content and water supply conditions commonly existing in the field could enhance the spatial variability of the water infiltration process. In agricultural management, accurate information of infiltration behavior and its spatial variability is necessary, e.g., for precision farming with optimal irrigation scheduling to save water and increase water use efficiency (Pereira et al., 2002). In environmental studies, it is also

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indispensable to incorporate spatial variation of infiltration characteristics into hydrological modeling with the aim to produce reliable predictions of soil water content, groundwater recharge, solute transport, surface runoff, and soil erosion (Loague, 1990; De Roo et al., 1992; Farajalla and Vieux, 1995; Jarvis, 2007). Therefore, spatial variability of infiltration characteristics has been studied at different regions and various spatial scales. In a 9.6-ha native grassland watershed named R-5, Sharma et al. (1980) reported strong spatial variability of infiltration parameters derived from field infiltration measurement as indicated by coefficients of variation ranging from 45% to 75%. Besides, an obvious pattern of infiltration distribution was found with respect to soil type and topographical positions. Using a constant infiltration parameter for the same R-5 watershed, Loague and Freeze (1985) reported a poor performance by a quasi-physically based rainfall-runoff model (QPBRRM) in predicting watershed runoff processes, which were attributed to the unexplained spatial variability of infiltration across the watershed. In their further work, the performance of the model QPBRRM was improved by incorporating the supplemental information on spatial variation of infiltration quantified by geostatistical methods (Loague and Gander, 1990; Loague, 1990). Based on semivariograms, Vieira et al. (1981) revealed the spatial structure of infiltration rate based on intensive field measurements at 1280 locations on an alluvial fan and found that steady state infiltration rate was autocorrelated within a distance of 50 m. For an agricultural soil, considerable spatial variation of infiltration was reported in a cultivated vineyard and explained mainly by the differences in local topsoil structure and history of cultivation (Leonard and Andrieux, 1998). Based on field infiltration measurement, Haghighi et al. (2014) investigated the spatial variability of final infiltration rate, sorptivity, and transmissivity on a flood spreading area in Iran and found a high degree of spatial dependence of these parameters as indicated by low nugget to sill ratios of their semivariograms. Despite of the widespread recognition of the existence of spatial variation of infiltration characteristics, little is known on the underlying mechanisms that control the spatial variability of infiltration processes.

One big obstacle to identifying the controlling factors of the spatial variation of infiltration is the scale-dependent relationships between infiltration and environmental factors (Goovaerts, 1999; Heuvelink and Webster, 2001; Biswas and Si, 2011). In a natural system, the overall observed spatial variation of soil properties is a reflection of integrated influences imposed by a number of processes occurring together at different intensities and different scales. Moreover, the tightly coupled system including abiotic and biotic factors could be nonlinear and nonstationary (Biswas and Si, 2011). Thus, in addition to classical statistics, several other methods have been employed in soil science to identify the scale-dependent variations of soil properties and their relationships with relevant environmental factors, i.e., elevation, topography, climate, land use type and vegetation species at different spatial scales, such as factorial kriging analysis (Goovaerts, 1992; Liu et al., 2013), state-space modeling (Wendroth et al., 2001; Liu et al., 2012), wavelet analysis (Si, 2003; Lark et al., 2004) and empirical mode decomposition (Biswas and Si, 2011; Hu and Si, 2013, Hu et al., 2014; She et al., 2014). However, few studies have addressed the scale-specific variation of infiltration characteristics and their relationships with environmental factors.

Soil infiltration characteristics, commonly represented by parameters such as soil hydraulic conductivity, sorptivity, infiltration rate and accumulative infiltration, can be directly measured or indirectly derived from infiltration models based on infiltration observations (Mubarak et al., 2010; Latorre et al., 2015). Using undisturbed soil samples taken from the field, it is easier to conduct infiltration measurements in the laboratory than with in-situ measurements where the boundary conditions may be difficult to control. However, the laboratory results could not fully represent the field condition due to the inevitable disturbance during sampling, small size of the soil samples, and the wall-effect of the cylinder or column used for sampling. On the contrary, in-situ infiltration measurement could be more difficult to control, but the results are considered to be more representative and valuable for subsequent applications (Mubarak et al., 2010). It also should be noted that some environmental factors, such as temperature, humidity and initial soil water content, could change during the time-consuming infiltration measurements performed at many locations in the field. It can affect infiltration processes and thus contribute to the in-situ observed spatial variability of infiltration characteristics (Jaynes, 1990; Lin et al., 1998).

Land use change is the most direct anthropogenic modification of the Earth's land surface, which largely depends on human decision driven by various purposes like expansion and intensification of agriculture, urbanization, deforestation and mining (Foley et al., 2005). Accompanied with land use change, a series of environmental factors are altered accordingly due to soil disturbance and different land management. Consequently, behavior of hydrological processes could markedly change with land use change. DeFries and Eshleman (2004) proposed the importance of understanding the consequences of land use change for hydrological processes in the coming decades. However, the lack of information of field-measured hydrological parameters and their variability under different land use types substantially reduces the accuracy of hydrological model outputs. In recent years, many researchers have focused on the effects of land use change on infiltration processes in different ecosystems and soil types (Schwartz et al., 2003; Bormann and Klaassen, 2008; Yimer et al., 2008; Gonzalez-Sosa et al., 2010; Chartier et al., 2011; Neris et al., 2012; Huang et al., 2015). They reached a consistent conclusion that land use change could greatly change infiltration processes. Nevertheless, few studies have investigated the land use dependent spatial variability of infiltration characteristics under field conditions and little is known on the underlying mechanisms with the consideration of scale effects.

Therefore, the objectives of the current study were (1) to investigate the effect of land use types on infiltration characteristics based on in-situ measurement in an intensively managed agricultural area; (2) to reveal the spatial variability of infiltration characteristics under different land use types; and (3) to identify the controlling factors at different spatial scales using a multivariate empirical mode decomposition method.

2. Materials and methods

2.1. Study area

The study area is located in Fengqiu County (114°14′–114°45′E, 34°53′–35°14′N), Henan Province in north China, a typical agricultural region in the hinterland of the Huang-Huai-Hai Plain. This region is dominated by a typical semi-humid monsoon climate. The annual precipitation is 615 mm, about 60–90% of which falls between May and October. The average annual temperature is 13.9 °C and average monthly temperature ranges from -1.0 °C in January to 27.2 °C in July. The annual potential evaporation is about 1587 mm. The area has a flat topography with elevation ranging from 65 m to 73 m above sea level. The groundwater table is located about 3–15 m below the land surface. The field experiment was conducted in an alluvial plain where the soil profiles are quite uniform across the landscape. The major soil type is fluvo-aquic soil and the soil profiles are generally characterized by three layers, with a sandy loam layer (sand 72.9%, silt 17.5%, clay 9.6%) at depth of 0–30 cm, silt clay layer (sand 47.0%, silt 34.5%, clay 28.1%) at depth of 30–60 cm, and sandy loam layer (sand 62.0%, silt 28.1%, clay 9.9%) at depth of 60–170 cm (Zhang et al., 2011). Most of the area is cultivated for agricultural production and the prevailing cropping system is wheat-corn rotation. Traditional land management with tillage using tine cultivators is predominant and the minimum tillage and no-tillage systems are gaining popularity. Windbreak belts planted with poplar trees (*Populus L.*) are usually located between adjacent agricultural fields. Besides, honeysuckle (*Lonicera japonica*) is