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Applying fractal analysis to detect spatio-temporal variability of soil moisture content on two contrasting land use hillslopes

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ABSTRACT

Soil moisture variations in space and time are critical in ecological, hydrological, pedological and environmental studies. This study used fractal analysis to detect the spatio-temporal variability of soil moisture on two contrasting land use hillslopes in the hilly area of Taihu Lake Basin of China. Surface (0–20 cm) soil moisture data from January 2013 to September 2015 (a total of 37 sampling days) were analyzed at 39 and 38 sites on the tea garden and forest hillslopes, respectively, with a spatial resolution of about 8 m. Results showed that the forest hillslope was significantly ($P < 0.05$) wetter than the tea garden hillslope. The spatial mean soil moisture on both hillslopes had a significant negative linear correlation ($R^2 = 0.753$ for tea garden ($P < 0.05$) and $R^2 = 0.459$ for forest ($P < 0.05$)) with corresponding CV for 37 sampling dates. The fractal dimension (D) was found to be better than the nugget/sill ratio in describing the spatial dependence of soil moisture. The advantage of the D is that it does not require the modelling of the semivariogram since it can be calculated on the basis of the experimental semivariogram. Soil moisture on the forest hillslope showed stronger spatial dependence than that on the tea garden hillslope according to D. However, the soil moisture on both hillslopes showed similar temporal dependence and a low-to-moderate autocorrelation structure. In addition, the temporal variability of soil moisture content was spatially correlated on tea garden hillslope. If a location is temporally autocorrelated, the locations nearby tend also to be temporally autocorrelated. It would be possible to make more accurate moisture trend predictions for temporal autocorrelated locations with small D. These findings had important applications related to sampling design, simulation of soil water flow and agricultural water resources management.

1. Introduction

Soil moisture is an important variable influencing water, solute and energy fluxes in the earth surface (Vereecken et al., 2007). It is a major component of the hydrologic cycle, controlling processes of runoff, infiltration and evapotranspiration at different scales (Pachepsky et al., 2003). In addition, soil moisture variations have substantial influence on soil nutrient status (Zhu et al., 2009; Schmidt et al., 2011). Therefore, soil moisture variation is critical in hydrological, ecological and environmental studies (Fu et al., 2003; Lin et al., 2005; Zhu and Lin, 2011). In addition, land-use/cover change (LUCC) plays a key role in the soil moisture variations at different scales (She et al., 2012; Zhu et al., 2014; Zucco et al., 2014). This is related to the fact that LUCC affects soil properties (e.g., soil texture, structure and organic matter), which determines hydraulic characteristics (Duan et al., 2011; Biro et al., 2013). For example, Duan et al. (2011) indicated that the soil silt-clay content and organic matter were significantly lower for the cultivated lands than for the meadow lands where there was no detectable erosion and sand accumulation. Biro et al. (2013) found that clay content was higher in the cultivated land and the fallow land as compared with that of the woodland in the surface soil layer. The LUCC also influences hydrological processes (e.g., evapotranspiration, interception loss, infiltration and runoff) (Fu et al., 2003; Feltrin et al., 2013), root characteristics (Sonneveld et al., 2003) and the distribution of preferential flow paths (Cheng et al., 2011). Therefore, LUCC may have substantial influence on soil moisture variations.

Soil moisture varies in space and time. Knowledge of soil moisture variability across spatio-temporal scales improves the understanding of land surface processes, which depends on topography, soil properties, vegetation, climate and land use as well (Koster and the GLACE Team, 2004; Bolten et al., 2010; Lin, 2011). Spatio-temporal variability of soil moisture has been investigated by several methods, including classical statistics and geostatistics. Classical statistical method was widely used at an early stage, assuming that the measured soil moisture data are

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independent. Such an independence of observation is a barrier to their accurate description and analysis (Myers, 1997). However, classical statistical techniques are useful in a preliminary assessment of the data. Geostatistics is a powerful tool for characterizing the spatial distribution of soil moisture content and its variability (Vieira et al., 2008). This is related to its ability to characterize spatial variability through a consistent probabilistic model. Therefore, the predictions made using the geostatistical methods are tailored to the intrinsic structure of the variable and not only to the sampling quantity or geometric pattern. Geostatistics can deal with soil moisture observations which are dependent in nature. During the last decades, great efforts were undertaken to detect spatio-temporal variability of soil moisture content by using geostatistics (Wang et al., 2001; Brocca et al., 2007; Hu et al., 2010; Schneider et al., 2011; Baroni et al., 2013; Korres et al., 2015; Yang et al., 2016), which applied the semivariogram function to fit a model of the spatio-temporal correlation of the observed phenomenon.

Semivariance can also be applied to determine the fractal nature of the parameter being studied. A fractal is a natural phenomenon, showing that a pattern at one scale is repeated at other scales (often called a self-similarity). The fractal theory, based on self-similarity, is a mathematical concept of describing natural structures characterized by the geometric heterogeneity of linearity or surfaces (Anderson et al., 1998). Fractal analysis has often been used to quantify the specific spatial/temporal dependences of mobile social networks (Zheng et al., 2016), economic data (Siokis, 2014), crop yield (Eghball et al., 2000), plant parameters (Linsenmeier et al., 2011), topographic attributes (Vidal-Vazquez et al., 2007), and soil properties (e.g., saturated hydraulic conductivity and bulk density) (Burrough, 1981; Wang and Shao, 2013). Recently, Vidal-Vazquez et al. (2012) applied the fractal technique to describe of the spatio-temporal variability of soil water content across an agricultural field. Korres et al. (2015) used fractal analysis to detect soil moisture patterns and found a multifractal behavior in all observed datasets. In their study where a long-term trend of soil moisture is of interest, it is valuable for developing statistical or numerical models to predict response of the soil moisture to environmental factors (e.g., climate and land use) and identify long-term variations.

Taihu Lake is suffering from eutrophication due to excessive nonpoint Nitrogen (N) and Phosphorus (P) inputs from the watershed (Jin et al., 2007). Agricultural and urban activities are major sources of N and P to lake ecosystems. In the hilly area of Taihu Lake Basin, fast LUCC (conversion of forest to tea garden) has been reported in recently years (Jin et al., 2007; Xu et al., 2011). This greatly influences the soil water movement and trigger severe non-point losses of N and P through water flow. Knowledge of the spatio-temporal patterns of soil moisture under these two contrasting land uses is very important for understanding water movement in soils, which is essential for understanding nutrient transport processes and reducing nutrient losses in this region. However, the fractal analysis has rarely been used for quantifying the spatio-temporal variability of soil moisture in Taihu Lake Basin.

Therefore, the objectives of this study are to: i) investigate the spatio-temporal variability of soil moisture content on tea garden and forest hillslopes by using classical statistics, geostatistics and fractal analysis; ii) detect the relationships between the fractal dimension and statistical or geostatistical parameters; iii) identify the best method for describing the spatio-temporal variability of soil moisture.

2. Materials and methods

2.1. Study sites

This study was conducted on two adjacent land use (tea garden and forest) hillslopes (31°21′N, 119°03′E) (each has an area of 0.3 ha) in the hilly area of Taihu Lake Basin, China (Fig. 1). This study area is characterized with a north subtropical-middle subtropical transition monsoon climate with four distinctive seasons. The annual mean temperature is 15.9 °C and the annual mean precipitation is 1157 mm. The tea garden (TG) and bamboo forest (BF) hillslopes are adjacent to each other (Fig. 1). Green tea (*Camellia sinensis (L.) O. Kuntze*) and Moso bamboo (*Phyllostachys edulis (Carr.) H. de Lehaie*) are dominant on the tea garden and forest hillslopes, respectively. The elevation of the tea garden hillslope ranges from 80 to 88 m and the slope ranges from 2 to 21%, while those of the forest hillslope ranges from 77 to 83 m and 0 to 19%, respectively. The soil type of these two hillslopes is shallow lithosols according to the FAO soil classification (Orthents according to Soil Taxonomy) (FAO/ISRIC/ISSS, 1998). Parent material is quartz sandstone. Soils are described as silt loam texture with silt content > 60%. Surface (0–20 cm) soil organic matter contents were about 2% on both hillslopes. The depth to bedrock varies from < 0.3 m at the summit slope position to about 1.0 m at the foot slope position (Liao et al., 2016).

When the tea plants were firstly planted on the tea garden hillslope 15 years ago, tillage (i.e., contour plowing) was applied and large rocks were removed. Spacing between two rows is about 1–1.5 m wide. The annual N, P and K rates for the TG are 700–800, 150–200 and 300–400 kg ha^{-1}, respectively. Organic fertilizer (rapeseed residuals after oil extraction) is usually applied by digging shallow trenches (< 0.2 m deep) between rows on November. In the tea growing season (From February to May), manure is surface broadcasted 2–3 times. After the tea leafs are harvested (late May), tea plants are pruned and the residuals are left on the surface of the soil. On the forest hillslope that has been established for 35 years, no fertilizer or tillage is applied. Bamboos are occasionally harvested when they are more five years old (Lv et al., 2016).

2.2. Soil moisture measurement

For monitoring volumetric soil water content, access polyvinyl chloride tubes were installed at 39 and 38 sites on the tea garden and forest hillslopes, respectively, with a spatial resolution of about 8 m (Fig. 1). Due to the irregular distribution of plants in space (especially on the forest hillslope), the distances between some sampling sites are not the same. A portable time-domain reflectometry TRIME-PICO-IPH soil moisture probe (IMKO, Ettlingen, Germany) was used at 37 dates from January 2013 to September 2015. The temporal resolution of the measurements (frequencies from 3 times during 5 days to 2 times during 61 days) is considered to be enough for capturing the soil water dynamics because the observation period contains both wet and dry periods representing a wide range of soil water status. For example, soil water content was measured three times from 10 May to 15 May 2013, with the total rainfall of 90 mm during this period. In addition, soil water content was also measured during winter months (e.g., 16 Dec 2013 and 6 Jan 2014), with very low precipitation.

Volumetric soil water was measured at the depth of 0 to 20 cm each time (note that the TRIME-PICO-IPH probe has a length of 18 cm). For each site, the probe was twisted in the access tube to face different directions and 2–3 readings were then taken. The average of these readings was used as the final water content for each site on a specific date. In addition, an outdoor mini weather station was set up to measure rainfall and air temperature. During the entire observation period, the total rainfall was 3544 mm with the mean temperature of 16 °C.

2.3. Soil properties and terrain attributes

Around each VSM access tube (within 1-m distance), soil samples at 0 to 20 cm depth interval were collected using a hand auger. Three subsamples were collected for each site and then fully mixed, in order to reduce measurement errors. These samples were air dried at room temperature (about 20 °C) for 14 days, weighted, ground and sieved through a 2 mm polyethylene sieve. Particles larger than 2 mm (rock