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Landscape characteristics influence the spatial pattern of soil water storage: Similarity over times and at depths

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ABSTRACT

Similarity in the spatial patterns of soil water storage (SWS) over time and at depths at multiple scales and locations reflects the similarity in the underlying hydrological processes. The objective of this study was to examine the similarity in the spatial patterns of SWS and its characteristic landscape positions for variable soil depths and over time at a field scale. Soil water content (further converted to SWS by multiplying with depth) was measured for five years (2007–2011) along a transect of 128 points at a study site that has representative hummocky landscape of the North American Prairie Pothole region. Surface (0–20 cm) and subsurface (20–140 cm at 20 cm interval) soil water contents were measured using time domain reflectometry and a neutron probe, respectively. High rank correlation coefficient between the measurements over time and at any depth layers (surface = 0–20 cm, root zone = 0–60 cm and total active soil profile = 0–120 cm) indicated strong similarity of the spatial patterns of SWS and thus the underlying hydrological processes. The spatial patterns at large scales (>72 m) were contributed by alternating knolls and depressions (dominant macro-topographical variations in this type of landscape) and were very similar between any measurement times and depth layers. Similarity over time was changed at medium scales (18–72 m) due to the changes in the landform elements. However, changes in the small-scale (<18 m) spatial patterns were not associated with any landscape characteristics. Similarity was increased at different scales with increase in soil depth owing to strong buffering capacity. Information on the similarity of the spatial patterns at different scales and locations can be used to identify change in sampling domain as controlled by hydrological processes operating at different scales and locations and thus can deliver maximum information with minimum sampling efforts.

1. Introduction

Soil water is a primary limiting factor for semi-arid ecosystem functioning (Porporato et al., 2004) and a key determinant factor in environmental health (Sun, 1986). It is involved in a wide variety of natural processes (ecological, climatic and geomorphological) that act at different spatio-temporal scales (Entin et al., 2000; Goovaerts, 1998). Knowledge on the behavior of soil water storage (SWS) and its spatio-temporal distribution provides essential information on various hydrologic, climatic, and general circulation models, weather prediction, evapotranspiration and runoff (Famiglietti and Wood, 1995), precipitation and atmospheric variability (Koster et al., 2004). A number of highly heterogeneous factors and processes acting in different intensities over a variety of scales make the distribution of SWS highly variable in space and time and pose a challenge in hydrology and climate studies (Quinn, 2004).

Due to high spatio-temporal variability in SWS, a large number of observations or samples are necessary to characterize a field. Fortunately, the factors and processes controlling SWS exhibit non-random spatial patterns consisting of a regular or systematic variation within a catchment or a field and are termed as the 'spatial organization' (Western et al., 1999). For example, factors like topography, lithology, parent material, climate and vegetation (Van Wambeke and Dulal, 1978) may result in a distinct and consistent pattern in the distribution of SWS within a catchment or a field (Grayson and Western, 1998; Kachanoski and Dejong, 1988). Moreover the scaling heterogeneity of factors makes the spatial pattern of SWS highly scale-dependent. For example, at small catchment and hill slope scale factors like water routing processes (Anderson and Burt, 1978), differential radiation (Western et al., 1999), heterogeneity in soil (Famiglietti et al., 1998) and vegetation (Hupet and Vanclooster, 2002) control SWS spatial pattern on and within the landscape. The saturation excess water at a particular location is important for runoff producing processes in many catchments (Anderson and Burt, 1978) resulting in a systematic organization in SWS associated with topographic convergence (Barling et al., 1994). Whereas, the atmospheric, geologic, and climatic variability determines the organization of SWS over a large area (Entin et al., 2000; Schneider et al., 2008). The contribution of infiltration, runoff, and lateral redistribution makes the small-scale variability in the spatial pattern of SWS of utmost interest in hydrological studies at small and medium catchments or watersheds.

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Spatial pattern of SWS was found to be similar from a repeated measurement within a catchment or a field. This is because some locations are found to be consistently wetter or drier than the field-averaged SWS yielding a similar spatial pattern over time. Vachaud et al. (1985) used Spearman's rank correlation to examine the similarity in the overall spatial pattern and cumulative probability function of relative mean difference to examine the similarity in the rank of individual locations over time. The concept of similarity in the spatial pattern of SWS was termed as time stability (Vachaud et al., 1985) and has been investigated over a range of study area, sampling scheme, sampling depth, study period, and land use (Hu et al., 2009; Kachanoski and Dejong, 1988; Martinez-Fernandez and Ceballos, 2003; Pachepsky et al., 2005). Time stability was defined as a time invariant association between spatial location and classical statistical measures of SWS most often the mean (Grayson and Western, 1998). One of the important applications of this concept has been the identification of time stable locations, which can considerably reduce the number of sampling locations in obtaining mean SWS for an area of interest.

Scale dependence in the time-stable spatial patterns of SWS was also investigated. Kachanoski and Dejong (1988) used the spatial coherency analysis to examine the similarity of the spatial patterns as a function of spatial scale. However, information on the characteristic landscapes of the scale-dependent time-stable spatial patterns was out of reach of this study. In extracting scale information, spectral analysis looses the spatial information. In a previous study, Biswas and Si (2011e) examined the scale-dependent time-stability of the spatial pattern of SWS within a season (intra-season), between different seasons (inter-season) and between same season from different years (inter-annual) using the wavelet coherency. The intra-season time stability was found to be stronger than inter-annual time stability, which was stronger than inter-season time stability (Biswas and Si, 2011e). However, information on how the similarity in the spatial pattern persists with the increase of the time difference between measurements is missing. The change in the similarity of the scale-dependent spatial patterns over time and its characteristic landscape positions can provide a complete picture of the hydrological dynamics in the field and is an important area to explore.

Similarity in the overall spatial pattern of SWS over time at a deep soil profile was also examined (Hu et al., 2009; Pachepsky et al., 2005). There are fewer studies that have explored the changes in the time stability of the overall spatial pattern with depth (Cassel et al., 2000). Biswas and Si (2011b) examined the scale-specific similarity of the spatial patterns of SWS of the surface and various subsurface layers measured at a point of time. However, there is no information on the scale-specific time stability of the spatial pattern of SWS at classified surface layer, root zone and total active soil profile. The surface layer is the part of the soil zone that is subject to climate forcing and the root zone is where the majority of the plant roots are located and exhibits strong variability in SWS over time. The total active soil profile is the zone below which seasonal changes in SWS are suppressed. Various processes operating at soil layers of different depths determine the hydrology of soil layers. As the depth of soil layer changes, the dominant processes controlling the spatial pattern of SWS within the layer may also change. Therefore, information on the similarity of the scale-specific spatial pattern of SWS at different layers of soil with variable depths and over time would help better understand soil water dynamics from the surface to the whole soil profile and its temporal evolution.

The objective of this study was to examine a) the similarity in the spatial patterns of SWS at variable soil depths over time at a field scale and b) the landscape characteristics of these similar spatial patterns over time and at depths. Information on the spatial variability of SWS over time and at depths would provide a complete picture of the hydrological dynamics within the soil profile. The similarity of the spatial patterns of SWS measured over five years was examined at multiple scales using the wavelet coherency along a transect from the prairie pothole region of North America.

2. Materials and methods

2.1. Study area and site selection

A field study was conducted at St. Denis National Wildlife Area (52°12′ N latitude, 106°50′ W longitude), Saskatchewan, Canada (Fig. 1). Detailed description of study site, measurement of soil water and controlling factors and instrument calibration can be found in Biswas and Si (2011b), Biswas and Si (2011d, 2011e) and Biswas et al. (2012). Briefly, the landscape of the study site is hummocky, typical of the North American Prairie Pothole region (Hogan and Conly, 2002), the largest wetland landscape in North America encompassing an approximately 780,000 km^2 area from the north-central United States to south-central Canada (Fig. 1) (National Wetlands Working Group, 1997). The hummocky landscape is formed during the last glacier retreat and is characterized by a complex sequence of slopes extending from different-sized rounded depressions to irregular complex knolls and knobs (Huel, 2000). A 571.5 m long transect was established with 128 sampling points extending in the north–south direction over several knoll–depression cycles ensuring repeatability (Fig. 1). Sampling points were selected at a regular interval (4.5 m) to catch the systematic variability in the landscape. Geographic locations and the elevation of the sample points were noted using a Trimble Pro XRS Global positioning system (Trimble Navigation, Sunnyvale, CA). Topographic survey of the study site was completed using an aerial light detection and ranging (LiDAR) survey at a 5 m ground resolution. A digital elevation map was prepared at the same ground resolution using SURFER (Golden Software Inc., Golden, CO) (Fig. 1). The landform elements along the transect were characterized as convex (CX), concave (CV), uncultivated wetlands (UW) and cultivated wetlands (CW) (Fig. 1) following Pennock and Corre (2001). Convex elements are topographically high positions with a positive profile curvature. Concave elements are positions with a negative profile curvature. Cultivated wetlands are depressions, roughly circular in shape, which temporally collect rain and snowmelt water and also known as seasonal depressions (Woo and Rowsell, 1993). Non-agricultural positions of the transect were classified as uncultivated wetlands. Soil of the study area is classified as Dark Brown Chernozem according to the Canadian System of Soil Classification (Mollisol in USDA soil classification system) and developed from moderately fine to fine textured, moderately calcareous, unsorted glacio-lacustrine deposits and modified glacial till (Saskatchewan Centre for Soil Research, 1989). The climate of the study area is mainly semiarid with the mean annual air temperature (at the Saskatoon airport, 40 km west of the study site) of 2 °C with the monthly mean of −19 °C in January and 18 °C in July. The vegetation of the study site was mixed grass seeded in 2004 and allowed to grow each year. Before the grass was seeded, the area was under cultivation and the history of cultivation was used in classifying landform elements (Fig. 1).

2.2. Data collection

Soil water content (SWC) at each sampling point was measured down to 140 cm. Surface 0–20 cm SWC was measured using vertically installed time domain reflectometry (TDR) probe and a metallic cable tester (Model 1502B Tektronix, Beaverton, OR). A standard calibration equation, $\theta = 0.115\sqrt{k_a} - 0.176$ following Topp and Reynolds (1998) was used to calculate the SWC for the surface layer. Where the dielectric constant $k_a = (L_2/L)^2$, L_2 is the distance between curves and L is the length of the TDR probe. SWC from 20 to 140 cm was measured using a neutron probe (Model-CPN 501 DR Depthprobe, CPN International, Martinez, CA). A site specific calibration was completed for the neutron probe comparing volumetric water content and neutron count ratio at different topographic locations along the transect over a three year time period (2007–2009) with different initial soil water conditions. The final calibration equation is $\theta_v = 0.8523\ R + 0.0612$ with $n = 101$ and $r^2 = 0.86$, where R is the ratio of the neutron count to