Catena 160 (2018) 366–375

Contents lists available at ScienceDirect

Catena

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

Comparing the spatio-temporal variations of soil water content and soil free water content at the hillslope scale

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ARTICLE INFO

Keywords:
Free water content
Hillslope
Spatio-temporal variation
Soil water content

ABSTRACT

The spatio-temporal dynamics of soil water are the key critical zone processes that control hydrological, biogeochemical and environmental processes at various spatial scales. Soil water content (SWC), which has been widely adopted in traditional studies, does not consider the energy state of soil water and thus cannot directly reflect the active status of subsurface fast flow (flux when SWC is above field capacity). By subtracting water content at field capacity (−33 kPa) from SWC, free water content (FWC) were calculated and used to indicate status of subsurface fast flow. In this study, the spatio-temporal variations and controlling factors of SWC and FWC were compared on a typical bamboo forest hillslope in Taihu Lake Basin, China. An improved temporal stability (TS) analysis replacing the spatial means of SWC in the equation by the field capacity was also proposed to better identify the active locations of subsurface fast flow. Results showed that the SWC and FWC had similar temporal trends and spatial patterns. Thresholds of spatial mean SWCs were found at 10- and 30-cm depths (0.17- and 0.18-$m^3\ m^{-3}$, respectively). Above these thresholds, the spatial means and variances of FWC started to increase with the spatial mean SWCs. This indicated that the subsurface fast flow starts to occur. Below these thresholds, nearly no free water existed and the subsurface fast flow ceased. The active locations of subsurface fast flow determined from the improved TS analysis were not always consistent with the high SWC locations. This indicated that traditional TS analysis was not adequate to interpret the active status of subsurface fast flow. Controlling factors of SWC and FWC spatial variations were generally similar. However, the spatial distribution of FWC was less affected by soil properties and topography. In addition, the influences of controlling factors on FWC were more temporally varied. These findings will be beneficial for identifying the "hot spots" of soil water movement and biogeochemical processes.

1. Introduction

Soil water has strong spatio-temporal variability and is widely acknowledged as a crucial control on hydrological and biogeochemical processes at different spatial scales (Robinson et al., 2009; Tague et al., 2010; Penna et al., 2013). It has been recognized as one of the primary factors of nutrient loss (e.g. Kleinman et al., 2005; Zhu et al., 2009), pollutant migration (e.g. Fox et al., 2004; Nordstrom, 2011), soil erosion (e.g. Keesstra et al., 2016), and etc. Thus, comprehensive and systematic investigation of the soil water spatio-temporal variations is essential for understanding the processes it is related to (Penna et al., 2013).

Soil water content (SWC) has been adopted in traditional researches of spatio-temporal variations of soil moisture (e.g., Western et al., 2004; Famiglietti et al., 2008; Seneviratne et al., 2010; Rosenbaum et al., 2012). Various methods, including geostatistical analysis, wavelet analysis and temporal stability (TS) analysis, have been applied to reveal the spatio-temporal characteristics of SWC and their controlling factors (e.g., Brocca et al., 2010; Biswas and Si, 2011; Hu et al., 2011; Wang et al., 2013). Generally, spatial variability of SWC was maximum when the soils are intermediately wet and decreased as the soils became wetter or drier (Brocca et al., 2010; Gao et al., 2015). However, contradictory observations also exist. For example, Famiglietti et al. (1998) found that the SWC spatial variation decreased in the drying process, while Hupet and Vanclooster (2002) observed an inverse relationship between the spatial variability and spatial mean SWC. This can be

Abbreviations: CV, coefficient of variation; CWC, capillary water content; DB, depth to bedrock; FWC, free water content; ITS, index of temporal stability; MAI, mean active index; MRD, mean relative difference; PLC, plane curvature; PRC, profile curvature; PTFs, pedotransfer functions; RFC, rock fragment content; SDAI, temporal standard deviation of the active index; SDRD, temporal standard deviation of the relative difference; SWC, soil water content; TS, temporal stability

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http://dx.doi.org/10.1016/j.catena.2017.10.008
Received 28 February 2017; Received in revised form 19 September 2017; Accepted 5 October 2017
Available online 11 October 2017

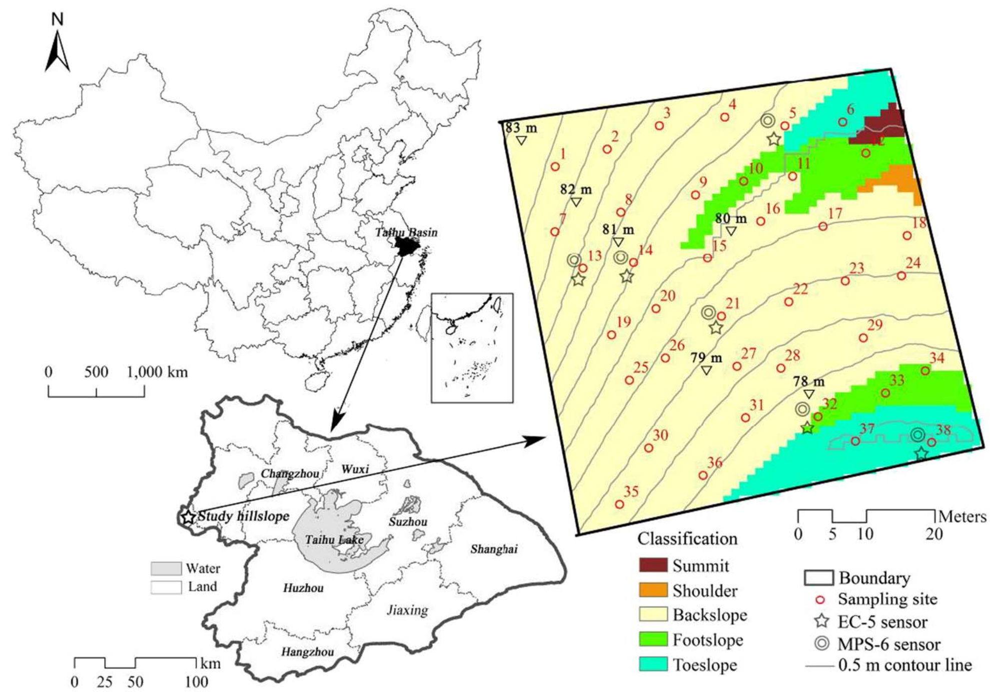

Fig. 1. Locations of the study area and sampling sites, as well as the classifications of hillslope positions based on the relief analysis developed by Miller and Schaetzl (2015). The EC-5 sensor and MPS-6 sensor were respectively used to measure the soil water content and matrix potential at sites 5, 13, 14, 21, 32 and 38.

explained by the differences in climate, soil, topography, timing and depth of sampling in different study areas (Famiglietti et al., 1998; Lawrence and Hornberger, 2007; Famiglietti et al., 2008).

A common perception is that the SWC spatial variability is dominated by topography in wet periods, while by soil properties during dry periods (Grayson et al., 1997; Western et al., 1999). Beside soil and topography, other factors, including vegetation and meteorology have also been recognized as important controlling factors of SWC (Famiglietti et al., 1998). For example, Zhu and Lin (2011) found the controls on SWC were different during growing and no-growing seasons. Qiu et al. (2001) observed that the mean SWC was also controlled by land use. In addition, the SWC is affected by the interaction of different factors (Famiglietti et al., 1998; Joshi et al., 2011; Huang et al., 2016). At different spatial scales, controlling factors of SWC can also be varied (Wagenet, 1998; Famiglietti et al., 2008; Joshi and Mohanty, 2010). For example, Zhu and Lin (2011) demonstrated both soil and terrain influenced SWC variation at the entire farm scale, while at the smaller spatial scales (plot and slope transect scales), soil properties exerted a first-order control. Gaur and Mohanty (2013) showed that soil texture was the dominant control at the airborne scales in Iowa and Oklahoma; while at the point support scale, topography overrode soil texture during a very wet year (2007).

However, since SWC does not consider the energy state of soil water (i.e. soil water potential), it cannot indicate the specific soil water status, such as the fast flow driven by gravitational force. Simulations of soil water transport and biogeochemical processes need an accurate description of the soil water status (Resurreccion et al., 2011). Therefore, different approaches have been proposed to characterize specific soil water status (Seneviratne et al., 2010). For example, Zhu and Lin (2009) used the proportion of SWC to saturated water content to validate the simulated spatial pattern of subsurface flow, and Morgan et al. (2003) and Jiang et al. (2007) explored the plant-available water capacity that can indicate the ability of soil to store and supply water to plants. However, more investigations need to be conducted to seek the indicators that can specifically reflect the active status of soil water movement.

Soil free water content (FWC), determined as gravitational water, is the SWC beyond the field capacity and has great potential in describing soil water movement (Bescansa et al., 2006; Seneviratne et al., 2010). Field capacity is the SWC at which the excess water has been drained away (Veihmeyer and Hendrickson, 1931) and the rate of downward soil water movement reaches a “negligibly small value” (e.g., 0.01 cm d^{-1} as proposed by Twarakavi et al., 2009). Thus, subsurface fast flow has been proposed to characterize the non-negligible drainage flux when SWC is above the field capacity. Since determination by the predefined negligibly drainage flux value is difficult, the field capacity has been commonly approximated as the SWC at matric potential of −33 kPa for fine-textured soils (Richards and Weaver, 1944; Givi et al., 2004). Up to now, many pedotransfer functions (PTFs) and their ensembles have been adopted to predict the field capacity from more easily measurable soil properties (e.g., Rawls et al., 1982; Canarache, 1993; Guber et al., 2009; Liao et al., 2014). Hence, FWC can be indirectly determined to indicate the potential of subsurface fast flow (Boyarskii et al., 2002; Jarvis, 2007). However, so far, few studies have investigated the spatio-temporal dynamics of FWC.

Temporal stability (TS) analysis has been used in uncovering the spatio-temporal characteristics of SWC. The soil water TS is the time persistence association between a sampling location and classical statistical parameters (Vachaud et al., 1985). It has been employed in several applications, including determining optimal locations for estimating SWC dynamics, predicting areal mean SWC, and downscaling remote sensing products (e.g., Cosh et al., 2004; Brocca et al., 2010; Heathman et al., 2012; Zhu et al., 2017). However, traditional TS analysis based on SWC cannot well recognize the consistently active locations of subsurface fast flow. If replacing the spatial means of SWC in the equation (Eq. (5) in hereinafter) by the field capacity, the improved TS analysis can be more accurate in identifying the active degree of subsurface fast flow and its spatial variation. However, this has seldom been tried in previous studies.

Therefore, the objective of this study was to investigate the spatio-temporal variations of SWC and FWC and their controlling factors. Specifically, we compared the spatio-temporal characteristics of SWC and FWC, revealed the differences of traditional and improved TS analyses and investigated the controlling factors of the spatial patterns of SWC and FWC.