Catena 119 (2014) 61–70

Contents lists available at ScienceDirect

Catena

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

Soil moisture response to rainfall at different topographic positions along a mixed land-use hillslope

Qing Zhu [a,*], Xiaofei Nie [a], Xiaobo Zhou [b], Kaihua Liao [a], Hengpeng Li [a]

[a] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167, USA

ARTICLE INFO

Article history:
Received 5 November 2013
Received in revised form 9 March 2014
Accepted 11 March 2014
Available online 3 April 2014

Keywords:
Hydropedology
Soil water content
Temporal variation
Topography

ABSTRACT

Soil moisture is one of the most important parameters controlling various critical zone processes including energy balance and nutrient cycling. However, hillslope soil moisture variation and its response to rainfall are not fully understood yet. Through real-time monitoring systems, mechanisms of soil moisture response to rainfall were investigated at top, upper, middle, lower and toe slope positions along a typical mixed land-use hillslope in Taihu Lake Basin, China. The corresponding land use types for these five hillslope position are woodland, tea (*Camellia sinensis*), tea, meadow and woodland, respectively. This hillslope has annual precipitation around 1100 mm. Soil moisture varied from <0.05 $m^3 m^{-3}$ at the top slope during the dry period to >0.40 $m^3 m^{-3}$ at the toe slope during wet period. Despite different land-use types, similar characteristics of soil moisture response to rainfall were observed at the top (woodland), upper (tea) and middle (tea) slope positions. At these three sites, degrees of soil moisture change (difference between maximum soil moisture during the rainfall and antecedent soil moisture) were significantly ($P < 0.05$) influenced by precipitation amount and intensity, as well as antecedent soil moisture in some cases. However, at the lower slope position (meadow), soil moisture variation during the rainfall was mainly influenced by lateral subsurface flow; the cumulative precipitation was less than the increased soil water storage, indicating that water must come from the upslope areas to recharge this site. At the toe slope position (woodland), precipitation interception by tree canopy and surface organic matter reduced the degree of soil moisture change during rainfall events. Lateral subsurface flow can recharge deep soils at the toe slope position in rainfalls >35 mm with relatively wet initial condition (e.g., soil moisture at 0.1-m depth of this site >0.30 $m^3 m^{-3}$). Results suggest that lower and toe slope positions are hot spots receiving lateral surface and subsurface recharge. Perennial vegetation at toe slope position can remove nitrogen in lateral subsurface flow by promoting denitrification. Therefore, maintaining toe slope area in perennial vegetation may help to mitigate dissolved nitrogen losses from upslope fertilized tea plantations.

1. Introduction

Soil moisture is a fundamental hydrological state variable and its spatial–temporal pattern is important for understanding agricultural, hydrological, pedological, and environmental processes in the critical zone (Gish et al., 2011; Grayson et al., 2002; Lin et al., 2005, 2006). As a basic hydrological research unit, hillslope soil moisture variation and its controlling factors have been investigated in a wide range of studies (e.g., Penna et al., 2013; Qiu et al., 2001; Sela et al., 2012). However, considerable spatial–temporal variability of soil moisture remains a challenge to be better understood (Grayson et al., 1997; Zhu et al., 2012).

Soil water movement was reported to be influenced by topography, soil properties and land use (e.g., Entin et al., 2000; Famiglietti et al., 1998; Zhu and Lin, 2011). However, soil water movement is also influenced by various other factors. In studies by Gish et al. (2005) and Zhu and Lin (2009), less permeable soil layer interface (e.g., clay layer and fragipan) and soil–bedrock interface are important in triggering lateral subsurface flow and influencing the soil moisture spatial variation. Precipitation characteristics (e.g., amount, intensity and duration) were also reported to have strong influence on soil water movement. For example, Li et al. (2013) observed that surface soil moisture was strongly affected by precipitation size in shrub-encroached grasslands; Albertson and Kiely (2001) demonstrated that the precipitation intensity has strong influence on root-zone soil moisture variation. In addition, antecedent soil moisture condition can act as a threshold to trigger preferential flow. For example, in the study by Hardie et al. (2011), antecedent soil water storage of 226 mm in the top 70 cm soil profile has been viewed as a threshold of whether preferential flow occurred in an agricultural site in Australia.

Although various factors have been identified as important controlling factors, hillslope soil moisture variation and its response to rainfall are not influenced by a single factor, but by many factors. Thus, it is

* Corresponding author. Tel.: +86 25 86882139; fax: +86 25 57714759.
E-mail address: qzhu@niglas.ac.cn (Q. Zhu).

http://dx.doi.org/10.1016/j.catena.2014.03.010
0341-8162/

difficult to understand the behavior of soil moisture response to rainfall and its controlling mechanism. Uchida et al. (2006) indicated that in steep, wet and thin soil hillslopes, bedrock permeability and water retention characteristics combine to form a first order control on the hillslope water movement. Soil moisture variation and its response to rainfall are usually different in hillslopes located in different areas. For example, Zhu and Shao (2008) reported that the spatial pattern of surface soil moisture was controlled by the rainfall pattern along a semi-arid hillslope in Loess Plateau of China with deep soil. However, also along semi-arid hillslope but with shallow soil depth in Spain, van Schaik et al. (2008) observed that the hillslope soil moisture variation was affected by subsurface flow at the bedrock interface. In addition, previous studies also observed that at different slope positions, soil moisture and its response to rainfall can be varied and the influence of preferential flow on soil moisture was also different (Graham and Lin, 2011; Lin and Zhou, 2008). Therefore, research for understanding hillslope soil moisture response to rainfall is needed in different areas with varied climate, geology, land use/cover and geomorphology.

Taihu Lake is suffering from eutrophication due to excessive non-point N and P inputs from the watershed. In recent years, in the hilly area of Taihu Lake Basin, one of the most typical land use/cover change (LUCC) is from forest to tea (or fruit) garden (Xu et al., 2011), which could trigger severe non-point losses of N and P in this region (Jin et al., 2007). This kind of land use change would increase the N and P inputs, decrease the surface coverage, and introduce the soil erosion and N and P losses through surface and subsurface flows (Jin et al., 2007; Zong et al., 2006).

The LUCC could affect the soil water movement by altering the canopy rainfall interception, vegetation uptake, and soil physio-chemical properties (Fu et al., 2003; Hupet and Vanclooster, 2002; Vepraskas et al., 2010). Soil water movement has been proved to have strong influence on N and P losses (e.g., Schmidt et al., 2011; Zhu et al., 2009). Therefore, proper land-use design can be effective in reducing nutrient losses. A land-use design has been adopted in the hilly area of Taihu Lake Basin to conserve the soil and water. In this design, top and toe slope areas are usually kept as woodland or meadow, while only the middle part of the hillslope is utilized as tea (or fruit) garden. This land use layout was designed to reduce the soil erosion and intercept sediments and nutrients by keeping nature vegetation in the top slope area and having a buffer zone in the toe slope area. Similar to this, filter strips have been adopted to reduce non-point N, P and sediment losses around the world. For example, Zhou et al. (2010) found that filter strips distributed at the toe slope position can effectively reduce the nitrate loss to ground water; Helmers et al. (2012) reported that the mean annual sediment yields were 0.36 and 8.30 tons per hectare for watershed with and without prairie filter strips, respectively. However, these studies all looked into this issue through the perspective of nutrient losses. Few of them tried to understand how the toe slope filter strips reduce nutrient losses through the perspective of soil water movement. The regime of soil water movement is important in nutrient losses. For example, fast subsurface soil water flow has been recognized as an important path in nitrogen (especially nitrate) losses (e.g., Tiemeyer et al., 2008; Van der Salm et al., 2012).

Soil moisture has received much less attention in studies conducted in humid regions of China, as compared with the arid and semi-arid regions of China. While the importance of soil moisture has been recognized in crop productivity and vegetation recovery in the arid and semi-arid regions, its importance in nutrient losses has not been fully noticed in humid regions. Therefore, hillslope soil water movement mechanisms and their potential effects on nutrient losses in humid region have to be better illustrated. This study aimed to investigate the patterns of soil moisture response to rainfall at different slope positions along a typical mixed land-use hillslope in Taihu Lake Basin. Findings of this study were used to evaluate the land use design for conserving soil and water in the hilly area of Taihu Lake Basin, from the perspective of soil water movement.

2. Materials and methods

2.1. Study hillslope

The study hillslope (31°16.28′N, 119°22.6′E; altitude: 40–80 m) is located in Liyang County in south-west of Taihu Lake Bain, China (Fig. 1). It is typical of northern subtropics monsoon climate. The annual precipitation, potential evapotranspiration and mean temperature are around 1100 mm, 770 mm, and 15.8 °C, respectively. The annual potential evapotranspiration rate was calculated with Penman–Monteith equation using the 1980–2010 metrology data from a weather station 2 km away from our study site. About 40% of the precipitation occurred during the summer (June to August) and only 10% occurred during the winter (December to February). In this county, woodland has been largely converted to tea garden during the last decade. To reduce soil erosion and nutrient losses, the local government requires that only the middle portion of the hillslope can be converted to tea garden, while the top and toe slope portions must be maintained as woodland or meadow. Our study hillslope is west-faced and a typical of this and has three major land uses along the hillslope (woodland, tea garden and meadow) (Fig. 1). In the top slope area (slope: >30%), the dominant vegetation is Masson Pine (*Pinus massoniana* Lamb) with tree diameter (1.3 m above the ground) <0.1 m. Tea plants (*Camellia sinensis*) were grown in the upper and middle slope areas (slope: 20–30%). They have been planted for five years and were all cut to <1.0 m tall in May every year. At the lower slope area (slope: 10–20%), clover (*Trifolium repens*) was dominant. In the toe slope area (slope: <15%), Masson Pine with and Magnolia grandiflora (*Magnolia grandiflora* Linn) with 0.1–0.2 m tree diameter (1.3 m above the ground) were dominant. The soil along this hillslope is Dystric Cambisols according to FAO classification, with depth to bedrock that varied from <0.2 m at the top slope area to >1.5 m at the toe slope area. In addition, thinner O horizon and less organic matter content were also observed at the top slope position. The detailed soil descriptions of these five sites were given in Table 1. In the study of Nie et al. (2013), the runoff coefficients (total runoff/total precipitation) of all five sites were <0.03, indicating good infiltration characteristics for soils along this hillslope.

2.2. Soil moisture collection

Automatic soil moisture monitoring systems were installed at five locations along the hillslope to represent major land use types and slope positions (Fig. 1). Before installing the monitoring systems, soil profiles were opened and described. The horizonation, structure, rock fragments, pores and roots were recorded for all five soil profiles following the procedures in “Soil Survey Manual” (Soil Survey Staff, 1993). Soil samples were also collected for major horizons and analyzed for particle size distribution using Laser Particle Analyzer (Mastersizer 2000, Malvern, UK) and for organic matter content using the dichromate oxidation method. A brief illustration of these five soil profiles was given in Table 1.

The EC-5 sensors and EM-50 data loggers (Decagon Devices, Inc., Pullman, USA) were used to monitor and record the soil moisture in these five sites. Sensors were installed at different depths in the soil pits opened for soil profile descriptions (Fig. 1). The installation depths were roughly 0.1-, 0.2-, 0.4-, 0.6- and 0.65-m and corresponded to critical soil horizons, horizon interfaces and soil–bedrock interfaces. Due to the shallower soil depths at sites 1 and 2, the deepest installation depths of EC-5 sensor were 0.3 and 0.6 m for these two sites, respectively (Fig. 1). An ECRN-100 rain gage (Decagon Devices, Inc., Pullman, USA) was installed at site 2 to collect the precipitation with 0.2-mm resolution. Both soil moisture and precipitation were recorded every 10 min. Before the EC-5 sensors were installed, calibrations of them for each site and soil depth were conducted (see Table 1 for example calibration equations). Due to the limited points that were used for the calibration, simple linear relationships were used in this study. However, differences