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Soil thickness effect on hydrological and erosion characteristics under sloping lands: A hydropedological perspective

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ABSTRACT

Soil thickness exerts a first-order control on the hydrological processes of the hillslopes. However, from a hydropedological perspective, the knowledge of soil thickness effect on hydrological and erosion characteristics under sloping lands is limited. Based on a comprehensive survey of an experimental watershed in the Three Gorges Area of China, five typical sloping land plots (2 m × 1 m) with different soil thickness were selected along a hillslope to investigate their hydrological processes and erosion response under three rainfall intensities (60, 90 and 120 mm h^{-1}) using a portable rainfall simulator. The results can be summarized as follows: (1) The surface flow coefficient was increased with increasing soil thickness, especially under the event of 60 mm h^{-1}. (2) The subsurface flow of the 23, 31 and 45 cm plots mainly took the form of preferential flow. Conversely, the 59 and 76 cm plots mainly took the form of matrix flow. (3) A prolonged low intensity rainfall is much more likely to facilitate deep percolation and subsurface flow than a short high intensity rainfall regardless of soil thickness. (4) Soil thickness and rock fragment cover were the most important factors than other soil properties in determining the hydrological and erosion behaviors. Thin soils showed higher infiltration capacity than thick soils due to their more distinct hydrological processes of subsurface flow and deep percolation. Rock fragment cover enhanced infiltration and served as a shield to protect the soil surface from detaching. Due to the synergies between thin soil thickness and high rock fragment cover, thin soils displayed significantly lower erosion rates than thick soils in all rainfall events, which increased from 211 g m^{-2} h^{-1} for the 23 cm plot with rainfall of 60 mm h^{-1} to 4220 g m^{-2} h^{-1} for the 76 cm plot with rainfall of 120 mm h^{-1}. Our study suggested that the emerging interdisciplinary field of hydropedology promotes synergistic integration of pedology (e.g. watershed scale soil thickness investigation and soil profile description) and hydrology (e.g. rainfall simulation, subsurface flow and deep percolation) to enhance the holistic study of soil–water interactions in the sloping lands with different soil thickness.

1. Introduction

From the landscape and pedology perspectives, the change in soil thickness over time depends on the processes of the formation of soil from weathering of bedrock, the loss of materials by chemical weathering and the transport of soil by erosion. Soil formation depends on the rate of breakdown or weathering of the underlying parent materials under physical, chemical and biological processes which are usually represented as an exponential decline with soil thickness (Gabet and Mudd, 2009). While soil erosion, mainly in the forms of water erosion and mass movement, is mainly governed by topography. In addition to soil age, soil thickness is highly correlated with topography (e.g. slope angle, relative height, curvature, and compound topographic index) (Gessler et al., 2000), parent material, organisms, and climate. Some studies also found that long-term human activities, such as tillage and hedgerow cultivation (Follain et al., 2006; Van Oost et al., 2003), can significantly alter within-field soil thickness variation. Steady-state soil thickness will be achieved over time, whereby erosion and surface removals are balanced by weathering at the base of the soil. On stable landscapes absent of distinct erosion, soil can progressively develop, which will lead to thick soil and profile differentiation (Lohse and Dietrich, 2005). Conversely, on steep landscapes which exhibit intensive soil redistribution by erosion, the soil development will be frequently

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disturbed or impeded, leading to no distinct soil profile. The typical case is the purple soil area around the Three Gorges Area of China (He, 2003).

From the hydrological perspective, numerous studies have defined soil thickness as a key factor for storing and redistributing storm rainfall and an important filter between rainfall input and lateral flow generation (Hopp and McDonnell, 2009; Lin, 2006). Buttle et al. (2000) concluded that soil thickness exerted a strong function on controlling the types of various runoff processes and was considered a decisive factor affecting them on the Precambrian Shield. The water inputted to the slope surface of thin soil reached the bedrock as preferential flow through soil macropores, and the slope runoff appeared to occur as subsurface stormflow. On the contrary, areas of thicker soil supplied runoff to the riparian zone largely as groundwater flow. Using hydropedologic approach in the Shale Hills catchment, Lin identified that shallow soil initiated subsurface preferential flow more readily than thick soil (Lin, 2006; Lin and Zhou, 2008). Based on measurements in a small forested basin on the Canadian Shield in south-central Ontario, Buttle et al. (2004) again highlighted that soil thickness exerted a first-order control on the propensity of a particular slope to contribute to the runoff: thin soil areas almost always generated runoff and exhibited a near-linear relationship between runoff and rainfall depth, however, this relationship was not found in thick soil areas. Moreover, soil thickness can also have a significant impact on the runoff hydrograph characteristics. For instance, at the plot scale, Peters et al. (1995) found that the runoff hydrographs of the shallow soil plots, compared with the deeper soil plots, closely resembled the shapes of the hyetographs, which were highly responsive to incoming rainfall, with synchronous peak intensities, and showed high recession rates after rainfall cessation. At the hillslope scale, Fujimoto et al. (2008) noted that convergent hillslopes with deep soils had delayed runoff responses, whereas hillslopes with shallow soils produced highly peaked hydrographs.

Various models have also confirmed that soil thickness has a profound influence on hydrological processes. From the sensitivity studies of numerical models, Woolhiser et al. (2006) illustrated the importance of soil thickness in controlling runoff and infiltration rates, and found that the greatest bedrock infiltration occurred on hillslope areas with thin soils and high values of bedrock hydraulic conductivity. The model results achieved by Van Wesemael et al. (2000) indicated that the highest rates of infiltration, evaporation and drainage, as well as the lowest rates of overland flow were all restricted to the shallow soils on the hilltops. In contrast, the deeper soils in the valley bottoms produced a more stable moisture regime than shallower soils. Additionally, Meerveld and Weiler (2008) demonstrated that simulated hillslope-scale subsurface stormflow was significantly impacted by spatial variations in soil thickness. Gochis et al. (2010) also highlighted that accounting for local soil depth variability could moderately improve land surface model flux estimation as compared with tower measurements from a currently operational land surface model over the North American Monsoon region. Because of its significant influences on hydrological processes at different scales, soil thickness is thus a standard variable used in many hydrological models (Arnold and Fohrer, 2005; Beven et al., 1984; Frankenberger et al., 1999). To face the growing demand of hydrological and ecological modeling, many geostatistical and process-based approaches have been developed to predict the spatial variation of soil thickness in recent studies (Dahlke et al., 2009; Kuriakose et al., 2009a; Pelletier and Rasmussen, 2009; Phillips, 2010; Tesfa et al., 2009).

Different hydrological processes will inevitably lead to different erosion behavior. Regarding the effect of soil thickness on erosion, a few studies have demonstrated that the landslide susceptibility and soil erodibility were obviously influenced by soil thickness (Kuriakose et al., 2009b; Martz, 1992; Mukhlisin et al., 2008; Rhoton and Lindbo, 1997). However, few studies have examined the soil thickness effects on the hydrological and erosion characteristics under sloping lands utilizing a hydropedology approach, which is a new emerging interdisciplinary field especially suitable for examining the flow regimes in undisturbed soils (Lin et al., 2008).

Of the total area of 62,640 km^2 in the Three Gorges Area, 52.1% has gradients of between 7° and 25°, and 37.5% has gradients of more than 25° (Zhou, 2001). After construction of the Three Gorges Dam, due to the socioeconomic pressure in this area and that purple rocks are characterized by fast physical weathering and richness of

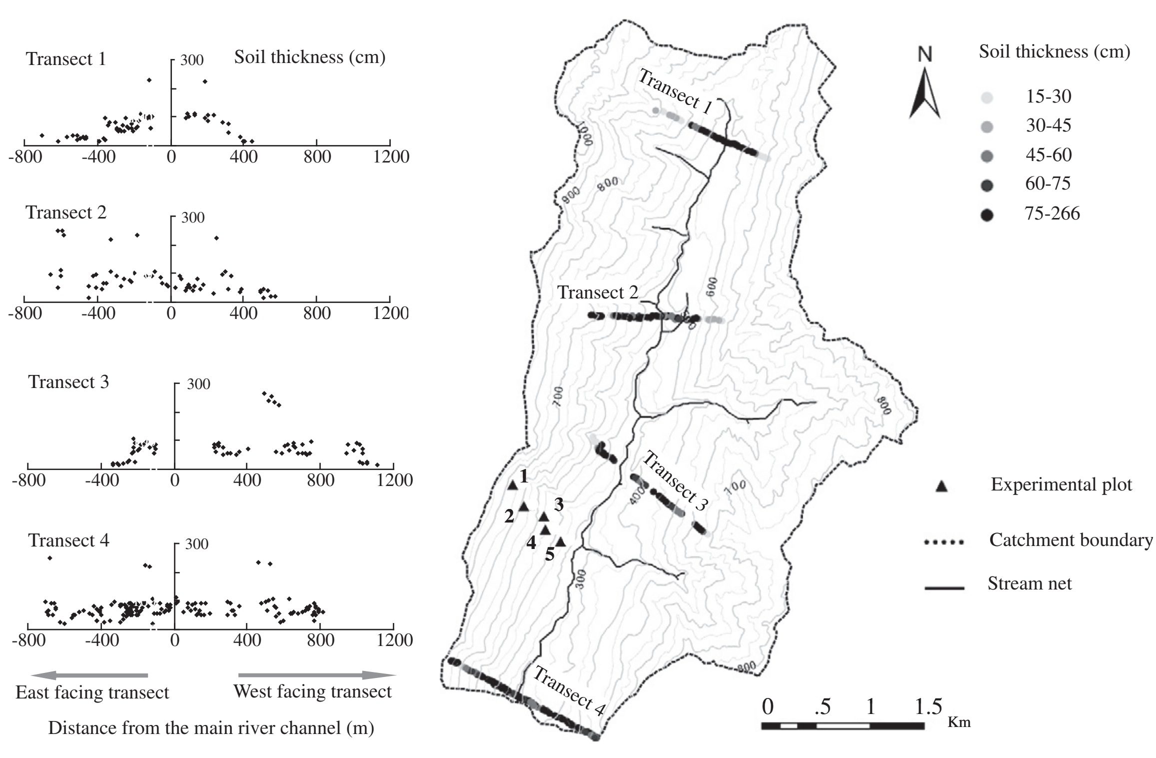

Fig. 1. Topographical map of the study watershed showing the experimental plots and the sampling transects with soil thickness values.