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Effects of rainfall intensity on runoff and sediment yields on bare slopes in a karst area, SW China

Youjin Yan[a], Quanhou Dai[a,*], Yingfei Yuan[a,b], Xudong Peng[a], Longshan Zhao[a], Jing Yang[a]

[a] College of Forestry, Guizhou University, Guiyang, Guizhou 550025, PR China
[b] Management Office of the Sci-Tech Demonstration Park of Soil and Water Conservation in Guizhou Province, Guiyang, Guizhou 550025, China

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ABSTRACT

Due to the impacts of global warming, extreme precipitation events are increasing in frequency and are accelerating the process of rocky desertification in the karst area in southwestern China. In this study, the dual structure of a karst system was simulated in a steel tank, and a rainfall simulation was employed to determine the intensity threshold of erosive rainfall at the surface and the effects of extreme rainfall on runoff generation and sediment yield on karst hillslopes. The results showed the following. i) In order of importance, the factors contributing to runoff were rainfall intensity, slope angle and underground pore fissure degree (UPD), and the factors contributing to sediment yield were rainfall intensity, UPD and slope angle. To cause surface soil erosion, the rainfall intensity had to be > 0.8 mm/min. ii) Under light (0.5 mm/min) and moderate rainfall (0.8 and 1.2 mm/min), underground pore fissures are the main pathway for runoff and sediment loss. iii) Under extreme rainfall (1.5 mm/min), surface runoff (and the associated sediment yield) represents the main part of soil erosion on the slope. During such events, the underground erosion proportion is lower, but the underground sediment yield is greater. Because underground pore fissures are the main pathway for underground soil loss, reducing the UPD is an immediate way to prevent and control underground leakage. Engineering measures have the fastest effect, but plant-based measures are more effective and worth popularizing to prevent and control underground soil loss in karst areas. These results provide information significant for controlling rocky desertification and preventing soil erosion in the karst area of southwestern China.

1. Introduction

Karst regions are one of the most ecologically fragile zones in the world (Parise et al., 2009). Globally, karst covers an area of 22 million km^2, occupying approximately 12% of the total global land area, and more than one billion people inhabit this landscape type (Ford and Williams, 2013). Karst regions are mainly located along Europe's Mediterranean shore, the eastern United States and southwestern China (Liu, 2009). IGCP 299 and IGCP 379 indicate that different geological backgrounds lead to differences in the ecological geological background among various karst regions. For example, the karst area of Perm in Ural, Russia, is the main agricultural base for the region (Yuan, 2011). However, because the porosity of carbonate rocks is low and the water retention capability is poor in the karst areas of Europe's Mediterranean shore and SW China, these regions suffer from soil depletion and erosion (Wang et al., 2004; Furlani et al., 2009), which are particularly severe in SW China. Karst areas form in regions of soluble carbonate rock (e.g., limestone) that has been subjected to geological and chemical dissolution, forming subsurface karst drainage consisting of a network of fissures, conduits, and caves (karst aquifer) (Gunn, 1981; Worthington, 2009; Kovačič and Ravbar, 2013). The surface and subsurface of a karst system form a spatially open double-layer hydrological system (Ford and Williams, 2013; Song et al., 2017). This special "dual structure" leads to the loss of water and soil resources both at the surface and underground (Peng and Wang, 2012; Gunn, 2013; Feng et al., 2016). Studies have shown that surface and underground processes can cause karst rocky desertification (KRD), soil subsidence/collapse, and other hazards (Gutiérrez et al., 2014). Because of the impact of natural factors (rainfall, geology, lithology, etc.) and human activities (deforestation, farming, etc.), the surface in the karst area of SW China presents a special KRD landscape, including bare rocks, vegetation degradation, and severe soil erosion, as shown in Fig. 1 (Liu et al., 2008; Zhang et al., 2014; Jiang et al., 2014; Wang et al., 2014; Cao et al., 2016).

KRD is an increasingly serious environmental problem in China and has become the third greatest ecological problem after desertification in northwestern China and soil erosion on the Loess Plateau (Wang et al., 2004). KRD is occurring mainly in karst regions with limestone soil.

* Corresponding author.
E-mail address: qhdairiver@163.com (Q. Dai).

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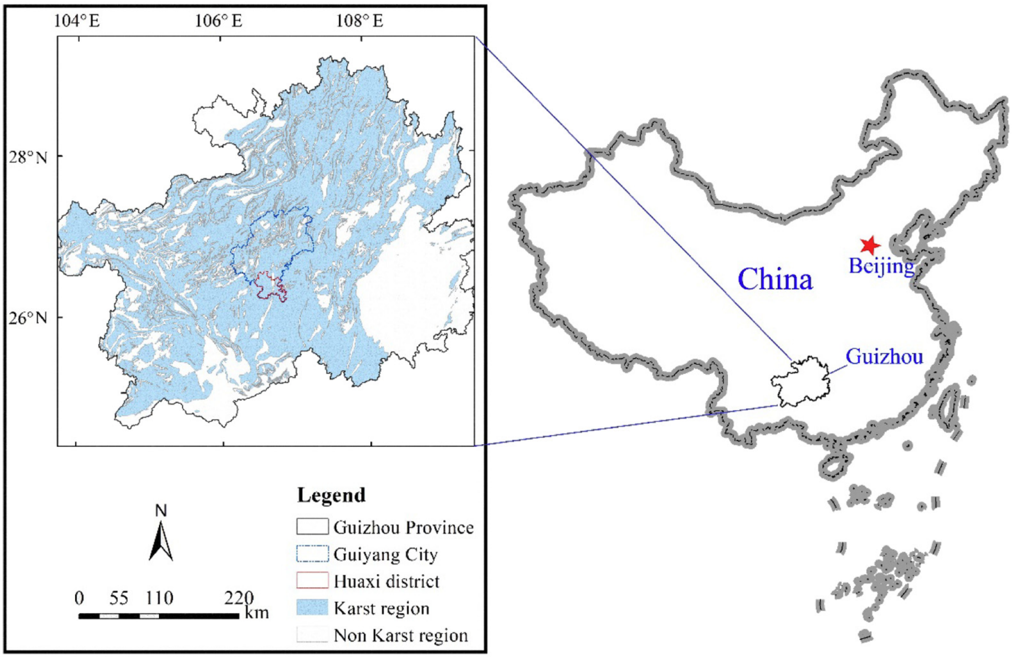

Fig. 1. Location of the study area in Huaxi District, Guiyang, Guizhou Province, Southwest China.

These areas are also major agricultural areas. Because of the effects of human activity and the extremely slow rate of limestone soil formation, the soil erosion rate is far greater than the soil formation rate, and over time, this imbalance has led to the formation of a rocky desertification landscape (Furlani et al., 2009; Fridley et al., 2011; Song et al., 2014; Zhao et al., 2017). For example, Guizhou Province, located in the centre of the karst area of SW China, is one of the areas most seriously impacted by KRD and represents an ecological barrier between the Yangtze and Pearl River Basins (Jiang et al., 2014; Tian et al., 2016). Guizhou Province features $6.8 \times 10^3\,km^2$ of limestone soil, which accounts for 7.9% of the cultivated land in this region (Zheng and Wang, 2002). Severe KRD has caused a shortage of land resources, human conflict, and damage to the ecological security of the Yangtze and Pearl River Basins. Thus, it is extremely important to control soil erosion, and the key is preventing underground leakage in the karst area.

Underground leakage in a karst area has received little attention so far. Given the lack of theoretical basis, good technical methods, and data support, researchers have seldom considered the contributions of underground leakage to soil erosion and have ignored the impacts of rainfall intensity changes on changes in the underground leakage. Most studies have focused only on surface soil erosion. For example, USLE, RUSLE, SWAT, and other models have been applied to describe and predict water erosion and sediment production (Xu et al., 2008; Li et al., 2016; Zeng et al., 2017). Factors involved in surface runoff and soil loss have been explored with experimental field plots (Calvo-Cases et al., 2003; Jiang et al., 2009b; Peng and Wang, 2012; Zhang et al., 2018). The total amount of soil loss in small watersheds has been estimated based on remote sensing and GIS methods (Bou Kheir et al., 2008; Navas et al., 2013). Research has been performed on surface soil erosion characteristics in karst regions using isotopic tracer (e.g., ^{137}Cs) and magnetic tracer methods, as well as rare earth elements (Wei et al., 2016; Han et al., 2017; Smirnova and Gennadiev, 2017). The above research has mainly explored the characteristics of runoff loss and soil erosion in karst regions and has obtained certain results. However, both surface and underground pathways exist for runoff and soil loss in karst areas (Guo et al., 2016).

In current research, little relevant data on karst underground leakage is available, and few studies have investigated it. Thus, the methods and techniques for studying underground soil erosion remain in the exploration stage. Zhang et al. (2007) demonstrated that underground leakage occurs in karst areas and that underground leakage mainly occurs at the slope scale. Zhou et al. (2012), through field monitoring, showed that underground leakage is the main mode of soil loss in karst areas and proposed a conceptual creep model for brown clay sliding along karst conduits. Wang et al. (2014) proposed the erosion-creep-collapse mechanism and suggested that underground soil loss can be prevented by controlling the soil collapse process. Wei et al. (2016) concluded that the underground loss in a karst area is 75% based on ^{137}Cs tracer data. Fu et al. (2016) explored characteristics of underground runoff in karst at the plot scale through rainfall simulation experiments. Dai et al. (2017a) explored the influence of the KRD level and underground pore fissure degree (UPD) on the runoff and sediment yield on a karst slope by artificial rainfall simulation. Generally, significant progress has been made on the topic of underground leakage in karst regions. However, recently, extreme precipitation events have become more frequent, causing more extreme rainfall and more significant impacts (Millán, 2014; Amin et al., 2017). Related studies indicate that the number and proportion of extreme precipitation events have been increasing in the karst area of SW China (Zhang et al., 2010; Li et al., 2017; Wu et al., 2017). Rainfall is one of the most important dynamic factors causing soil erosion, and changes in the rainfall intensity have had a substantial effect on soil erosion (Cuomo and Della Sala, 2013). Therefore, the main contributions of the present study include revealing the factors that determine the distribution of runoff and sediment yield and identifying the mechanisms that influence the impacts of runoff and sediment yield on karst slopes under extreme rainfall.

In this study, a new simulator was used to simulate the "dual structure" of the micro-geomorphology on a karst slope, and the influences of the UPD, slope gradient and rainfall intensity on soil erosion on hillslopes in the karst area were investigated. The study has the following objectives: (1) explore the mechanisms by which rainfall intensity changes influence surface and underground runoff and erosion and (2) determine whether runoff and sediment yield exhibit significant relationships with the rainfall intensity, slope angle, and UPD by performing multiple regression. This study provides a methodology and data references for studying the impacts of rainfall intensity and to help prevent and control soil erosion (especially underground leakage) in the karst region in SW China.