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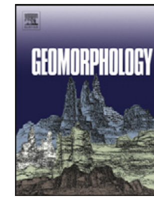

Subsurface flow in a soil-mantled subtropical dolomite karst slope: A field rainfall simulation study

Z.Y. Fu [a,b], H.S. Chen [a,b,*], W. Zhang [a,b], Q.X. Xu [a,d], S. Wang [a,b,c], K.L. Wang [a,b]

[a] Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, Hunan 410125, China
[b] Huanjiang Observation and Research Station for Karst Ecosystems, Chinese Academy of Sciences, Huanjiang, Guangxi 547100, China
[c] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[d] College of Environmental Science and Engineering, Guilin University of Technology, Guilin 541004, China

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ABSTRACT

Soil and epikarst co-evolve resulting in complex structures, but their coupled structural effects on hydrological processes are poorly understood in karst regions. This study examined the plot-scale subsurface flow characteristics from an integrated soil–epikarst system perspective in a humid subtropical cockpit karst region of Southwest China. A trench was excavated to the epikarst lower boundary for collecting individual subsurface flows in five sections with different soil thicknesses. Four field rainfall simulation experiments were carried out under different initial moisture conditions (dry and wet) and rainfall intensities (114 mm h^{-1} (high) and 46 mm h^{-1} (low) on average). The soil–epikarst system was characterized by shallow soil overlaying a highly irregular epikarst surface with a near-steady infiltration rate of about 35 mm h^{-1}. The subsurface flows occurred mainly along the soil–epikarst interface and were dominated by preferential flow. The subsurface flow hydrographs showed strong spatial variability and had high steady-state coefficients (0.52 and 0.36 for high and low rainfall intensity events). Irregular epikarst surface combining with high vertical drainage capacity resulted in high threshold rainfall depths for subsurface flows: 67 mm and 263 mm for initial wet and dry conditions, respectively. The above results evidenced that the irregular and permeable soil–epikarst interface was a crucial component of soil–epikarst architecture and consequently should be taken into account in the hydrological modeling for karst regions.

1. Introduction

In karst regions, soil and epikarst co-evolve during karstification (Klimchouk, 2004; Williams, 2008). The soil–epikarst system is the foundation for the vadose critical zone of epigenic karst (Schwartz et al., 2013). It is a complex network of soil pockets, rock matrix, and flow paths of variable hydraulic conductivity (Estrada-Medina et al., 2013). This architecture is structurally different from the regoliths of non-karst areas which exhibit weathered non-soluble bedrock horizons beneath soils. Soil–epikarst architecture determines various near-surface hydrological processes in a karst system just as soil architecture dictates various flow pathways and soil water distribution patterns in the soil (Lin et al., 2005; Lin, 2010; Zhang et al., 2011). These karst-area, near-surface hydrological processes have received considerable attention, mainly due to their important roles in: 1) soil erosion (Cerdà, 1998d; Feng et al., 2014); 2) groundwater recharge (Wilcox et al., 2008; Jiang et al., 2015); 3) karst land degradation (Bai et al., 2013; Xu and Zhang, 2014; Yan and Cai, 2015); and 4) vegetation restoration (Nie et al., 2014).

Since the 1990s, surface hydrological processes of karst hillslopes have mainly been investigated in semi-arid and arid areas (Cerdà, 1997c, 1998d; Li et al., 2011). As a widespread methodology for measuring the runoff and soil erosion in different ecosystems (Iserloh et al., 2012, 2013; Martínez-Murillo et al., 2013; Ziadat and Taimeh, 2013; Moreno-Ramón et al., 2014), rainfall simulation was frequently used in their studies. These findings clarified the infiltration–runoff regulatory roles played by climate (Cerdà, 1997a, 1998a, 1998b), parent material (Cerdà, 1999), soil surface components (such as vegetation, rock outcrop, fracture, rock fragment, and soil crust) (Cerdà, 1997c, 1998c, 2001), topographic position (Cerdà, 1998d; Calvo-Cases et al., 2003), antecedent soil moisture (Li et al., 2011), and land abandonment (Cerdà, 1997b). The Hortonian discontinuous runoff model and the mixed infiltration and saturation excess runoff generation model have been the two major runoff-generation conceptual models for Mediterranean karst areas (Cerdà, 1998d; Calvo-Cases et al., 2003; Lange et al., 2003).

More recently, recognizing that karst landscapes are typically rich in solution features and the overlying shallow soil is highly permeable,

* Corresponding author at: Institute of Subtropical Agriculture, Chinese Academy of Sciences, No. 644, Yuanda 2nd Road, Changsha, Hunan 410125, China.
E-mail addresses: zyfu@isa.ac.cn (Z.Y. Fu), hbchs@isa.ac.cn (H.S. Chen), zhangw@isa.ac.cn (W. Zhang), xqx@glut.edu.cn (Q.X. Xu), hjdx@foxmail.com (S. Wang), kelin@isa.ac.cn (K.L. Wang).

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many researchers have focused on the roles played by underground properties (especially the epikarst architecture) on subsurface flow through sub-humid and semi-arid karst hillslopes using a number of different methods: (1) trench investigation (Wilcox et al., 2008); (2) dye-tracer testing (Nobles et al., 2010); (3) time-domain reflectometry (TDR) (Dasgupta et al., 2006); and (4) ground penetrating radar (GPR) and electrical resistance (Leh et al., 2008). For example, Wilcox et al. (2007) described a unique soil–epikarst architecture formed in a sequence of limestone and dolomite beds in the Texas Hill Country. In this unique architecture; water flow from uplands to valley floors was a combination of surface and subsurface flow conducted through a series of cascading recharge/discharge microtopographic units (Nobles et al., 2010). After that, by conducting rainfall simulation experiments on trenched plots within the Edwards Aquifer region, Wilcox et al. (2008) again demonstrated the importance of subsurface flow in semi-arid karst shrub lands, revealing that the differences in surface runoff and subsurface flow could be attributed to vegetation and epikarstic differences. On a Savoy karst hillslope, Leh et al. (2008) found that hillslope fractures acted as reservoirs which, when filled up, could impede infiltration excess surface flow while facilitating saturated subsurface flow. They also suggested that it was essential to know sub-surface fractures, joints, bedding planes and distinctive soil horizons locations in order to understand the three-dimensional details of flow pathways that control runoff processes in karst regions. In a shallow epikarst, Dasgupta et al. (2006) observed from a trenched plot that subsurface flow occurred as a combination of preferential flow and matrix flow. Most of the flow moved rapidly through open limestone conduits and fractures and root channels, with a smaller amount moving through narrower fractures. The least amount of subsurface flow was through soil matrix. Preferential flow at the trench face depended on total rainfall and was independent of antecedent soil matrix moisture levels (Dasgupta et al., 2006). The subsurface flow pathways in shallow epikarst usually display great variability and a high level of interconnectedness (Taucer et al., 2005).

An integrated soil–epikarst system extends down from the soil surface to the epikarst base (Schwartz et al., 2013). Soil and epikarst co-evolution leads to a highly connected preferential flow pathway network embedded throughout a soil–epikarst system (Klimchouk, 2004). A complete understanding of the karst subsurface flow can only be achieved using an integrated soil–epikarst system perspective. Most previous studies focused exclusively on the soil layer or a soil–epikarst system that did not extend deep enough into the epikarst base. This limits a thorough understanding of the role that the soil–epikarst architecture system plays in the subsurface flow of landscapes underlain by carbonate rocks.

All of the studies identified were conducted in either sub-humid, semi-arid or Mediterranean karst areas (Leh et al., 2008; Wilcox et al., 2008; Li et al., 2011). These results are not able to represent humid subtropical karst near-surface hydrological regimes as karstification intensity is primarily controlled by the specific climatic hydrothermal conditions of the region (Klimchouk, 2004). Chandler and Bisogni (1999) conducted one of the few tropical humid karst area studies. Results indicated that forest clearance decreased both epikarst and soil surface water infiltration capacities leading to higher runoff. Subsurface flow is more prevalent in humid environment than drier climates as most studies have shown that subsurface flow occurs at saturated, or near saturated, conditions (Weiler et al., 2005). These considerations suggest that soil–epikarst architecture effects on subsurface flow generation remain poorly understood, and recent experimental data of subsurface flow for humid subtropical karst regions is very limited.

Karst terrain covers about 14% (1.3 million km^2) of China. Much (42%) is located in Southwest China, making this area the world's largest contiguous, humid, subtropical climate, karst area. Regional bedrock is primarily pure carbonate with an older stratum deposited during the Triassic period. It has a denser structure, lower porosity (<3%), and less hydrochloric acid (HCl) insoluble matter (<4%) than the sub-humid and semi-arid karst regions noted above (Yuan, 1994). Furthermore, high temperatures and abundant precipitation in humid subtropical areas results in their karst landscapes being classified as cockpit karst, which has been intensively affected by karstification dynamics and is characterized by similar dimension enclosed depressions surrounded by overlapping hills and ridges (Day, 2004; Chen et al., 2012; Huang et al., 2014).

Cockpit karst is the most typical landscape style present in Southwest China. Locally called “fengcong” (Chen et al., 2012; Huang et al., 2014) (Fig. 1), it is markedly different from either Edwards Plateau, or Mediterranean, karst as they have relatively gentle terrains. The flat depression area suitable for human habitation and cultivation in cockpit karst areas of Southwest China is less than 50% of the entirety. Most of the catchment area has a 20% or greater slope. High population densities create socioeconomic pressures. Excessive use of land for agriculture makes karst rocky desertification to be the most severe ecological issue threatening this region (Bai et al., 2013; Xu et al., 2015; Yan and Cai, 2015). Much of the footslope land (the base of the cone karst) adjacent to the depressions had heavily forested, but has been cleared for human utilization. The soils of this footslope land are shallow and usually underlain by highly irregular epikarst surface (Peng and Wang, 2012). These soil–epikarst architectural features resemble other non-karst landforms where shallow soil is underlain by undulate bedrock having a high subsurface flow generation potential (Weiler et al., 2005; Hopp and McDonnell, 2009).

Karst-region soil–bedrock architectures have unique characteristics due to karstification which do not exist at other geological areas (Klimchouk, 2004). Surficial karst processes facilitate the solutional enlargement of carbonate rock fissures, resulting in increased bedrock permeability. These processes also produce an irregular, pitted and etched epikarst sub-surface that increases epikarst surface topographical irregularity (Zhou and Beck, 2011). Recent studies suggest that subsurface topography and bedrock permeability were major factors influencing the threshold behavior of subsurface flow at the hillslope scale (Hopp and McDonnell, 2009; Graham et al., 2010). Whether subsurface topography and bedrock permeability also exert their effects on near-surface hydrological processes of karst hillslopes is unknown. If they do, then to what extent, and how, are questions remaining to be answered.

This study for the first time [to our knowledge] from an integrated soil–epikarst system perspective, conducted plot-scale, in situ, rainfall simulation experiments to investigate subsurface flow regimes in a humid sub-tropical cockpit karst region. A trench excavated to the epikarst lower boundary allowed the simultaneously identification of flow pathways in soil and epikarst zones. This method facilitated evaluation of subsurface flow regimes in an integrated soil–epikarst system which extended from the shrub-top to epikarst base. The primary objectives of this study were to: (1) understand of the nature and origin of subsurface flow processes occurring in a soil-mantled sub-tropical dolomite karst slope; and, (2) analyze how the integrated soil–epikarst architecture system, initial moisture conditions, and rainfall intensity, effect subsurface flow onset, rate, and spatio-temporal patterns.

2. Materials and methods

2.1. Study site

The experiments were conducted in the Mulian catchment located in Huanjiang County of northwest Guangxi, in Southwest China (Fig. 2a). It is an area of 1.14 km^2 used for long-term field research by the Huanjiang Observation and Research Station for Karst Ecosystems of the Chinese Academy of Science. It is a representative cockpit karst catchment developed on dolomite and characterized by a flat depression (28% of the total catchment area) surrounded by overlapping hills and ridges except for an outlet in its northeast (Fig. 2a, b). About 60% of slopes have a gradient greater than 25°. Elevation ranges from 272 to 647 m above sea level. The climate is classified as sub-tropical, with