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Hydraulic properties of karst fractures filled with soils and regolith materials: Implication for their ecohydrological functions

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ABSTRACT

In regions with shallow soils underlain by fractured bedrock, hydrological processes of substrate are no longer only limited to soil layers. However, ecohydrological functions of bedrock fractures, especially those filled with different soil and regolith materials, have not been fully understood. In this study, we aimed to evaluate water transport and supplying capacities of the filled fractures through investigating hydraulic properties, and explore their dominant influencing factors. Three typical fractures, a vertical one filled with fine-textured soil (VSF), a vertical one filled with soil and regolith materials (VSRF), and a non-vertical one filled with coarse-textured soil (NSF) were selected from a large newly excavated trench on a karst hillslope of southwest China. Stratified samples of fracture fillings were collected to measure saturated hydraulic conductivity (K_s), water retention curves and basic physicochemical properties. Additionally, twenty soil profiles in different topographic locations in the same study area were also analyzed in order to support the results derived from the filled fractures. All fractures exhibited extremely high K_s (87–149 mm h^{-1}) in surface soil (0–10 cm), which allowed rapid infiltration of rainwater into subsurface. Subsurface water transport was smooth when underlying fracture fillings were loamy with relatively high K_s (about 10 mm h^{-1}) like in NSF, but was blocked when they were clayey with low K_s (<0.1 mm h^{-1}) like in VSF and VSRF. All fracture fillings had abilities to hold water and available water was the most in NSF, which provided an extra water source for plant growth in shallow soil regions. The ecohydrological functions of the filled fractures often depend on the properties and layering of fracture fillings, which was supported by those obtained from the twenty soil profiles. These results are helpful for better understanding of the ecohydrological processes and functions of fractures filled with different materials in karst regions.

1. Introduction

Worldwide, large portions of terrestrial landscapes are characterized by shallow soils underlain by weathered bedrock (Graham et al., 1997; Schwinning, 2010; Estrada-Medina et al., 2013). Unlike many other regions, hydrological functions of substrate in these regions depend not only on the soil layer, but also on the weathered bedrock layer (Williams, 1983; Bonacci et al., 2009). In regions dominated by uniformly weathered bedrock, granite for instance, bedrock weathering degree decreases with increasing depth, mainly due to the depletion of dissoluble water (Berhane et al., 2013). Hydrological functions of bedrock layer could be simply related to its spatial distribution with different weathering degrees, and the total weathering depth (Jones and Graham, 1993). While in other regions, typically in karst area, bedrock experiences uneven weathering processes and is manifested by networks of fractures and fissures (Stothoff et al., 1999; Bonacci et al., 2009). Compared to granite regions, hydrological functions of weathered bedrock layer in karst areas are more complicated related to its characteristics.

Karst landscapes are known to be dominated by soluble bedrock (limestone and dolomite) and occupy about 15% of the total continental surface area (Yuan, 1991). Most weathered materials were removed by water flow which resulted in the shallow soil coverage, especially on hillslopes (Wang et al., 2004). Previous studies revealed that surface runoff on hillslopes was extremely low (<5%) as most precipitation infiltrates quickly through the soil layer to underneath (Gregory et al., 2009; Chen et al., 2012b; Peng and Wang, 2012). Chen et al. (2012b) further suggested that surface runoff generation was more related to the local substrate structure rather than land use. However, we are still far from fully understanding the hydrological processes of infiltrated soil water in karst regions.

Empty fractures are obviously fast flow paths for the downward movement of water flows; connected fractures further facilitate rapid

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transmission of infiltrated soil water to groundwater (White, 2002; Wilcox et al., 2008; Chen et al., 2009; Caputo et al., 2010). However, under field conditions, fractures are usually filled with different types of materials. For example, in the karst regions of southwest China, most of the exposed fractures (except those without soil coverage) on fresh road cross-sections were filled with soils or the combination of soil and regolith materials (Feng et al., 2011). Despite the important role that filled fractures may play in karst hydrological processes, it has largely been ignored in previous studies (Dasgupta et al., 2006). Lack of related knowledge inevitably brings additional uncertainties to karst hydrological models.

One of the other main functions for weathered bedrock layers is their water supplying capacity. In regions with shallow soils, low soil water holding capacity often fail to support plant growth, especially in seasonally dry climate (Zwieniecki and Newton, 1996; Schwinning, 2010). Water supplying capacity of weathered granitic bedrock has been investigated based on direct measurement of bedrock in different weathering degrees, as well as in situ monitoring of water dynamics (Jones and Graham, 1993; Hubbert et al., 2001). Nevertheless, in karst areas, water supplying capacity of weathered bedrock layer is mostly based on indirect results, and it is commonly assumed that plants utilize bedrock-stored water (Liu et al., 2004; Schwinning, 2010; Nie et al., 2011). There is also evidence suggesting that potential water availability is much higher in soil filled rock pockets than in top soil layers (Estrada-Medina et al., 2013). However, we still lack direct evidence on water supplying capacity of karst fractures, especially those filled with different materials.

The optimal way to study water transport and supplying capacity of filled fractures within bedrock is in situ monitoring, which requires bedrock excavation (Dasgupta et al., 2006). However, once the excavated profile is exposed to air, properties of the fracture-fillings may change during the monitoring period as surrounding environment changes. An alternative way is in-situ sampling from newly excavated fractures in combination with lab analysis. Saturated hydraulic conductivity (K_s) and water retention curves (as well as other water retention based parameters) have been widely used to evaluate soil water transport and supplying capacity, respectively (Julià et al., 2004; Adamcova et al., 2005; Toran et al., 2006; Schwen et al., 2014). These parameters have also been used to reflect the hydraulic properties of highly weathered bedrock (regolith) materials as they behave much like soil (Jones and Graham, 1993; Katsura et al., 2009; Rouxel et al., 2012). As most fractures in karst regions are filled with soil and/or regolith materials, samples collected from fractures can also be tested for the above-mentioned parameters.

In the present study, various types of fractures, filled with different materials, were selected from a newly excavated experimental profile at the lower slope position of a typical karst hillslope. Stratified samples of fracture fillings were collected from different fractures and subjected to laboratory analysis. The main objectives here were to: (1) characterize the hydraulic properties of soil and regolith materials that distributed within the filled fractures, and (2) evaluate their water transport and supplying capacities as well as dominant influencing factors.

2. Materials and methods

2.1. Site description

The study area is a small catchment (1.14 km^2) located in the Huanjiang Observation and Research Station for Karst Ecosystems of the Chinese Academy of Sciences (24°43′58.9″–24°44′48.8″N, 108°18′56.9″–108°19′58.4″E) in Huanjiang County of northwest Guangxi, Southwest China. The catchment is a typical karst (dolomite) area with a flat depression surrounded by mountains on three sides and an outlet in the northeast. Elevation ranges from 272 m to 647 m. This area experienced severe deforestation from 1958 to the mid-1980s and has been under natural restoration for almost 30 years. Most hillslopes are dominated by tussock grasses and shrubs. Secondary forest is found on the continuous dolomite outcrops and on deep soils at the foot of hillslopes (Nie et al., 2011).

Hillslopes in this study area are steep, with about 60% >25°. Bare rock ratio is 30%, and the relative soil depth in this area is 10–30 cm. The shallow and discontinuous soils are mostly underlain by weathered dolomite and contain large amounts of rock fragments. The soil depth decreases upslope as rock fragment content increases (Chen et al., 2011). Steady-state infiltration rate measured by disc permeameter on the hillslopes is 42–126 mm h^{-1} (Chen et al., 2012a). Overland flow on hillslopes is rare, with runoff often <5% (Chen et al., 2012b). A subtropical mountainous monsoon climate dominates, with annual rainfall of 1389.1 mm and annual temperature of 18.5 °C. The wet season lasts from late April until the end of September and provides >60% of total annual rainfall (Yang et al., 2012). A pronounced 4–6 month dry season in winter/spring provides only 20–30% of total annual rainfall.

2.2. Fractures selection and filling materials sampling

A big experimental trench (about 90 m in length and 4 m in depth) was excavated at the lower slope position (covered by dense shrubs) of a southeast-facing hillslope. Soil distributed discontinuously (ranged from 0 to >100 cm) along the profile with an average depth of 50 cm, which was much deeper than both upper and lower slopes because of the relatively gentle slope (2–5°) at that position. Rare rock fragments occurred in soils that covered on and filled within the fractures. Many fractures, fissures and soil pockets, varied in size, depth and orientation, were found and investigated on the big trench. There were 16 filled fractures and 9 soil pockets in total. Fracture fillings varied in textures and combination types. Most of these filled fractures were narrowly developed, which made it difficult to collect soil and regolith core samples. In order to obtain enough samples for K_s and water retention curve measurement, three wide fractures (Fig. 1) were selected as representative of the main types: a 360 cm deep vertical soil-filled fracture (VSF); a 360 cm deep vertical soil-regolith fracture (VSRF) whose composition varied gradually from soil to regolith material; and a non-vertical (408 cm in depth and 700 cm in length) soil-filled fracture (NSF).

Undisturbed (taken by stainless steel cylinders with 5 cm in height and 5 cm in diameter) and disturbed samples were collected simultaneously in this study. Sampling intervals were set as 0–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm in the upper 100 cm depth, and as every 50 cm increase vertically below 100 cm for the two vertical fractures (VSF and VSRF). Samples from 30 to 225 cm in NSF fracture were unable to be obtained because of the weakly weathered bedrock. Below 225 cm, samples were collected every 50 cm horizontally along the extension of NSF. Detailed sampling points are shown in Fig. 1. At each point, two undisturbed (one for K_s and the other one for water retention curve measurement) and one mixed disturbed samples were collected. Due to the limited width of these fractures, no repetitions at each point were able to be obtained. Lack of repetitions might reduce the reliability and also representativeness of the observed data. In order to support the results we found, hydraulic properties of twenty soil profiles (0–100 cm) in different topographic locations (eight in upslope, seven in downslope and five in depression) in the same study area (data from Fu et al. (2015b)) were also analyzed in this study.

2.3. Lab analysis

K_s was measured with constant head method based on Darcy's law (Lado et al., 2004; Gwenzi et al., 2011). Cylinder cores were firstly placed in a large container with constant water depth of about 5 mm to absorb water until constant weight (m_1) was obtained. Then, more water was added to the plastic container until the water surface was just below the top of the cores. The cores were dipped in water for about 24 h until constant weight (m_2) was obtained. Subsequently, these cores were connected to a mariotte bottle to measure outflow