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ORIGINAL RESEARCH ARTICLE

Rock outcrops change infiltrability and water flow behavior in a karst soil

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Abstract
Rock outcrops are widespread across the surface of the earth, particularly in karst environments, and they play an important role in infiltration-runoff processes by triggering preferential flow. However, the characteristics of the preferential flow network at the soil–rock interface and its influencing factors in karst areas remain poorly understood. To clarify how the emergence of outcrops on the land surface affects soil infiltrability and water flow behavior, soil hydraulic conductivity (\(K\)) measurements and dye tracing experiments were conducted in a karst area with two contrasting surface features (i.e., rock outcrop plot [RP] and non-rock-outcrop plot [NRP]) in Yunnan Province, Southwest China. Results showed that (i) in the immediate vicinity of rock outcrops in the RP, \(K\) values were significantly increased, and other soil properties and plants were also improved when compared with results 1 m away from outcrops and in the NRP; and (ii) in the RP, the soil–rock interface dominated the preferential flow network surrounding outcrops, and the connected conduits produced by plant roots and soil fauna were also involved in this infiltration process. Matrix flow was the dominant flow behavior in the NRP. We concluded that rock outcrops, by improving soil properties and building a well-connected preferential flow network, can greatly change infiltrability and water flow behavior in karst soil. This implied that outcrops will facilitate quick infiltration after most rainfall events and thus reduce rain-induced surface runoff and soil erosion, as well as increasing groundwater recharge and the water supply to nearby plants.

1 | INTRODUCTION

Water infiltration through soil layers is an important process in the terrestrial hydrological cycle, affecting surface runoff, groundwater recharge, soil erosion, and the water budget of vegetation in both arid and semiarid areas (Michaelides, Lister, Wainwright, & Parsons, 2009; Ward & Robinson, 1989). The hydrological processes related to soil infiltration rate and water flow behavior are key in determining water distribution and the relationship between surface water and groundwater (Bowmer, 1987; Hillel, 1987). Karst landscapes with emerged rock outcrops always behave as a mosaic of local infiltration and runoff generation (Lavee, Imeson, Pariente, & Benyamini, 1991; Yair, 1996; Yair & Lavee, 1985). Thus, the heterogeneity of the surface structure may strongly influence hydrological processes in these regions. However, the understanding of how rock outcrops change infiltrability and water flow behavior in a karst soil remains limited.
In regions with shallow soil layers underlain by fractured bedrock, rainfall runoff and hydrological process are particularly complex (Wilcox, Owens, Dugas, Ueckert, & Hart, 2006; Wilcox et al., 2008). In the world’s major karst regions, such as the European Mediterranean basin, and the karst in southwestern China, the rainfall pattern, rainwater infiltration, and runoff generation can have high spatial variability on different scales because of a dual hydrological system in the epikarst (Ford & Williams, 2007; Williams, 2008). In general, the soil in a karst ecosystem is characterized by high soil clay content and bulk density, along with low hydraulic conductivity, particularly when a soil crust is formed on the ground surface (Morin, Keren, Benjamini, Ben-Hur, & Shainberg, 1989). Runoff generation in these regions is commonly attributed to an infiltration-excess mechanism (Laine-Kaulio, Backnas, Koivusalo, & Lauren, 2015). However, in the specific location surrounding an outcrop, the soil infiltration rate can be extremely high, typically exceeding the highest natural rainfall intensity (e.g., Calvo- Cases, Boix-Fayos, & Imeson, 2003; Cerdà, 1996, 1997, 1998). Rainwater infiltrates quickly into the subsurface with scarcely any generation of surface runoff on the karst hill slope (Gregory et al., 2009; Wilcox et al., 2008).

Specific types of water flow are responsible for infiltration in the vadose zone, including matrix flow and preferential flow (Wilcox et al., 2006, 2008; Williams, 2008). Matrix flow is the slow movement of water through bulk soil (Allaire, Roulier, & Cessna, 2009), and preferential flow is nonuniform water flow that allows water to rapidly flow through soil layers without penetrating the fine porous matrix (Abrahams & Parsons, 1991; Bergkamp, 1998; Cantón et al., 2011; Cerdà, 1997; Edwards, Shipitalo, Owens, & Norton, 1989; Edwards, Shipitalo, Owens, & Dick, 1993; Ruiz Sinoga & Martinez Murillo, 2009), thus reducing the travel time of water from the surface to groundwater more than would be expected from the soil matrix properties (de Rooij, 2000; Gish, Gimenes, & Rawls, 1998; Gish & Jury, 1983; Jamieson, Gordon, Sharples, Stratton, & Madani, 2002). In particular, secondary preferential flow paths formed in shallow surfaces are responsible for the locally high hydraulic conductivity of the clay-rich soils found in karst areas (Ford & Williams, 2007; Sohrt, Ries, Sauter, & Lange, 2014). Soil macropores can also cause great difficulty in predicting and modeling hydrological processes in ecosystems. The direct measurement of preferential flow is often difficult because of the heterogeneity and instability of water pathways. Therefore, dye tracing is often used to assess the degree of preferential flow in soils (e.g., Flury & Flühler, 1994, 2008; Ghodrati & Jury, 1990).

The infiltration of water in soil can be greatly affected by multiple external factors, such as the rainfall regime (de Lima & Singh, 2002; Moody & Martin, 2009), vegetation cover (Beven & Germann, 1982; Castellano & Valone, 2007), and human activity (Fleischner, 1994; McGarry, Bridge, & Radford, 2000). In addition, the surface characteristics of the earth are also important in affecting infiltration, primarily the properties of the soil matrix, such as texture, porosity, repellency, and permeability (Bond, 1964; Bond & Harris, 1964; Cerdà, 1997; Czarnes, Hallett, Bengough, & Young, 2000). Cracks and fissures generated during the swelling and shrinking of unsaturated soils can provide preferential flow paths that promote the deep penetration of water (Alakukku, Nuutinen, Ketoja, Koivusalo, & Paasonen-Kivekäs, 2010; Sohrt et al., 2014). Non-soil constituents incorporated into soil (e.g., plant roots, fallen woody debris, rock fragments, and residual plastic) can prevent soil sealing and hence increase soil porosity (Jiang, Liu, Wang, Zhou, & Xin, 2017; Jiang et al., 2018). They can also strongly modify local infiltration and affect water flow behavior (Kodešová, Němeček, Kodeš, & Žigová, 2012; Laine-Kaulio et al., 2015). When rock is exposed on the soil surface, the soil–rock interface always acts as the major preferential flow path of water infiltration into the nearby soil (Crowther, 1982; Descroix, Viramontes, Vauclain, González Barrios, & Esteves, 2001; Sohrt et al., 2014; Wilcox et al., 2008). Outcrops can funnel rainwater and moisturize and fertilize nearby soil patches (Goransson, Edwards, Perreijn, Smittenberg, & Venterink, 2014; Shen, Wang, Chen, Tang, & Chen, 2019; Sohrt et al., 2014); this may further favor the growth of roots and increase faunal activities in neighboring soil. Those factors may jointly influence the interface flow between the soil and outcrops to some extent, but the characteristics of the preferential flow network at the soil–rock interface and its influencing factors remain poorly understood.

To understand the behavior of water flow in hydrological systems in karst areas, the determination of the porosity, extent, and connectivity of these structures is crucial (Calvo-Cases et al., 2003; Solé-Benet et al., 1997; Wilcox, Wood, & Tromble, 1988). Preferential flow paths characterize soils in karst areas (Bockgard & Niemi, 2004; Jarvis, Koestel, & Larsbo, 2016; Sohrt et al., 2014). However, their interactions and relative importance in influencing the

Core Ideas

- Rock outcrops change infiltrability and water flow behavior in a karst soil.
- The soil hydraulic conductivity (K) is spatially variable in a karst area.
- The K is also particularly high at the soil–rock interface.
- Runoff from outcrops is guided by the rock surface, root channels, and soil fauna burrows.
hydrology of karst systems remain unclear (Mayor, Bautista, & Bellot, 2009; Seeger, 2007). Previously, we discovered that rock outcrops have considerable influence on the water infiltration pattern and spatial distribution of soil loss in different directions (Zhao, Shen, Shan, Yu, & Zhao, 2018). In the current study, we visualized the infiltration behavior in rock outcrop plots (RP) and non-rock outcrop plots (NRP) using the dye tracer Brilliant Blue FCF and specifically observed the preferential flow guided by the soil–rock interface, root channels, and soil faunal burrows in soils surrounding outcrops. Soil hydraulic conductivity (K), along with other soil properties and plant characteristics, were also measured in the two plots. The aims of this study were to identify the characteristics of the preferential flow network at the soil–rock interface and its influencing factors.

2 | Materials and Methods

2.1 | Study site

The study site was in the Stone Forest World Geopark (24°38′–24°58′ N, 103°11′–103°29′ E; 1776–1789 m asl) in Yunnan Province, Southwest China (Figure 1). A typical subtropical monsoon climate prevails, with contrasting seasons of rain and drought, and of combined rainfall and heat. The climate records from a local weather monitoring station show the mean annual temperature is 16.3°C, fluctuating from the mean maximum temperature of 20.7°C in July to the mean minimum temperature of 8.2°C in January. The mean annual precipitation is 939.5 mm, with approximately 80–88% occurring between May and October. The mean annual evaporation is 2097.7 mm (Wang, Shen, Huang, & Li, 2016).

The geomorphological background of the region is a typical karst landscape, featuring variable microtopography shaped by rock outcrops that rise above the ground. As a result, small patches of sloped cropland are scattered among the emerged rocks. The experiments were conducted in two types of 20-m × 20-m plots: RP and NRP (Figure 1). In the RP area, the landscape was a mosaic of rock outcrops and patches of bare soil, interspersed with a cover of vegetation and rock fragments. By contrast, rocks were rare in the NRP area. The soil is classified as Plinthudults (USDA Soil Taxonomy). Vegetation at the site consists of Imperata cylindrica (L.) P. Beauv., Heteropogon contortus (L.) P. Beauv. ex Roem. & Schult., and Arthronax hispidus (Thunb.) Makino. In April 2019, when it was still the dry season, the soil physical properties were measured at three locations—very close to outcrops, 1 m away from outcrops in the RP, and on the soil surface in the NRP (Figure 1)—using the methods described by Danielson and Sutherland (1986):

\[
\text{Initial gravimetric water content (\%)} = \left[ \frac{W_{\text{CRWS}} (g) - W_{\text{CRDS}} (g)}{W_{\text{CRDS}} (g) - W_C (g)} \right] \times 100
\]

Bulk density (g cm\(^{-3}\)) = \frac{W_{\text{CRDS}} (g) - W_C (g)}{100 (cm^3)}

Total porosity (%) = \left[ 1 - \frac{\text{Bulk density (g cm}^{-3}\text{)} \times \text{Capillary holding capacity (g cm}^{-3}\text{)}}{\rho_{\text{water (g cm}^{-3}\text{)}}} \right] \times 100

Capillary porosity (%) = \frac{\text{Bulk density (g cm}^{-3}\text{)} \times \text{Capillary holding capacity (g cm}^{-3}\text{)}}{\rho_{\text{water (g cm}^{-3}\text{)}}}

Noncapillary porosity (%) = \text{Total porosity (\%)} - \text{Capillary porosity (\%)}

Capillary holding capacity (\%) = \left[ \frac{W_{\text{WD2h}} (g) - W_{\text{CRDS}} (g)}{W_{\text{CRDS}} (g) - W_C (g)} \right] \times 100

where \(W_C (g)\) is the weight of the cutting rings (i.d. = 50.46 mm, height = 50.0 mm, volume = 100 cm\(^3\)), \(W_{\text{CRWS}} (g)\) is the weight of the cutting rings filled with natural wet soil, \(W_{\text{WD2h}} (g)\) is the weight of the cutting rings saturated with distilled water for 24 h and then drained by gravity for 2 h, and \(W_{\text{CRDS}} (g)\) is the weight of the cutting rings oven dried at 105°C for 24 h. To calculate total soil porosity, the particle density of the soil was set to 2.65 g cm\(^{-3}\). For the sampling close to outcrops, we attempted to put the ring as close as possible to an outcrop while not allowing it to actually touch. If it failed, we tried another until it succeeded.

In June 2019, the plant height, aboveground biomass, and belowground (root) biomass (0–30 cm) were measured in six quadrats (30 × 30 cm) at each of three locations: very close to outcrops and 1 m away from outcrops in the RP, and on the soil surface in the NRP (Figure 1). The plant samples were oven dried at 80°C to a constant weight.

2.2 | Soil hydraulic conductivity

The field \(K\) (cm s\(^{-1}\)) of the microplots was measured during April 2019 when the region was suffering its worst drought in decades, so no rainfall occurred in the period. A portable mini-disc infiltrometer (WA 99163, Decagon Devices) was used at a pressure head of −2 cm, and the measurements of \(K\)
were conducted at 2-m intervals on the soil surface. To ensure good contact between the soil and the infiltrometer, a thin layer of fine silica sand was applied directly underneath the infiltrometer disk. The $K$ was calculated from the slope of the curve of the cumulative infiltration vs. the square root of time (Zhang, 1997). In total, 100 in situ field measurements of $K$ were obtained in the study.

2.3 Trace dye to measure soil water infiltration

Dye tracing experiments were conducted in the two types of microplots to investigate the flow pathways of water in the soils and the infiltration pattern of runoff from outcrops. Before the dye experiment, plants and litter were carefully removed from the ground surface. Then, three 20-cm by 20-cm square, stainless steel cylinders (Figure 2) were embedded 5 cm into the soil in each area ($n = 3$ for RP, $n = 3$ for NRP), and 1 L of 4.0-g L$^{-1}$ Brilliant Blue FCF dye solution was added to simulate a 25-mm rainfall event.

In the RP area, the cylinders were placed adjacent to rock outcrops for the application of dye (Figure 2) to ensure the participation of soil–rock interface flow in the infiltration events. The outcrops we selected had an almost vertical soil–rock interface, which ensured that the embedding of cylinders near outcrops was practicable. To study the infiltration pattern of runoff from outcrops, a quantity of dye was applied using a 20-cm-long, line-type perforated sprinkler on the rock surface (with a rainwater-collecting area of ~400 cm$^2$) in the RP area (see Zhao et al., 2018, for details). To simulate the natural outcrop runoff generated under different rainfall conditions, two amounts of infiltration dye solution (i.e., 250 and 500 ml, to simulate 12.5- and 25-mm rainfall events, respectively) were applied, with each test requiring 10 min to complete.

Three replicates were used for each treatment amount. All positions with added dye were covered with a large plastic film to protect them from the sun, wind, and rain. After 24 h, a vertical soil section was carefully excavated through the center of each dyed area and then photographed using a digital camera at a distance of 50 cm with a calibrated scale placed aside. If a loose rock fragment appeared (actually very few did), we removed it carefully. Finally, soil patches were removed, the images of the dye-stained zone on the rock surface were also photographed, and the maximum infiltration depth was measured.

To analyze the infiltration patterns occurring in the RP and NRP areas, a 20-cm (width) $\times$ 30-cm (depth) image was extracted from the original photographs of the dye irrigation experiments (Figure 3). The photographs were processed according to Zhao et al. (2018), and the following parameters of the infiltration pattern were calculated:

1. Dye coverage (%), or the ratio of stained area to total area of a certain soil profile (Flury, Flühler, Jury, & Leuenberger, 1994; Ghodrati & Jury, 1990).
2. Uniform infiltration depth (cm), defined as the depth at which the dye coverage is 80%. When a stripe of dye is
FIGURE 2  (a) Infiltration patterns for vertical soil sections and (b) experimental design of dye tracing application in the microplots. In the tracing experiments, the rock surface was sprinkled (1 and 2) and the soil surface was irrigated (3 and 4) with dye. The dye sprinkling experiment was used specifically to study the preferential flow at the soil–rock interface, and the dye irrigating experiment was used to study the degree of preferential flow in soil. The dark blue and light blue indicate the strong and weak exchanges between the macropore and the surrounding soil matrix, respectively.

FIGURE 3  An illustration shows the analysis process of dye-stained soil profiles for (a) a non-rock outcrop plot and (b) a rock outcrop plot. The first two panels on the left are the photograph and the extracted image of dye infiltration, and the parameters used to assess infiltration patterns are shown in the graphs of dye coverage vs. soil depth on the right. The arrows denote the soil–rock interface. MID, maximum infiltration depth (cm); UID, uniform infiltration depth (cm); DC, dye coverage (%); \( f_{PF} \), fraction of preferential flow (%).
observed with a low uniform infiltration depth, the matrix flow is limited in top soil layers, and generally the degree of preferential flow is high (Benegas, Ilstedt, Roupsard, Jones, & Malmer, 2014; van Schaik, 2009).

3. Preferential flow fraction (%), or the ratio of the preferential flow area to the total dye-stained area of the image (van Schaik, 2009), calculated as

\[
\text{Preferential flow fraction (\%)} = \left(1 - \frac{\text{Uniform infiltration depth (cm)} \times \text{Width (cm)}}{\text{Total dye-stained area (cm}^2)}\right) \times 100
\]

These procedures were used to extract the information on soil permeability and water flow behavior from the dye-stained soil profiles. A disadvantage of the dye tracing experiment is that, because of the destructive excavation, the dyeing cannot be repeated at the same location. However, many high-resolution images of dye-stained cross sections (i.e., infiltration patterns) were obtained in the study.

2.4 | Statistical analyses

All the data were tested for normality and homogeneity of variance. A one-way ANOVA was applied to compare the different parameters between the plot types. The significant differences between the means were detected on the basis of the LSD at \(P < .01\). All statistical procedures were performed in the IBM SPSS version 19.0 statistical software package.

3 | RESULTS

3.1 | Soil hydrological conductivity

The \(K\) was significantly different \((P < .01)\) between the RP and the NRP (Figure 4a). The \(K\) values in the RP ranged from \(1.67 \times 10^{-3}\) to \(10.6 \times 10^{-3}\) cm s\(^{-1}\), with an average of \(6.02 \times 10^{-3}\) cm s\(^{-1}\), which was higher than that in the NRP (average = \(3.30 \times 10^{-3}\) cm s\(^{-1}\), range = \(1.17 \times 10^{-3}\) to \(6.17 \times 10^{-3}\) cm s\(^{-1}\)). The \(K\) in the RP exhibited high spatial variability (Figure 4b), with the values much higher close to outcrops than the generally lower values in the soil matrix. The maximum \(K\) value in the study occurred at the soil–rock interface. However, the \(K\) values for the soil matrix were not significantly different between the two types of plots.

3.2 | Soil properties and plant characteristics

The soil properties and vegetation characteristics at the locations close to outcrops were significantly different from those 1 m away from outcrops and in the NRP (Table 1). Over a depth range of 0–30 cm, the initial soil moisture, total porosity, capillary porosity, and noncapillary porosity near the soil–rock interface were significantly higher than those at the other two locations, whereas the average bulk density of soil at the interfaces was significantly lower. The soil at the soil–rock interface in the RP was characterized by numerous macropores and visible gaps (Figure 5a) resulting from severe drought, and these plots had the highest values for plant height and aboveground and belowground biomass (Figure 5f, Table 1), where more soil fauna (ants and white grubs) and their burrows were also observed (Figures 5g–5i). However, the soil properties and vegetation characteristics at the locations 1 m from outcrops and in the NRP had no significant difference between them.

3.3 | Water flow behavior

The water flow paths and infiltration patterns were directly interpreted from the images of the dye-stained soil profiles. In the dye irrigating experiment, the water infiltrated uniformly in the NRP, and a large proportion of the stained area was generally confined to the upper 20 cm of the soil profile. The uniform infiltration depth in the NRP was 14.7 cm, and the maximum dye-stained depth was 20.6 cm (Table 2). The preferential flow fraction was only 5.2%. These results indicate that matrix flow was the dominant flow behavior in the NRP. In the RP, however, the soil infiltration of the dye solution followed preferential pathways (primarily soil–rock interfaces) and bypassed the other part of the soil matrix (Figure 3b). The dye coverage was reduced rapidly in the subsoil horizon, and the dye accumulated around the rock surface. The maximum depth reached by the dye was 29.6 cm, and the preferential flow fraction was 38.1% (Table 2). The uniform infiltration depth was 9.6 cm, lower than that in the NRP. All the parameters of the infiltration pattern in the RP indicated that the soil–rock interface was predominant in guiding water flow behavior in the rocky environment.

The images from the dye sprinkling experiments showed that the preferential flow at soil–rock interfaces continued belowground and quickly infiltrated into the bedrock within a narrow space (Figure 2). When the infiltration amount increased, the infiltration depth also increased, but without a significant difference in the width. For infiltration of 250 ml, the average maximum infiltration depth was 27.3 cm, and for 500 ml, the depth was 49.3 cm (Table 2). Although lateral dispersion of dye into the soil matrix was observed (<10 cm in width), the vertical soil–rock interface flow dominated the infiltration patterns of outcrop runoff in the RP. In addition, individual flow paths formed by roots and soil fauna burrows were also identified. Notably, roots were laterally spread on rock surfaces (Figure 5d), and plants generally had greater...
aboveground and belowground biomass when close to rocks (Table 1). In the dye experiment, roots reached the same depth in the soil as the dye solution. Additionally, the burrows produced by soil fauna living near rocks were observed in the excavation. These sometimes had an influence on the dye infiltration process, as indicated by the accumulation of dye in burrows. However, this phenomenon was not commonly observed. In the sprinkling experiments, because of the rapid infiltration of the dye solution, ponding or surface runoff seldom occurred in the RP. The exception was a steep position with immediate surface runoff, which was blocked by another rock below, triggering rapid infiltration (Figure 5c).

4 | DISCUSSION

4.1 | Spatial variation of $K$

The similar physical properties of the soil matrix in the two different types of plots provided the opportunity to study the influence of rock outcrops on hydrological processes. In the study site, $K$ was highly heterogeneous in space, and the values in the RP were much higher than those in the NRP (Figure 4). Thus, the rock outcrops had a positive impact on soil infiltrability in this karst area, which is a conclusion consistent with that of previous studies. For example, Wilcox et al. (1988) and Poesen, Ingelmo-Sanchez, and Mucher (1990)
found that rocks protect soil against splash erosion and surface sealing, resulting in a remarkable correlation between rock cover and $K$. Gregory et al. (2009) reported an extremely low surface runoff coefficient (<5%) in a limestone karst landscape because of the extremely high infiltration rate of soil, which changed the runoff generation mechanism in the region. Runoff generation generally combines saturation-excess and infiltration-excess runoff (Ries, Lange, Schmidt, Puhlmann, & Sauter, 2015). In karst regions, runoff always occurs by infiltration excess (Calvo-Cases et al., 2003; Wilcox et al., 2006), but such occurrences may also be very infrequent (Cerdà, 1996, 1997, 1998). The high $K$ variation at a small scale implied high heterogeneity of runoff generation in space, and the increase in the threshold of surface runoff in a karst area is important in shaping the rainfall–runoff processes and providing rapid response to rainstorms.

Soil characteristics play a crucial role in the process of soil infiltration (Cerdà, 1997). The high $K$ observed in the RP may be explained by the improvement in soil properties and structure surrounding rock surfaces. The moisture and porosity...
increased remarkably in soils near rock outcrops, in contrast with those soils at a distance (Table 1), and these two properties are the most important factors affecting water infiltration rates (Edwards et al., 1989; Schwen, Zimmermann, & Bodner, 2014; Steenhuis & Muck, 1988). Because the rate of soil evolution in semiarid conditions is primarily limited by the abundance of water (Cooley, 2002), the findings of this study are consistent with those of previous research in the West Bank Mountains in which the organic C content was higher but the clay content was lower in the soil at the rock–soil interface than in the soil matrix distant from the rock outcrops (Sohrt et al., 2014). Soils with a high content of organic matter commonly have a high content of soil macroaggregates, which can greatly increase the soil porosity and penetrability (Bonell et al., 2010; Don, Schumacher, & Freibauer, 2011; Richter & Markewitz, 2001; Solomon, Lehmann, & Zech, 2000). The values of $K$ normally decrease with increasing clay content (Adamcova et al., 2005; Fu et al., 2015), and therefore, the reduced clay content of soil at the rock–soil interface may also contribute to the high infiltration rate observed in the RP. In addition, gaps between the soil and rock were observed (Figure 5a), particularly when soil shrinking became more intense during dry conditions. In karst areas, soil cracks (Sohrt et al., 2014; Zhu et al., 2019), together with rock fragment (Poesen et al., 1990), can greatly promote water movement from surface to groundwater, because they provide preferential flow paths and greatly reduce the infiltration time; this may also explain the high $K$ of few locations found in the NRP.

Additionally, a relatively dense distribution of rock outcrops on the ground surface can prevent soil from being compacted by human activities, such as grazing, plowing, and trampling, which increase soil bulk density and negatively affect soil porosity and infiltration (Blevins, Holowaychuk, & Wilding, 1970; Boix et al., 1995; Chandler & Chappell, 2008; Dadkhah & Gifford, 1980; Mwendera & Saleem, 1997; Whalley, Leeds-Harrison, Leech, Risely, & Bird, 2004). Human activities tend to increase the surface roughness and limit flow connectivity, causing more surface water ponding (Cerdà, 1998; Hanson, Steenhuis, Walter, & Boll, 2004; Mendoza & Steenhuis, 2002; Verbiest et al., 2007; Ziegler, Negishi, Sidle, Noguchi, & Nik, 2006), which, in a region of high evapotranspiration, is likely not beneficial for plants.

### 4.2 Preferential flow in the karst area

With the dye irrigation experiments, the two-dimensional images of stained soil profiles provided detailed information on the infiltration patterns and preferential flow pathways. The uniform infiltration depth, maximum infiltration depth, dye coverage, and preferential flow fraction all indicated that the degree of preferential flow was higher in the RP than in the NRP. In particular, the uniform infiltration depth was lower in the RP (Figure 3). A large portion of the dye solution applied in the RP was channeled into the underlying soil through preferential pathways, as indicated by the large preferential flow fraction. Therefore, preferential flow is proposed as the dominate type of water movement in the karst area. Many previous studies support this conclusion. Dasgupta, Mohanty, and Köhne (2006) used field rainfall simulation experiments to reveal that the drainage network in an epikarst zone was characterized by high flow capacity and rapid response. Sohrt et al. (2014) used dye sprinkling experiments and demonstrated the dominance of preferential flow at the soil–rock interface in guiding water flow and recharging the groundwater. The phenomenon of preferential flow has long been recognized as a defining feature of watershed hydrological processes in karst areas—that is, the occurrence of preferential flow is the rule rather than the exception (Bouma & Dekker, 1978; Lawes, Gilbert, & Warington, 1882; Steenhuis & Parlange, 1991).

Karst lands contain complex and variable pathways for water infiltration into deeper layers because of the heterogeneous composition of the ground surface, which is a mosaic of shallow soil layers and bare rock outcrops (Ford & Williams, 2007; Laine-Kaulio et al., 2015). At the study site, the preferential pathways were primarily composed of soil–rock
interfaces and conduits formed by roots and soil fauna, which were prominent in affecting the deep vertical infiltration and high hydrological conductivity in the region. As observed in the dye tracing experiment, all the solution (regardless of the initial amount) applied on rock outcrops flowed underground along the narrow interface between rocks and soil, indicating that rocks in the clay soil could create preferential flow paths for rainwater. Particularly in karst areas, the emergence of rock outcrops is very common, and they always act as a bypass promoting water infiltration (e.g., Bouma & Dekker, 1978; Lawes et al., 1882; Steenhuis & Parlange, 1991; Wilding & Tessier, 1988). When water flow encountered gaps along the interface, the downward movement of water was rapid, with no delay or ponding. More importantly, the dye sprinkling experiments also revealed that the preferential flow at soil–rock interface can be affected by the plant roots and soil fauna near the rock outcrops. For example, when channeled by plant roots, the dye reached deeper in the soil profile than in the soil matrix, indicating that water flow in root channels was another important mechanism of infiltration for the outcrop runoff. The roots stained by the dye tracer in this study (Figure 5d) were an indication of the flow channeled by plant roots. According to previous studies, roots improve soil physical properties by forming soil aggregates (Cerdà, 1998; Hartemink, Veldkamp, & Bai, 2008), reducing bulk density (Lado, Paz, & Ben-Hur, 2004; Tarafdar & Jungk, 1987), and increasing soil porosity (Benegas et al., 2014; Mitchell, 1995). The localized compaction from root growth can also generate additional channels for preferential flow (Barzegar, Yousefi, & Daryashenas, 2002; Johnson & Lehmann, 2006). In addition, soil fauna had an impact on the preferential flow at soil–rock interface. Holes or burrows produced by ants and white grubs were observed during excavation; these produce a subset of preferential flow (Alaoui, Caduff, Gerke, & Weingartner, 2011). The soil contained some burrows formed by soil fauna that, although not prominent, contributed to infiltration in the soil matrix.

The results strongly support previous findings that soil–rock interfaces, root channels, and soil fauna burrows are important contributors to preferential flow (Ruiz Sinoga & Martinez Murillo, 2009). However, because of the variability in number, extent, and connectivity of these preferential pathways, hydrologic processes can be complex and thus difficult to study. In general, soil–rock interfaces served as primary pathways for water transport, and the involvement of root channels and soil fauna burrow was detected when they were in intimate contact with the rock surface. In such cases, the roots adjacent to interfaces may influence the preferential flow, positively or negatively, depending on their position and distribution pattern. The dye sprinkling experiment indicated that water infiltration was deeper when channeled by a taproot than by lateral roots (as shown in Figure 5e) and that lateral flow could occur at the soil–rock interfaces when water was blocked by some lateral roots. According to Archer, Quinton, and Hess (2002), roots can even clog the soil pore space, causing a decrease in infiltration rate. Moreover, the closed-end conduits created by new roots and soil fauna may also not form a continuous flow network, acting more for water storage than for water transport. Therefore, the interconnectivity of preferential pathways is the key factor in influencing the infiltration pattern of water in soil. Further research on the interconnectivity is essential to understand the ecohydrological processes in karst areas.

4.3 | Implications

In karst areas, the underground transport of water and soil is an important part of ecosystem material circulation, whereas in most cases, surface runoff is inconspicuous and movement is not fluid (Lavee et al., 1991; Yair, 1996; Yair & Lavee, 1985). Rainwater, the main force shaping landform configuration (de Lima & Singh, 2002; Kinnell, 2005; Moody & Martin, 2009; Nearing & Bradford, 1985), can be concentrated, particularly in areas where rock outcrops occupy large portions of the ground surface (Lange et al., 2003; Yair, 1983). However, as shown in the dye experiments, the water received by rock outcrops was not immediately redistributed to nearby soil patches but was channeled into the ground through preferential pathways. Infiltration or saturation excess runoff did not occur because of the high saturated conductivity and large storage capacity of soil in the area covered with rocks. Thus, the runoff from rock outcrops may continue to rapidly infiltrate the subsurface until reaching the groundwater, or it may be confined or perched in epikarst surface depressions (Figure 6). Because of the rock outcrops and preferential pathways, the soil response to a rainstorm would be rapid, with increased potential for groundwater recharge and less ponding and runoff generated on the ground surface compared with a non-karst area. In addition, the mosaic of rock and soil increases the complexity of the topography, so surface runoff can be blocked (Figure 5c). The discontinuous runoff among exposed rocks may contribute to reduce the risk of rain-triggered natural hazards, such as landslides and floods.

However, with the increased emergence of outcrops over the land surface, both a decrease in soil thickness and an increase in water leakage always occur, thereby reducing the water storage and supply capacity for plants. The limited water storage of shallow soils in karst regions often fails to support plant growth (Khan, Hanjra, & Mu, 2009; Schwinning, 2010; Zwieciecki & Newton, 1996). A crucial strategy to relieve this water shortage, to a certain degree, is to maximize the use of runoff water from outcrops. At the study site, roots in areas close to rock outcrops were much more developed and the biomass of aboveground vegetation was also much higher, implying that the runoff from outcrops could be a substantial supplement of water and nutrients to nearby plants, as
also suggested by Conn and Snyder-Conn (1981) and Goransson et al. (2014). Shen et al. (2019) recently quantified the water supply capacity of outcrops and found multifold differences among different ecosystems in semihumid southern China. However, regardless of how much water is exported, the involvement of roots in preferential flow at soil–rock interfaces (as demonstrated by the dye experiment) was evidence of the close ties between outcrops and nearby plants. Therefore, the patchwork of infiltration and runoff may contribute to the heterogeneity of the microclimate and thus to the biodiversity in karst areas, depending on the closeness of the relation. The relation between outcrops and nearby plants (as well as soil fauna) needs to be evaluated further to increase understanding of the complex ecohydrological processes and to improve the karst ecosystem environment.

4.4 Limitations of the research

The microplot study revealed preferential flow was an important hydrological process affecting the soil water infiltrability in the rocky environment. However, the characteristics of the preferential pathways, such as tortuosity, continuity, and degree of branching, remain largely unknown. With this type of valuable information, the rapid penetration mechanisms could be described and the actual recharge rates on a typical karst hill slope could be predicted. Although dye tracing experiments are useful to study the infiltration pattern of water, the direct application of dye to the outcrops may result in the increased involvement of the soil–rock interface in solute transport. Additionally, although all of the above-mentioned pathways increased water infiltrability, the relative flux along individual structures is difficult to measure, and the preferential pathways may vary on different parts of a hill slope because of the importance of soil properties and topography in shaping infiltration–runoff processes. Therefore, future research needs to be scaled up to complement these findings and to build a model for the connection between surface cover and water flow behavior.

5 CONCLUSIONS

Rock outcrops are widespread across the surface of the earth. The results of this study indicate that the emergence of outcrops on the land surface improved soil physical properties, with higher $K$ values, moisture content, and porosity in the soils surrounding outcrops. The dye-stained soil profiles showed differences in the infiltration pattern and preferential pathways between the RP and the NRP. Contrasting with the homogeneous infiltration in the NRP, preferential flow at the soil–rock interface was the main water movement type in the RP, leading to deep infiltration of the runoff from rock surfaces into the ground. Furthermore, due to the root growth and fauna activity in soil surrounding outcrops, outcrop-induced preferential flow was also connected to the conduits formed by these biological factors. Thus, this study demonstrated that rock outcrops, by improving soil properties and building a well-connected preferential flow network, can greatly change infiltrability and water flow behavior in karst soil, and
further research should be conducted on their hydrological functions.

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REFERENCES

Abrahams, A. D., & Parsons, A. J. (1991). Relation between infiltration and stone cover on a semiarid hillslope, southern Arizona. *Journal of Hydrology, 122*, 49–59. https://doi.org/10.1016/0022-1694(91)90171-D

Adamcova, R., Ottner, F., Durn, G., Greifeneder, S., Dananaj, I., Dubikova, M., … Kapelj, S. (2005). Problems of hydraulic conductivity estimation in clayey karst soils. *Geologia Croatica, 58*, 195–203.

Alakukku, L., Nuutinen, V., Ketoja, E., Knivusalo, H., & Paasonen-Kivekäs, M. (2010). Soil macroporosity in relation to subsurface drain location on a sloping clay field in humid climatic conditions. *Soil & Tillage Research, 106*, 275–284. https://doi.org/10.1016/j.still.2009.11.002

Alaoui, A., Caduff, U., Gerke, H. H., & Weingartner, R. (2011). A preferential flow effects on infiltration and runoff in grassland and forest soils. *Vadose Zone Journal, 10*, 367–377. https://doi.org/10.2136/vzj2010.0076

Allaire, S. E., Roulier, S., & Cessna, A. J. (2009). Quantifying preferential flow in soils: A review of different techniques. *Journal of Hydrology, 378*, 179–204. https://doi.org/10.1016/j.jhydrol.2009.08.013

Archer, N. A. L., Quinton, J. N., & Hess, T. M. (2002). Below-ground relationships of soil texture, roots and hydraulic conductivity in two-phase mosaic vegetation in South-east Spain. *Journal of Arid Environments, 52*, 535–553. https://doi.org/10.1016/j.jaridenv.2002.10.011

Barzegar, A. R., Yousefi, A., & Daryashenas, A. (2002). The effect of addition of different amounts and types of organic materials on soil physical properties and yield of wheat. *Plant and Soil, 247*, 295–301. https://doi.org/10.1023/A:1021561628045

Benegas, L., Ilstedt, U., Rouparsd, O., Jones, J., & Malmer, A. (2014). Effects of trees on infiltrability and preferential flow in two contrasting agroecosystems in central America. *Agriculture, Ecosystems & Environment, 183*, 185–196. https://doi.org/10.1016/j.agee.2013.10.027

Bergkamp, G. (1998). A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. *Catena, 33*, 201–220. https://doi.org/10.1016/S0341-8162(98)00092-7

Beven, K. J., & Germann, P. (1982). Macropores and water flow in soils. *Water Resources Research, 18*, 1311–1325. https://doi.org/10.1029/WR018i005p01311

Blevins, R. L., Holowaychuk, N., & Wilding, L. P. (1970). Micro-morphology of soil fabric at tree root-soil interface. *Soil Science Society of America Journal, 34*, 460–465. https://doi.org/10.2136/sssaj1970.036159950034000301x

Bockgard, N., & Niemi, A. (2004). Role of rock heterogeneity on lateral diversion of water flow at the soil-rock interface. *Vadose Zone Journal, 3*, 786–795. https://doi.org/10.2136/vzj2004.0786

Boix, C., Calvo, A., Imeson, A. C., Schoorl, J. M., Soto, S., & Tiemessen, I. R. (1995). Properties and erosional response of soils in a degraded ecosystem in Crete (Greece). *Environmental Monitoring and Assessment, 37*, 79–92. https://doi.org/10.1007/BF00546881

Bond, R. D. (1964). The influence of the microflora on the physical properties of soils. II. Field studies on water repellent sands. *Soil Research, 2*, 123–131. https://doi.org/10.1017/SR9640123

Bond, R. D., & Harris, J. R. (1964). The influence of the microflora on the physical properties of soils. I. Effects associated with filamentous algae and fungi. *Soil Research, 2*, 111–122. https://doi.org/10.1017/SR9640111

Bonell, M., Purandara, B. K., Venkatesh, B., Krishnaswamy, J., Acharya, H. A. K., Singh, U. V., … Chappell, N. (2010). The impact of forest use and reforestation on soil hydraulic conductivity in the western Ghats of India: Implications for surface and sub-surface hydrology. *Journal of Hydrology, 391*, 47–62. https://doi.org/10.1016/j.jhydrol.2010.07.004

Bouma, J., & Dekker, L. W. (1978). A case study on infiltration into dry clay soil. I. Morphological observations. *Geoderma, 20*, 27–40. https://doi.org/10.1016/0016-7061(78)90047-2

Bowmer, K. H. (1987). Nutrient removal from effluents by an artificial wetland: Influence of rhizosphere aeration and preferential flow studied using bromide and dye tracers. *Water Research, 21*, 591–599. https://doi.org/10.1016/0043-1354(87)90068-6

Calvo-Cases, A., Boix-Fayos, C., & Imeson, A. (2003). Runoff generation, sediment movement and soil water behaviour on calcareous (limestone) slopes of some Mediterranean environments in SE Spain. *Geomorphology, 50*, 269–291. https://doi.org/10.1016/S0169-555X(02)00218-0

Castellano, M. J., & Valone, T. J. (2007). Livestock, soil compaction and water infiltration rate: Evaluating a potential desertification recovery mechanism. *Journal of Arid Environments, 71*, 97–108. https://doi.org/10.1016/j.jaridenv.2007.03.009

Cantón, Y., Solé-Benet, A., de Vente, J., Boix-Fayos, C., Calvo-Cases, A., Asensio, C., & Puigdefábregas, J. (2011). A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain. *Journal of Arid Environments, 75*, 1254–1261. https://doi.org/10.1016/j.jaridenv.2011.03.004

Cerdà, A. (1996). Seasonal variability of infiltration rates under contrasting slope conditions in southeast Spain. *Geoderma, 69*, 217–232. https://doi.org/10.1016/0016-7061(95)00062-3

Cerdà, A. (1997). The effect of patchy distribution of Stipa tenacissima L. on runoff and erosion. *Journal of Arid Environments, 36*, 37–51. https://doi.org/10.1006/jare.1995.0198

Cerdà, A. (1998). The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a Mediterranean hillslope. *Hydrological Processes, 12*, 661–667. https://doi.org/10.1002/(SICI)1099-1085(19980330)12:4<661::AID-HYP607>3.0.CO;2-7

Chandler, K. R., & Chappell, N. A. (2008). Influence of individual oak (Quercus robur) trees on saturated hydraulic conductivity. *Forest Ecology and Management, 256*, 1222–1229. https://doi.org/10.1016/j.foreco.2008.06.033
Conn, J. S., & Snyder-Conn, E. K. (1981). The relationship of the rock outcrop microhabitat to germination, water relations, and pheno-logy of Erythrina flabelliformis (Fabaceae) in Southern Arizona. South-western Naturalist, 25, 243–251. https://doi.org/10.2307/3670843

Cooley, T. (2002). Geological and geotechnical context of cover collapse and subsidence in mid-continent US clay-mantled karst. Environmental Geology, 42, 469–475. https://doi.org/10.1007/s00254-001-0507-6

Crowther, J. (1982). Ecological observations in a tropical karst terrain, west Malaysia. I. Variations in topography, soils and vegetation. Journal of Biogeography, 9, 65–78. https://doi.org/10.2307/2844731

Czarnes, S., Hallett, P. D., Bengough, A. G., & Young, I. M. (2000). Root- and microbial-derived mucilages affect soil structure and water transport. European Journal of Soil Science, 51, 435–443. https://doi.org/10.1046/j.1365-2389.2000.00327.x

Dadkhah, M., & Gifford, G. F. (1980). Influence of vegetation, rock cover, and trampling on infiltration rates and sediment production. Journal of the American Water Resources Association, 16, 979–986. https://doi.org/10.1111/j.1752-1688.1980.tb02537.x

Danielson, R. E., & Sutherland, P. L. (1986). Porosity. In: A. Klute (Ed.), Methods of soil analysis. Part I. Physical and mineralogical methods (Agronomy Monograph No. 9, pp. 443–461). Madison, WI: ASA and SSSA. https://doi.org/10.2136/sssabookser5.1.2ed.c18

Dasgupta, S., Mohanty, B. P., & Köhne, J. M. (2006). Impacts of juniper vegetation and karst geology on subsurface flow processes in the Edwards Plateau, Texas. Vadose Zone Journal, 5, 1076–1085. https://doi.org/10.2136/vzj2005.0073

de Lima, J. L. M. P., & Singh, V. P. (2002). The influence of the pattern of moving rainstorms on overland flow. Advances in Water Resources, 25, 817–828. https://doi.org/10.1016/S0309-1708(02)00067-2

de Rooij, G. H. (2000). Modeling fingered flow of water in soils owing to wetting front instability: A review. Journal of Hydrology, 231, 277–294. https://doi.org/10.1006/jhyc.2000.0201-8

Descroix, L., Viramontes, D., Vauclin, M., Gonzalez Barrios, J. L., & Esteves, M. (2001). Influence of soil surface features and vegetation on runoff and erosion in the western Sierra Madre (Durango, Northwest Mexico). Catena, 43, 115–135. https://doi.org/10.1016/S0341-8162(00)00124-7

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks: A meta-analysis. Global Change Biology, 17, 1658–1670. https://doi.org/10.1111/j.1365-2486.2010.02336.x

Edwards, W. M., Shipitalo, M. J., Owens, L. B., & Norton, L. D. (1989). Water and nitrate movement in earthworm burrows within long-term no-till cornfields. Journal of Soil and Water Conservation, 44, 240–243.

Edwards, W. M., Shipitalo, M. J., Owens, L. B., & Dick, W. A. (1993). Factors affecting preferential flow of water and atrazine through earthworm burrows under continuous no-till corn. Journal of Environmental Quality, 22, 453–457. https://doi.org/10.2134/jeq1993.00472425002200030008x

Fleischner, T. L. (1994). Ecological costs of livestock grazing in western North America. Conservation Biology, 8, 629–644. https://doi.org/10.1046/j.1523-1739.1994.08030629.x

Flury, M., & Flühler, H. (1994). Brilliant blue FCF as a dye tracer for solute transport studies: A toxicological overview. Journal of Environmental Quality, 23, 1108–1112. https://doi.org/10.2134/jeq1994.00472425002300050037x

Flury, M., & Flühler, H. (1995). Tracer characteristics of brilliant blue FCF. Soil Science Society of America Journal, 59, 22–27. https://doi.org/10.2136/sssaj1995.03615995005900010003x

Ford, D., & Williams, P. W. (2007). Karst hydrogeology and geomorphology. Chichester, UK: John Wiley & Sons.

Fu, T. G., Chen, H. S., Zhang, W., Nie, Y. P., Gao, P., & Wang, K. L. (2015). Spatial variability of surface soil saturated hydraulic conductivity in a small karst catchment of Southwest China. Environmental Earth Sciences, 74, 2381–2391. https://doi.org/10.1007/s12665-015-4238-5

Ghodrati, M., & Jury, W. A. (1990). A field study using dyes to characterize preferential flow of water. Soil Science Society of America Journal, 54, 1558–1563. https://doi.org/10.2136/sssaj1990.03615995005400060008x

Gish, T. J., Gimenes, D., & Rawls, W. J. (1998). Impact of roots on ground water quality. Plant and Soil, 200, 47–54. https://doi.org/10.1023/A:1004202103802

Gish, T. J., & Jury, W. A. (1983). Effect of plant roots and root channels on solute transport. Transactions of the ASAE, 26, 440–444. https://doi.org/10.13031/2033.33955

Goransson, H., Edwards, P. J., Perreijn, K., Smittgen, R. H., & Venterink, H. O. (2014). Rocks create nitrogen hotspots and N:P heterogeneity by funneling rain. Biogeochemistry, 121, 329–338. https://doi.org/10.1007/s10533-014-0031-x

Gregory, L., Wilcox, B. P., Shade, B., Munster, C., Owens, K., & Veni, G. (2009). Large-scale rainfall simulation over shallow caves on karst shrublands. Ecohydrology, 2, 72–80. https://doi.org/10.1002/eco.41

Hanson, D., Steenhuis, T. S., Walter, M. F., & Boll, J. (2004). Effects of soil degradation and management practices on the surface water dynamics in the Talgua River watershed in Honduras. Land Degradation & Development, 15, 367–381. https://doi.org/10.1002/ldr.603

Hartemink, A. E., Veldkamp, T., & Bai, Z. (2008). Land cover change and soil fertility decline in tropical regions. Turkish Journal of Agriculture and Forestry, 32, 195–213.

Hillel, D. (1987). Unstable flow in layered soils: A review. Hydrological Processes, 1, 143–147. https://doi.org/10.1002/hyp.3360010203

Jamieson, R. C., Gordon, R. J., Sharples, K. E., Stratton, G. W., & Madani, A. (2002). Movement and persistence of faecal bacteria in agricultural soils and subsurface drainage water: A review. Canadian Biosystems Engineering, 44, 1.1–1.9.

Jarvis, N., Koestel, J., & Larsbo, M. (2016). Understanding preferential flow in the vadose zone: Recent advances and future prospects. Vadose Zone Journal, 15(12). https://doi.org/10.2136/vzj2016.09.0075

Jiang, X. J., Liu, W. J., Chen, C. F., Liu, J. Q., Yuan, Z. Q., Jin, B. C., & Yu, X. Y. (2018). Effects of three morphometric features of roots on soil water flow behavior in three sites in China. Geoderma, 320, 161–171. https://doi.org/10.1016/j.geoderma.2018.01.035

Jiang, X. J., Liu, W. J., Wang, E. H., Zhou, T. Z., & Xin, P. (2017). Residual plastic mulch fragments effects on soil physical properties and water flow behavior in the Minqin Oasis, northwestern China. Soil & Tillage Research, 166, 100–107. https://doi.org/10.1016/j.still.2016.10.011
Johnson, M. S., & Lehmann, J. (2006). Double-funneling of trees: Stem flow and root-induced preferential flow. *Ecoscience*, 13, 324–333. https://doi.org/10.2980/11195-6860-13-3-324.1

Khan, S., Hanjra, M. A., & Mu, J. X. (2009). Water management and crop production for food security in China: A review. *Agricultural Water Management*, 96, 349–360. https://doi.org/10.1016/j.agwat.2008.09.022

Kinnell, P. I. A. (2005). Raindrop-impact-induced erosion processes and prediction: A review. *Hydrological Processes*, 19, 2815–2844. https://doi.org/10.1002/hyp.5788

Kodešová, R., Němeček, K., Kodeš, V., & Žigová, A. (2012). Using dye tracer for visualization of preferential flow at macro- and microscales. *Vadose Zone Journal*, 11, 12–22. https://doi.org/10.2136/vzj2011.0088

Lado, M., Paz, A., & Ben-Hur, M. (2004). Organic matter and aggregate-size interactions in saturated hydraulic conductivity. *Soil Science Society of America Journal*, 68, 234–242. https://doi.org/10.2136/sssaj2004.2340

Laine-Kaulio, H., Backnas, S., Koivusalo, H., & Lauren, A. (2015). Dye tracer visualization of flow patterns and pathways in glacial sandy till at a boreal forest hillslope. *Geoderma*, 259–260, 23–34. https://doi.org/10.1016/j.geoderma.2015.05.004

Lange, J., Greenbaum, N., Husary, S., Ghanem, M., Leibundgut, C., & Schick, A. P. (2003). Runoff generation from successive simulated rainfalls on a rocky, semi-arid Mediterranean hillslope. *Hydrological Processes*, 17, 279–296. https://doi.org/10.1002/hyp.1124

Lavee, H., Ineson, A. C., Pariente, S., & Benyamini, Y. (1991). The response of soils to simulated rainfall along a climatological gradient in an arid and semi-arid region. In H. R. Bork, J. de Ploey, & A. P. Schick (Eds.), *Erosion, transport and deposition processes: Theories and models* (Catena Supplement 19, pp. 19–37). Stuttgart, Germany: Catena.

Lawes, J. B., Gilbert, J. H., & Warington, R. (1882). Macropores and water flow in soils. *Royal Agricultural Society of England*, 17, 241–279.

Mayor, A. G., Bautista, S., & Bellot, J. (2009). Factors and interactions controlling infiltration, runoff, and soil loss at the macroscale in a patchy Mediterranean semiarid landscape. *Earth Surface Processes and Landforms*, 34, 1702–1711. https://doi.org/10.1002/esp.1875

McGarry, D., Bridge, B. J., & Radford, B. J. (2000). Contrasting soil physical properties after zero and traditional tillage of an alluvial soil. *Soil Science Society of America Journal*, 64, 125–131. https://doi.org/10.2136/sssaj2002.1501

Michaëlies, K., Lister, D., Wainwright, J. L., & Parsons, A. J. (2009). Vegetation controls on small-scale runoff and erosion dynamics in a degrading dryland environment. *Hydrological Processes*, 23, 1617–1630. https://doi.org/10.1002/hyp.7293

Mitchell, W. T. (1995). *Picture theory: Essays on verbal & visual representation*. Chicago: University of Chicago Press.

Moody, J. A., & Martin, D. A. (2009). Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. *International Journal of Wildland Fire*, 18, 96–115. https://doi.org/10.1071/WF07162

Morin, J., Keren, R., Benjamiini, Y., Ben-Hur, M., & Shainberg, I. (1989). Water infiltration as affected by soil crust and moisture profile. *Soil Science*, 148, 53–59.

Mwendera, E. J., & Saleem, M. A. M. (1997). Infiltration rates, surface runoff, and soil loss as influenced by grazing pressure in the Ethiopian highlands. *Soil Use and Management*, 13, 29–35. https://doi.org/10.1111/j.1475-2743.1997.tb00553.x

Nearing, M. A., & Bradford, J. M. (1985). Single waterdrop splash detachment and mechanical properties of soils. *Soil Science Society of America Journal*, 49, 547–552. https://doi.org/10.2136/sssaj1985.0361599500490003003x

Richter, D. D., & Markewitz, D. (2001). Long-term soil potassium availability from a Kanapludult to an aggrading loblolly pine ecosystem. *Forest Ecology and Management*, 130, 109–129. https://doi.org/10.1016/S0378-1127(99)00175-9

Poesen, J., Ingelmo-Sanchez, F., & Mucher, H. (1990). The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. *Earth Surface Processes and Landforms*, 15, 653–671. https://doi.org/10.1002/esp.3290150707

Ries, F., Lange, J., Schmidt, S., Pühlmann, H., & Sauter, M. (2015). Recharge estimation and soil moisture dynamics in a Mediterranean, semi-arid karst region. *Hydrology and Earth System Sciences*, 19, 1439–1456. https://doi.org/10.5194/hess-19-1439-2015

Ruiz Sinoga, J. D., & Martinez Murillo, J. F. (2009). Hydrological response of abandoned agricultural soils along a climatological gradient on metamorphic parent material in southern Spain. *Earth Surface Processes and Landforms*, 34, 2047–2056. https://doi.org/10.1002/esp.1890

Schwen, A., Zimmermann, M., & Bodner, G. (2014). Vertical variabilities of soil hydraulic properties within two soil profiles and its relevance for soil water simulations. *Journal of Hydrology*, 156, 169–181. https://doi.org/10.1016/j.jhydrol.2014.01.042

Schwinning, S. (2010). The ecohydrology of roots in rocks. *Ecohydrology*, 3, 238–245. https://doi.org/10.1002/eco.134

Seeger, M. (2007). Uncertainty of factors determining runoff and erosion processes as quantified by rainfall simulations. *Catena*, 71, 56–67. https://doi.org/10.1016/j.catena.2006.10.005

Shen, Y. X., Wang, D. J., Chen, Q. Q., Tang, Y. Y., & Chen, F. J. (2019). Large heterogeneity of water and nutrient supply derived from runoff of nearby rock outcrops in karst ecosystems in SW China. *Catena*, 172, 125–131. https://doi.org/10.1016/j.catena.2018.08.020

Sohrt, J., Ries, F., Sauter, M., & Lange, J. (2014). Significance of preferential flow at the rock soil interface in a semi-arid karst environment. *Catena*, 123, 1–10. https://doi.org/10.1016/j.catena.2014.07.003

Solé-Benet, A., Calvo, A., Cerdà, A., Lázaro, R., Pini, R., & Barbero, J. (1997). Influences of micro-relief patterns and plant cover on runoff related processes in badlands from Tabernas (SE Spain). *Catena*, 31, 23–38. https://doi.org/10.1016/S0341-8162(97)00032-5

Solomon, D., Lehmann, J., & Zech, W. (2000). Land use effects on soil organic matter properties of chromic Luvisols in semi-arid northern Tanzania: Carbon, nitrogen, lignin, and carbohydrates. *Agroecology Ecosystems & Environment*, 78, 203–213. https://doi.org/10.1016/S0167-8809(99)00126-7

Steenhuis, T. S., & Muck, R. E. (1988). Preferred movement of nonadsorbed chemicals on wet, shallow, sloping soils. *In T.J. Gish & A. Shirmohammadi (Eds.), Preference of Environmental Quality, 17, 376–384. https://doi.org/10.2134/jeq1988.00472425001700030006x

Steenhuis, T. S., & Parlane, J. Y. (1991). Preferential flow in structured and sandy soils. In T.J. Gish & A. Shirmohammadi (Eds.), *Preferential flow. Proceedings of the national symposium* (pp. 12–21). St. Joseph, MI: American Society of Association Executives.
Tarfadar, J. C., & Jungk, A. (1987). Phosphatase activity in the rhizosphere and its relation to the depletion of soil organic phosphorus. *Biology and Fertility of Soils, 3*, 199–204. https://doi.org/10.1007/BF00460630

van Schaik, N. (2009). Spatial variability of infiltration patterns related to site characteristics in a semi-arid watershed. *Catena, 78*, 36–47. https://doi.org/10.1016/j.catena.2009.02.017

Verbist, K., Cornelis, W. M., Schiettecatte, W., Oltenfreiter, G., Van Meirvenne, M., & Gabriels, D. (2007). The influence of a compacted plow sole on saturation excess runoff. *Soil & Tillage Research, 96*, 292–302. https://doi.org/10.1016/j.still.2007.07.002

Wang, D. J., Shen, Y. X., Huang, J., & Li, Y. H. (2016). Rock outcrops redistribute water to nearby soil patches in karst landscapes. *Environmental Science and Pollution Research, 23*, 8610–8616. https://doi.org/10.1007/s11356-016-6091-9

Ward, R. C., & Robinson, M. (1989). *Principles of hydrology*. London: Mc Graw-Hill.

Whalley, W. R., Leeds-Harrison, P. B., Leech, P. K., Risely, B., & Bird, N. R. A. (2004). The hydraulic properties of soil at root–soil interface. *Soil Science, 169*, 90–99. https://doi.org/10.1097/01.ss.0000117790.98510.e6

Wilcox, B. P., Owens, M. K., Dugas, W. A., Ueckert, D. N., & Hart, C. R. (2006). Shrubs, stream flow, and the paradox of scale. *Hydrological Processes, 20*, 3245–3259. https://doi.org/10.1002/hyp.6330

Wilcox, B. P., Taucer, P. I., Munster, C. L., Owens, M. K., Mohanty, B. P., Sorenson, J. R., & Bazan, R. (2008). Subsurface storm flow is important in semiarid karst shrublands. *Geophysical Research Letters, 35*(10). https://doi.org/10.1029/2008GL033696

Wilcox, B. P., Wood, M. K., & Tromble, J. M. (1988). Factors influencing infiltrability of semiarid mountain slopes. *Journal of Range Management, 41*, 197–206. https://doi.org/10.2307/3899167

Wilding, L. P., & Tessier, D. (1988). Genesis of Vertisols: Shrink-swell phenomena. In L.P. Wilding & R. Puentes (Eds.), *Vertisols: Their distribution, properties, classification and management* (pp. 55–82). College Station, TX: Texas A&M University.

Williams, P. W. (2008). The role of the epikarst in karst and cave hydrogeology: A review. *International Journal of Speleology, 37*, 1–10. http://doi.org/10.5038/1827-806X.37.1.1

Yair, A. (1983). Hillslope hydrology water harvesting and areal distribution of some ancient agricultural systems in the northern Negev Desert. *Journal of Arid Environments, 6*, 283–301. https://doi.org/10.1016/S0140-1963(83)31514-3

Yair, A. (1996). Spatial variability in runoff in semiarid and arid areas. In J. L. Rubio & A. Calvo (Eds.), *Soil degradation and desertification in Mediterranean environments* (pp. 71–90). Logroño, Spain: Geoflora.

Yair, A., & Lahee, H. (1985). Runoff generation in arid and semi-arid zones. In M. G. Anderson & T.P. Burt (Eds.), *Hydrological forecasting* (pp. 183–220). New York: John Wiley and Sons.

Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal, 61*, 1024–1030. https://doi.org/10.2136/ssaj1997.03615995006100040005x

Zhao, Z. M., Shen, Y. X., Shan, Z. J., Yu, Y., & Zhao, G. J. (2018). Infiltration patterns and ecological function of outcrop runoff in epikarst areas of southern China. *Vadose Zone Journal*. 17(1). https://doi.org/10.2136/vzj2017.11.0197

Zhu, X. A., Chen, C. F., Wu, J. N., Yang, J. B., Zhang, W. J., Zou, X., … Jiang, X. J. (2019). Can intercrops improve soil water infiltrability and preferential flow in rubber-based agroforestry system? *Soil & Tillage Research, 191*, 327–339. https://doi.org/10.1016/j.still.2019.04.017

Ziegler, A., Negishi, J. N., Sidle, R. C., Noguchi, S., & Nik, A. R. (2006). Impacts of logging disturbance on hillslope saturated hydraulic conductivity in a tropical forest in peninsular Malaysia. *Catena, 67*, 89–104. https://doi.org/10.1016/j.catena.2006.02.008

Zwieniecki, M. A., & Newton, M. (1996). Seasonal pattern of water depletion from soil–rock profiles in a Mediterranean climate in southwestern Oregon. *Canadian Journal of Forest Research, 26*, 1346–1352. https://doi.org/10.1139/x96-150

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