ORIGINAL ARTICLE

Soil hydraulic properties on the steep karst hillslopes in northwest Guangxi, China

Hongsong Chen · Jianwei Liu · Wei Zhang · Kelin Wang

Abstract Soil hydraulic properties such as soil infiltration rate and hydraulic conductivity are closely linked to runoff generation and infiltration processes but little is known about them on karst hillslopes. The objectives of this paper were to investigate the change in soil stable infiltration rate (q_s) and near-saturated hydraulic conductivity (K_{ns}) in different slope positions and to understand their relationship with rock fragment content and soil texture within the topsoil in subtropical karst regions of southwest China. Tension infiltrometers (20 cm in diameter) were used to measure q_s and K_{ns} at pressure head of -20 mm on hillslopes 1 (a disintegrated landslide failure) and 2 (an avalanche slope). The change of q_s and K_{ns} was great and they mostly had a moderate variability with coefficient of variations (CV) between 0.1 and 1.0 in the different slope positions. On average, q_s ranged from 0.43 to 4.25 mm/min and K_{ns} varied from 0.75 to 11.00 mm/min. These rates exceed those of most natural rainfall events, confirming that overland flow is rare on karst hillslopes. From bottom to top, q_s and K_{ns} had a decrease–increase–decrease trend due to the presence of large rock outcrops (>2 m in height) on hillslope 1 but had an increasing trend on hillslope 2 with less complex landform. They tended to increase with increase in total rock fragment content (5–250 mm) within the topsoil as well as slope gradient on both hillslopes. Pearson correlation analysis suggested that higher coarse pebble (20–75 mm), cobble (75–250 mm), and sand (2–0.05 mm) contents as well as total rock fragment content could significantly facilitate water infiltration into soils, but higher clay (<0.002 mm) content could restrict water movement. This result indicated that rock fragment, sand, and clay contents may remarkably affect water flow in the topsoil layers, and should be considered in hydrological modeling on karst hillslopes in subtropical regions.

Keywords Soil hydraulic properties · Hillslope · Karst region · Rock fragment content · Slope gradient

Introduction

Soil hydraulic properties such as soil infiltration rate and hydraulic conductivity play a key role in controlling the processes of infiltration and runoff generation. In most stony mountain areas, soil surface and topsoil are generally characterized by the presence of rock fragments. Rock fragments often refer to all mineral particles >5 mm in diameter because they are considered to behave as relatively immobile particles and not easily transported by interrill flow (Poesen et al. 1998). Rock fragments at the soil surface and within the topsoil are closely linked to various hydrological and geomorphic processes and may influence soil hydraulic properties which in turn will affect the amount, distribution, and routing of overland flow (Poesen and Ingelmo-Sanchez 1992; Brakensiek and Rawls 1994; Poesen and Lavee 1994; Sauer and Logsdon 2002; Cousin et al. 2003). However, many studies are mainly

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concerned with the effects of land use, vegetation, rock fragments, and topography on runoff and infiltration, but less attention has been paid to soil hydraulic properties (Cerdà 2001; Wei et al. 2007; Li et al. 2008; Garcia-Estringana et al. 2010). Vegetation generally decreases overland flow and increases infiltration. Steep slopes usually tend to generate more runoff than gentle slopes. However, rock fragments have an ambivalent effect on overland flow and infiltration rate, which depends on their position, size, and cover as well as structure of the fine earth (Poesen and Ingelmo-Sanchez 1992; Brakensiek and Rawls 1994; Poesen and Lavee 1994; Cerdà 2001; Cousin et al. 2003). When free on the soil surface, rock fragments generally prevent the soil from sealing and the infiltration rate increases, but embedded in the surface, they participate in the establishment of a continuous crust inhibiting infiltration and reinforcing runoff (Poesen and Lavee 1994; Cousin et al. 2003). Soils with similar rock fragment content are often found to have disparate infiltration rates and hydraulic conductivity values, and source of the rock fragments and adhesion with the surrounding fine-earth fraction are suggested to influence water flow by affecting hydraulic continuity on fragment surfaces (Sauer and Logsdon 2002). Therefore, to investigate soil hydraulic properties and their relationship with rock fragments and fine-earth fraction it is important for us to have a better understanding about runoff generation mechanisms at hillslope and small catchment scales.

Surface vegetation or rock fragment cover can affect runoff either by altering surface characteristics (e.g., surface roughness, litter absorption) or subsurface characteristics (e.g., hydraulic conductivity) (Abrahams and Parsons 1991; Wilcox et al. 2003; Li et al. 2008). Rock fragment content within the topsoil also has a close relationship with soil hydraulic properties as well as infiltration and runoff generation (Mehuys et al. 1975; Poesen and Lavee 1994; Sauer and Logsdon 2002; Cousin et al. 2003; Verbist et al. 2009). However, most of the studies dealing with infiltration in soils containing rock fragments were restricted to semiarid and arid or Mediterranean zones. The spatial variability of soil hydraulic properties under near-saturated conditions has been widely investigated using a disc infiltrometer, for its suitability not only in saturated but also in unsaturated conditions, as well as its water-saving and easiness to move (Mohanty et al. 1994; Logsdon and Jaynes 1996; Sauer and Logsdon 2002; Hu et al. 2008; Li et al. 2008; Caputo et al. 2010). Li et al. (2008) indicated that soil hydraulic conductivity may be one of the determining factors for high infiltration rates on vegetated surfaces, and runoff and infiltration behavior of the rock fragment-covered surfaces may be mainly influenced by surface rock fragment mulching itself instead of subsurface soil hydraulic conductivity in the limestone dolines of

southeastern Spain. According to Mehuys et al. (1975), embedded rock fragments reduce the soil's porosity and increase the tortuosity of water flow paths, restricting overall water movement. However, Sauer and Logsdon (2002) observed slightly positive (not distinct) relations between rock fragment content and soil hydraulic properties, and the fine-earth fraction provided hydraulic connection between and around nonporous rocks in a small limestone watershed of northwestern Arkansas, USA. One of the reasons may be that rock fragment content not only increased tortuosity, but also created new voids, thereby positively influencing infiltration rates (Ravina and Magier 1984). Verbist et al. (2009) discovered that rock fragment content correlated significantly with both saturated and unsaturated conductivities, probably due to a positive correlation between rock fragment content and coarse lacunar pore space. They concluded that rock fragment content was possibly the most important factor influencing infiltration rates in the soils with small textural differences. Therefore, soil hydraulic properties and their relationship with rock fragment content and fine-earth fraction are complex and still unclear.

In karst environments, soils are often thin and rocky, and solution-enlarged fissures, gaps, and channels in the underlying bedrock facilitate the rapid transport of surface water to groundwater (Williams 1983; White 2002; Wilcox et al. 2008). Compared with other regions, the high spatial variability of the vegetation and rock fragment cover, the underlying stony soils, and the parent materials in subtropical regions may result in significant differences in soil hydraulic properties. The objectives of this study were to investigate the change in soil stable infiltration rate (q_s) and near-saturated hydraulic conductivity (K_{ns}) in different slope positions with the disc infiltrometer and to understand their relationship with rock fragment content and soil texture within the topsoil on steep hillslopes in karst regions of southwest China.

Materials and methods

Site description

The study was conducted at the Huanjiang Observation and Research Station for Karst Ecosystems under the Chinese Academy of Sciences (24°43′–24°44′N, 108°18′–108°19′E) in Huanjiang County of northwest Guangxi, southwest China. The experimental site is a typical peak-cluster depression area with a subtropical mountainous monsoon climate. The mean annual temperature is 19°C, and the mean annual precipitation is 1389 mm, mostly falling from May to September. This area has about 146-hm^2 lands with an elevation mainly ranging from 272

to 647 m above sea level, and about 60% of slope land has a slope gradient larger than 25°. The cover of exposed bedrock is 15% on average in the depression and about 30% on hillslopes, and the relative soil depth is 20–160 cm and 10–50 cm, respectively. Some rock outcrops containing many fissures are large (2–10 m in height) and they are covered mostly by deep-rooted trees. The shallow and discontinuous soils have been developed from dolostone and contain significant amounts of rock fragments (Chen et al. 2011).

All residents have moved away and the cultivated lands have been abandoned since 1985. Most common land uses are grassland and sparse scrubland as fire and grazing often occur in this area. However, there are zonal dense scrubland and forestland in patches with high cover of exposed bedrock. Overland flow is rare and the corresponding runoff coefficient is often <5% on the hillslopes under various land use types. However, there is a small stream flowing from the southwest into the reservoir in the northeast, and soils are often saturated in the depression in the southwest parts. Due to more than 20 years of vegetation restoration, seepage springs sometimes appear at the bottom of hillslopes in the rainy season. The groundwater table fluctuates and is often below 1–3 m depth in the depression.

Measurements and data analysis

Infiltration measurements were conducted at the soil surface in the different topographic positions of two representative southeast-facing hillslopes 1 and 2. From bottom to top, hillslope 1 (a disintegrated landslide failure) with complex landform was divided into seven segments (bottom, lower, lower-middle, middle, upper-middle, upper, and top), and hillslope 2 (an avalanche slope) with relatively simple landform was five segments (bottom, lower, middle, upper, and top) based on slope gradient and vegetation condition (Fig. 1). The detailed descriptions of landform and vegetation of the two hillslopes and measurements of rock fragments refer to Chen et al. (2011). According to the landform and vegetation, five sites (four corners and the center) within a 10 by 10 m area were chosen in each segment on hillslope 1, but five sites were subdivided longitudinally in the first segment at the bottom and three sites in the other four segments on hillslope 2. Vegetation was cut away from the soil surface and slope gradient was measured in each site. All rock fragments (>5 mm) lying on the soil surface, or with <50% of its volume embedded in the topsoil, were moved away after rock fragment cover at the soil surface was investigated by digital photographs and processing techniques. Subsequently, a pit of 0.5 × 0.5 m and 1 × 2–3 m was dug out at shallow depths of 10–20 cm and nonporous rock

fragments (5–20, 20–75, 75–250, 250–600, and >600 mm) with an average density of 2,650 kg/m^3 were sorted by sieving and their contents were determined by weight in each site on hillslopes 1 and 2, respectively (Chen et al. 2011). Rock fragments (>5 mm) at the soil surface and within the topsoil and particle size distribution of the <2 mm fraction in the different segments on the two hillslopes are shown in Table 1. According to USDA classification, soil texture is clay from bottom to lower-middle and clay loam from upper-middle to top on hillslope 1, and it is clay except clay loam on the top on hillslope 2. The mean volumetric content of fine pebbles (2–5 mm) within the topsoil was small and it was 2.3% on hillslope 1 and 1.0% on hillslope 2. According to the mean volumetric contents of rock fragments within the topsoil, the dominant sizes were 5–20 and 20–75 mm on hillslopes 1 and 2.

Infiltration measurements with five replications were made with a 20-cm diameter tension infiltrometer at pressure head of −20 mm near the sites for the measurement of rock fragment content in each segment on the two hillslopes. The infiltrometer used in the study was of the same design as described by Perroux and White (1988). K_{ns} and q_s were determined from the calculated sorptivity and
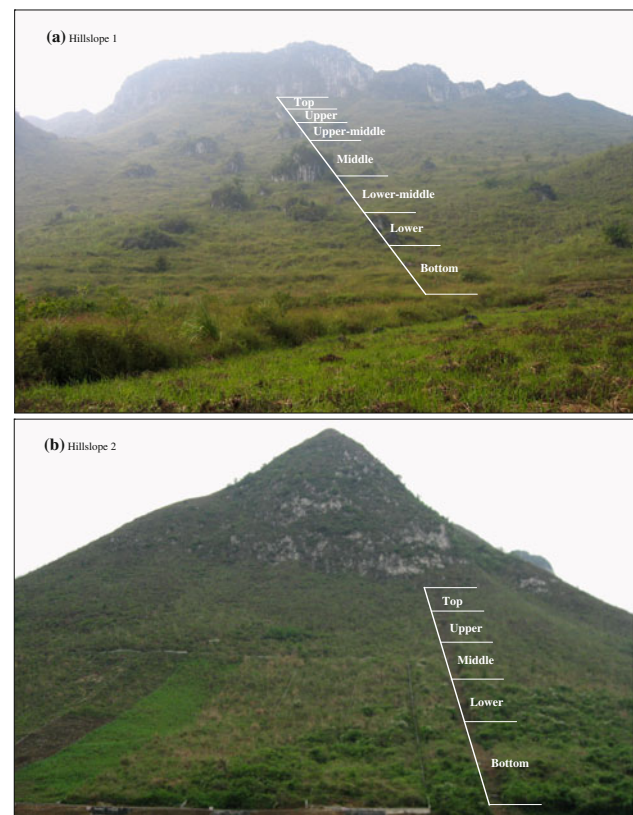

Fig. 1 View on the study hillslopes **a** 1 and **b** 2 (after Chen et al. 2011). As shown are the different slope segments on the two hillslopes

Table 1 Selected soil surface properties on hillslopes 1 and 2 (after Chen et al. 2011)

Slope position	Length (m)	Gradient (°)	Soil depth (cm)[a]	Plant cover (%)	Rock fragment cover (%)[b]	Volumetric rock fragment content within the topsoil (%)[b]				Organic matter content (%)	Particle size composition USDA (%)		
						5–20 mm	20–75 mm	75–250 mm	5–250 mm		Sand	Silt	Clay
Hillslope 1													
Bottom	90.7	5–22	20–50	80–90	4.6	12.4	3.5	0.0	16.0	2.6	18.7	25.7	55.6
Lower	60.3	22–26	20–80	70–80	9.4	7.3	8.7	1.9	18.0	4.5	11.9	34.2	53.9
Lower-middle	59.0	18–26	10–24	60–80	12.1	1.4	2.2	0.8	4.5	4.6	11.3	31.9	56.8
Middle	40.0	18–31	8–65	50–60	4.0	9.6	4.7	2.6	17.0	3.0	12.4	28.2	59.4
Upper-middle	93.0	26–31	6–16	40–60	21.7	8.1	8.5	5.6	22.2	6.7	26.3	41.8	31.9
Upper	118.0	26–38	16–24	30–40	7.8	9.2	14.7	7.6	31.5	5.2	24.4	34.7	40.9
Top	80.3	36–38	14–20	30–40	10.4	13.8	13.5	11.4	38.7	4.9	15.6	49.0	35.5
Hillslope 2													
Bottom	112.3	10–25	10–18	80–90	5.1	3.0	5.0	1.5	9.6	5.4	7.7	39.5	52.8
Lower	79.0	18–26	15–20	80–90	4.5	7.6	4.9	0.4	13.0	4.1	8.2	32.3	59.5
Middle	72.0	18–31	11–31	70–80	7.4	5.5	13.4	3.3	22.2	4.7	18.8	29.4	51.8
Upper	61.0	26–30	12–26	40–60	12.9	9.3	10.1	5.2	24.5	4.0	10.8	32.5	56.6
Top	118.0	28–38	11–36	30–40	21.2	11.4	7.8	8.1	27.3	5.1	28.8	32.8	38.4

[a] Depth to bedrock or petrocalcic horizon

[b] Mean value in each segment on hillslopes 1 and 2

measured change in volumetric soil water content for the steady-state three-dimensional infiltration into dry soil according to the method of Wooding (1968) and White and Sully (1987). Measurements at each location were made in accordance with procedures outlined by White and Sully (1987) and Ankeny et al. (1991). Prior to infiltration measurements, vegetation was clipped to ground level, and litter and rock fragments at the soil surface were completely removed to expose the underlying soil. The soil was then carefully leveled with minimal disturbance to facilitate infiltration measurements while maintain the native pore structure (Li et al. 2008). At each location, a sharpened ring was inserted a few millimeters into the soil and a thin (3 mm) layer of pure fine sand (about 0.25 mm in diameter) was applied to the ground surface and leveled. Then the infiltrometer base was placed onto the sand surface with the pre-set pressure head (−20 mm). Infiltration was recorded after 15 s, and then 30 s, until steady-state flow conditions had been reached. After infiltration measurement was completed, sand was removed immediately and soil samples at 2–3 cm depth were collected to determine final gravimetric soil water content. Soil bulk density and initial gravimetric water content at 0–10 cm depth were determined from five undisturbed soil samples collected with 200 cm³ cutting ring (7 cm in diameter and 5.2 cm in height) near the infiltration measurement point before the infiltration measurement. The initial and final volumetric water content could be calculated based on the corresponding gravimetric water content and soil bulk density at each site.

Some main statistical parameters, including description of the mean, standard deviation (SD), coefficient of variation (CV), and extreme maximum (Max) and minimum (Min) values of q_s and K_{ns} on the two hillslopes, were analyzed and the results are shown in Tables 2 and 3, respectively. Mean comparisons were made using the least significant difference (LSD) method with $p < 0.05$. According to CV values of q_s and K_{ns} in each segment on hillslopes 1 and 2, their variation was often considered to be as follows: high ($CV \geq 100\%$), moderate ($10\% < CV < 100\%$), and small ($CV \leq 10\%$). The higher CV values of q_s and K_{ns} within the topsoil indicated that they had larger spatial variability on hillslope.

Results and discussion

The change of q_s in different slope positions

According to the process of water infiltration into the stony soils, a steady-state condition was achieved after about 10–30 min later on the two steep karst hillslopes. The initial infiltration rate reached 5–13 mm/min on hillslope 1

and 7–18 mm/min on hillslope 2, respectively. In the different slope positions of hillslopes 1 and 2, the change in q_s was great and it had a moderate variability except a small variability occurred at the top of hillslope 2 (Table 2). The maximum variability of q_s appeared in the middle (CV = 64.52%) and at the bottom (CV = 62.81%) of hillslope 1, and in the middle (CV = 47.75%) of hillslope 2, respectively. On hillslope 1, the highest value of q_s was 6.22 mm/min in the upper position, followed by 2.59 mm/min at the top, and the lowest value was 0.20 mm/min at the bottom, followed by 0.25 mm/min in the middle. However, on hillslope 2, the highest value of q_s was 3.79 mm/min at the top, followed by 2.21 mm/min in the middle, and the lowest value was 0.64 mm/min at the bottom. These rates exceed those of most natural rainfall events, confirming that surface runoff is rare on the karst hillslopes.

Based on the average value of q_s at each segment, the highest value was 4.25 mm/min in the upper position of hillslope 1 and 3.48 mm/min at the top of hillslope 2. The lowest value was 0.43 mm/min in the middle of hillslope 1 and 0.81 mm/min at the bottom of hillslope 2. From bottom to top, q_s had an increasing trend on hillslope 2, but it had a decrease–increase–decrease trend on hillslope 1 (Table 2). This may have a close relationship with the geomorphologic and hydro-geological conditions, vegetation cover and rock fragment content, and fine-earth

fraction within the topsoil at each location on hillslopes 1 and 2. Cerdà (1996) indicated that slope aspect, position, and vegetation cover determined q_s on hillslopes in southeast Spain. Dunkerley (2002) discovered that infiltration rates increased rapidly from the lowermost intergroove to reach maxima within the upper to middle grove, from where rates once again declined toward the next intergroove in an Australian desert landscape. However, Shukla et al. (2003) found that different soil management systems had a significant influence on the parameters related to initial infiltration rate or sorptivity and q_s or K_{ns}, whereas landscape positions had significant influence on the sorptivity parameter only in the north Appalachian region of Ohio, USA. Sauer and Logsdon (2002) and Sauer et al. (2005) found that upland and side slope soils (Nixa and Clarksville) had consistently lower infiltration rates compared with the soil in the valley bottom (Razort) with significantly higher rock fragment content and lower silt content in Northwestern Arkansas, USA.

The change of K_{ns} in different slope positions

In the different slope positions, the change of K_{ns} was great and it had a moderate variability, except a high variability at the bottom of hillslope 1 (Table 3). On hillslope 1, the highest value of K_{ns} was 13.64 mm/min in the upper position, followed by 8.45 mm/min at the top and

Table 2 The change of stable infiltration rate (q_s) in different slope positions on hillslopes 1 and 2

Slope position	Mean (mm/min)	Max (mm/min)	Min (mm/min)	SD (mm/min)	CV (%)
Hillslope 1					
Bottom	0.83 c	1.48	0.20	0.52	62.81
Lower	0.80 c	1.23	0.40	0.34	42.36
Lower-middle	0.69 c	1.16	0.35	0.29	42.33
Middle	0.43 c	0.90	0.25	0.27	64.52
Upper-middle	1.14 c	1.39	0.94	0.19	16.68
Upper	4.25 a	6.22	2.87	1.23	28.97
Top	2.08 b	2.59	1.43	0.43	20.91
Hillslope 2					
Bottom	0.81 c	0.95	0.64	0.11	14.19
Lower	0.89 bc	1.01	0.71	0.12	13.99
Middle	1.21 bc	2.21	0.82	0.58	47.75
Upper	1.29 b	1.67	0.90	0.29	22.63
Top	3.48 a	3.79	3.13	0.28	8.12

Column for each group by the same letter is not significantly different at $p = 0.05$

Table 3 The change of near-saturated hydraulic conductivity (K_{ns}) in different slope positions on hillslopes 1 and 2

Slope position	Mean (mm/min)	Max (mm/min)	Min (mm/min)	SD (mm/min)	CV (%)
Hillslope 1					
Bottom	2.81 bc	7.88	0.28	3.02	107.64
Lower	1.66 c	2.82	0.81	0.84	50.90
Lower-middle	1.04 c	1.82	0.49	0.48	46.47
Middle	0.75 c	1.72	0.36	0.56	75.44
Upper-middle	2.18 c	3.08	1.40	0.81	37.21
Upper	10.60 a	13.64	7.84	2.37	22.38
Top	5.31 b	8.45	3.11	1.95	36.78
Hillslope 2					
Bottom	1.90 c	2.34	1.17	0.46	24.04
Lower	1.68 c	1.94	1.26	0.29	17.42
Middle	3.75 bc	7.36	1.09	2.75	73.38
Upper	5.26 b	8.08	2.44	2.31	43.86
Top	11.00 a	12.60	9.32	1.58	14.35

Column for each group by the same letter is not significantly different at $p = 0.05$

7.88 mm/min at the bottom, and the lowest value was 0.28 mm/min at the bottom. However, on hillslope 2, the highest value of K_{ns} was 12.60 mm/min at the top, followed by 8.08 mm/min in the upper position and 7.36 mm/min in the middle, and the lowest value was 1.09 mm/min in the middle.

Based on the average value of K_{ns} at each segment, the highest value was 10.60 mm/min in the upper position of hillslope 1 and 11.00 mm/min at the top of hillslope 2. The lowest value was 0.75 mm/min in the middle of hillslope 1 and 1.68 mm/min in the lower position of hillslope 2. From bottom to top, K_{ns} had an increasing trend on hillslope 2 but had a decrease–increase–decrease trend on hillslope 1 (Table 3). This may also have a close relationship with the geomorphologic and hydro-geological conditions as well as rock fragment content and fine-earth fraction within the topsoil at each location on hillslopes 1 and 2. The change trend of K_{ns} on hillslope 1 may be affected mostly by the distribution of large rock outcrops and total rock fragment content. The change trend of K_{ns} on hillslope 2 was in agreement with the results obtained by Li et al. (2008), who discovered that the unsaturated hydraulic conductivity tended to be higher in the upper position than in the lower position of the dolines of southeastern Spain. However, Sauer and Logsdon (2002) found that upland and side slope soils had significantly lower hydraulic conductivities at and near saturation compared with the valley bottom soil due to the significant differences in rock fragment and silt contents in a small limestone watershed of northwestern Arkansas, USA.

The relationship of q_s and K_{ns} with rock fragment content and fine-earth fraction

The relationship between q_s (Table 2) and K_{ns} (Table 3) with mean total volumetric content of rock fragments (5–250 mm) within the topsoil (Table 1) in each segment on hillslopes 1 and 2 is shown in Fig. 2. Five types of regression functions were tested for a best-fit with SPSS 11.5 for Windows: linear, logarithmic, power, exponential, and quadratic equations were considered for all relations. q_s and K_{ns} both tended to increase as an exponential function of rock fragment content on hillslopes 1 and 2, respectively (Fig. 2). These relations were significant ($p < 0.05$) except that the relationship of q_s and rock fragment content was not significant on hillslope 2. If the data collected from the two hillslopes were analyzed together, the exponential relations of q_s and K_{ns} with rock fragment content would be very significant ($p < 0.01$) (Fig. 3). This indicated that rock fragments within the topsoil may significantly facilitate water infiltration into soils due to the creation of new voids. Verbist
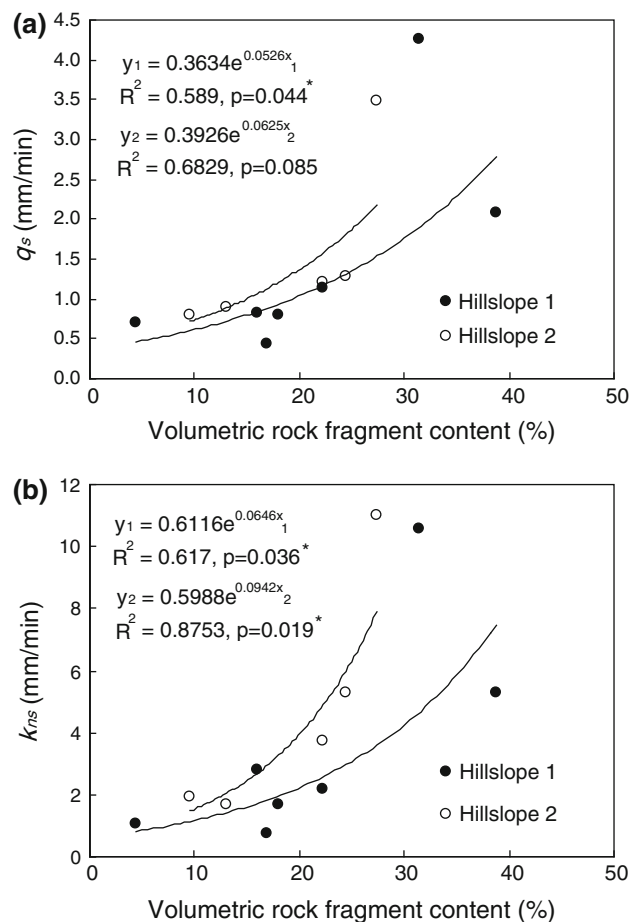

Fig. 2 The relationship of **a** q_s and **b** k_{ns} with mean total volumetric rock fragment content within the topsoil on hillslopes 1 and 2

et al. (2009) obtained similar results but Sauer and Logsdon (2002) discovered that the relationship of K_{ns} and rock fragment content was not distinct. Chen et al. (2011) suggested that rock fragment content increased with the increase in slope gradient on hillslopes 1 and 2. Therefore, q_s and K_{ns} also had an exponentially increasing trend with slope gradient except a linear relationship between K_{ns} and slope gradient on hillslope 2 (Fig. 4). These relations were significant ($p < 0.05$) except the relationship of q_s and slope gradient on hillslope 2. Similarly, Verbist et al. (2009) found that transects with steeper slopes and more, but smaller, rock fragments had higher infiltration rates.

The differences of q_s and K_{ns} in various slope positions may be closely linked to their soil textures and various rock fragment sizes and contents within the topsoil. Pearson correlation analysis showed that q_s and K_{ns} had a significantly ($p < 0.05$) positive linear relationship with coarse pebble (20–75 mm), cobble (75–250 mm), and sand (2–0.05 mm) contents as well as total volumetric rock fragment content (5–250 mm) on hillslopes 1 and 2
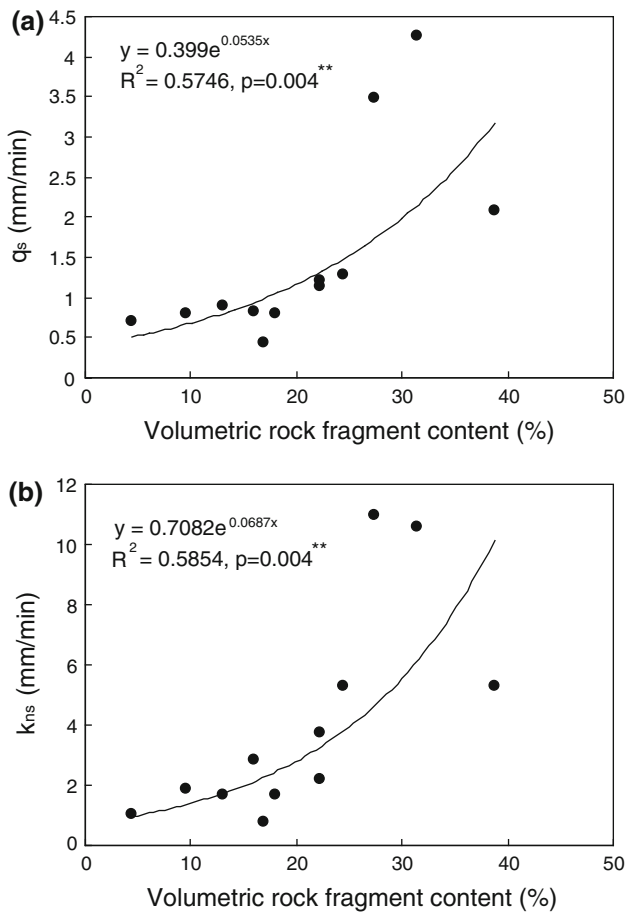
Fig. 3 The relationship of **a** q_s and **b** k_{ns} with mean total volumetric rock fragment content within the topsoil on karst hillslopes. Data collected from the two hillslopes 1 and 2 were analyzed together

Fig. 4 The relationship of **a** q_s and **b** k_{ns} with slope gradient on hillslopes 1 and 2

(Table 4). However, they had a negative linear relationship with clay (<0.002 mm) content, and the correlation was significant and marginally significant ($p = 0.058$), respectively. This indicated that total rock fragment content and the contents of rock fragments larger than 20 mm (especially >75 mm) and sand would facilitate water infiltration into soils, but clay content (30–60%) would restrict water movement. Fiès et al. (2002) discovered that the shrinkage of the fine phase in stony soils with a clay content >30% led to the formation of coarse lacunar pores due to cracking, which would increase water infiltration into soils. Verbist et al. (2009) suggested that rock fragment content was the dominant factor affecting water infiltration into soils in degraded drylands of Chile. However, Sauer and Logsdon (2002) concluded that rock fragment, silt, or clay content did not significantly affect water flow in the surface soil layer in a small limestone watershed of northwestern Arkansas, USA. This may result from the difference in soil texture and the sources of rock fragments and their size distribution.
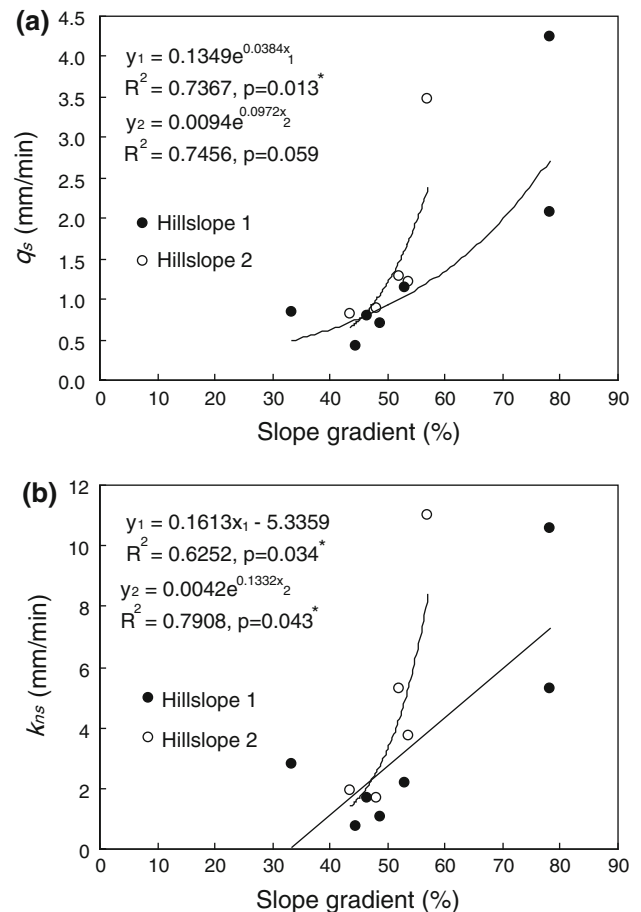
Conclusions

On the steep karst hillslopes, the change in q_s and K_{ns} was great and they mostly had a moderate variability ($0.1 < CV < 1.0$) in the different slope positions. On average, q_s ranged from 0.43 to 4.25 mm/min on hillslope 1 and from 0.81 to 3.48 mm/min on hillslope 2. K_{ns} ranged from 0.75 to 10.60 mm/min on hillslope 1 and from 1.68 to 11.00 mm/min on hillslope 2. These rates exceed those of most natural rainfall events, confirming that overland flow is rare on the karst hillslopes. From bottom to top, q_s and K_{ns} both had a decrease–increase–decrease trend on hillslope 1 but they had an increasing trend on hillslope 2. This had a close relationship with rock fragment content and soil texture within the topsoil as well as the geomorphologic and hydro-geological conditions at each location on hillslopes 1 and 2. q_s and K_{ns} both tended to increase with an increase in rock fragment content and slope gradient on both hillslopes. They had a significant ($p < 0.05$) positive correlation with coarse pebble, cobble, and sand contents as well as total rock fragment content, but a significant or marginally significant ($p = 0.058$) negative correlation

Table 4 The Pearson correlation between soil stable infiltration rate (q_s) and near-saturated hydraulic conductivity (K_{ns}) and rock fragments as well as fine-earth fraction on hillslopes 1 and 2

Soil hydraulic properties	N	Rock fragments (mm)					Fine earth (mm)		
		2–5	5–20	20–75	75–250	5–250	2–0.05	0.05–0.002	<0.002
q_s	12	−0.115	0.392	0.614[b]	0.721[a]	0.690[b]	0.681[b]	0.211	−0.628[b]
K_{ns}	12	−0.042	0.454	0.592[b]	0.712[a]	0.699[b]	0.674[b]	0.113	−0.560

[a] Correlation is significant at the 0.01 level (2-tailed)

[b] Correlation is significant at the 0.05 level (2-tailed)

with clay content, respectively. This suggested that rock fragments and fine-earth fraction within the topsoil were closely linked to hydrological processes and should be considered in modeling on the karst hillslopes in subtropical regions.

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