

# Vertical distribution of soil saturated hydraulic conductivity and its influencing factors in a small karst catchment in Southwest China

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**Abstract** Saturated hydraulic conductivity ( $K_s$ ) is one of the most important soil hydraulic parameters influencing hydrological processes. This paper aims to investigate the vertical distribution of  $K_s$  and to analyze its influencing factors in a small karst catchment in Southwest China.  $K_s$  was measured in 23 soil profiles for six soil horizons using a constant head method. These profiles were chosen in different topographical locations (upslope, downslope, and depression) and different land-use types (forestland, shrubland, shrub-grassland, and farmland). The influencing factors of  $K_s$ , including rock fragment content (RC), bulk density (BD), capillary porosity (CP), non-capillary porosity (NCP), and soil organic carbon (SOC), were analyzed by partial correlation analysis. The mean  $K_s$  value was higher in the entire profile in the upslope and downslope, but lower value, acting as a water-resisting layer, was found in the 10–20 cm soil depth in the depression. Higher mean  $K_s$  values were found in the soil profiles in

the forestland, shrubland, and shrub-grassland, but lower in the farmland. These results indicated that saturation-excess runoff could occur primarily in the hillslopes but infiltration-excess runoff in the depression. Compared with other land-use types, surface runoff is more likely to occur in the farmlands. RC had higher correlation coefficients with  $K_s$  in all categories concerned except in the forestland and farmland with little or no rock fragments, indicating that RC was the dominant influencing factor of  $K_s$ . These results suggested that the vertical distributions of  $K_s$  and RC should be considered for hydrological modeling in karst areas.

**Keywords** Saturated hydraulic conductivity · Hydrological process · Topographical location · Land-use type · Influencing factor · Runoff generating mechanisms

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## Introduction

Soil saturated hydraulic conductivity ( $K_s$ ) is a key parameter affecting soil water movement, rainfall infiltration, and runoff generation mechanism. Numerous previous studies focused on the spatial variability of  $K_s$  in the surface soil from hillslope scale to regional scale (Sobieraj et al. 2002; Lewis et al. 2011; Gao et al. 2012). However, only occasionally did previous studies address the vertical distribution of  $K_s$  in the soil profile (Coquet et al. 2005; Schwen et al. 2014). Many hydrological modeling studies suggested that  $K_s$  decreased

with increasing soil depth and, in addition, a reduction factor was used as a parameter in the model (Güntner et al. 1999; Ibbitt and Woods 2004; Hwang et al. 2012). However, the vertical distribution of  $K_s$  in the soil profile is irregular at times. For example, among three cultivated soil profiles in France, Coquet et al. (2005) found that  $K_s$  increased consistently with increasing soil depth in two of their soil profiles while first increased then begun to show decrease as soil depth increased in the third profile. Schwen et al. (2014) found an increasing trend in the vertical distribution of soil hydraulic conductivity in farmlands but some fluctuation with a maximum value at 50 cm depth in forestland in Austria. These results indicate a need for further studies of the vertical distribution of  $K_s$  in order to better understand hydrological process and improve accuracy in hydrological modeling.

Factors such as topographical locations (Elsenbeer et al. 1992; Wang et al. 2008a), land-use types (Sobieraj et al. 2002; Halabuk 2006; Kelishadi et al. 2014), and soil parameters (Lado et al. 2004; Zhao et al. 2010) can influence the vertical distribution of  $K_s$ . Topographical locations and land-use types mainly influence  $K_s$  by changing soil parameters. However, the argument that which soil parameters play the most important role on  $K_s$  is still under debate. For instance, Buttle and House (1997) found that macropore, overriding other soil parameters, was the main influencing factor of  $K_s$ . Jarvis et al. (2013) contended that  $K_s$  depended more strongly on bulk density (BD) and soil organic carbon (SOC) than other soil parameters. The effect of SOC on  $K_s$  is controversial. Lado et al. (2004) found that  $K_s$  increased with SOC content in sandy loam while Peng et al. (2010) demonstrated that  $K_s$  first increased and then decreased as SOC moved upward in loam soils. For soils with abundant rock fragments, Sauer and Logsdon (2002) found that  $K_s$  increased with increasing rock fragment content (RC), while Novák et al. (2011) offered an inverse conclusion. These studies mostly considered the influencing factors of  $K_s$  or its spatial distribution. There is little understanding of how these factors affect the vertical distribution of  $K_s$ , as well as the dominant factors for different topographical locations and land-use types.

Karst areas are a special style of landscape occurring on soluble rocks with high heterogeneity, where fissures, gaps, and channels are found. These characteristics form a dual system resulting in rapid hydrological processes (Bonacci 1993; Ford and Williams 2007;

Williams 2008). The vertical distribution of  $K_s$  and its influencing factors tend to be more complex in karst areas than in non-karst areas (Li et al. 2008; Chen et al. 2012a). Soils are often thin (20–30 cm) and rocky in karst areas with high infiltration rates, resulting in low-surface runoff coefficients (Chen et al. 2011, 2012a). However, it is still possible to find patches with deeper soils, and soil layer can play an important role in karst hydrological process. Previous studies have addressed  $K_s$  and its influencing factor in karst areas. For example, Li et al. (2008) found significant differences of hydraulic conductivity among different topographic units of the dolines, and the influence of RC was not obvious. Chen et al. (2009) focused on the influence of land-use types and found a significant difference of hydraulic conductivity among forest, agriculture, and bare soil areas. Chen et al. (2012a) found the soil near-saturated hydraulic conductivity to be high and to exceed the rates of most natural rainfall events, confirming that overland flow is rare on karst hillslopes. Although these studies have contributed to a better understanding of factors directly and indirectly influencing  $K_s$ , the effect of vertical distribution of  $K_s$  on hydrological process is still missing in existing hydrological models.

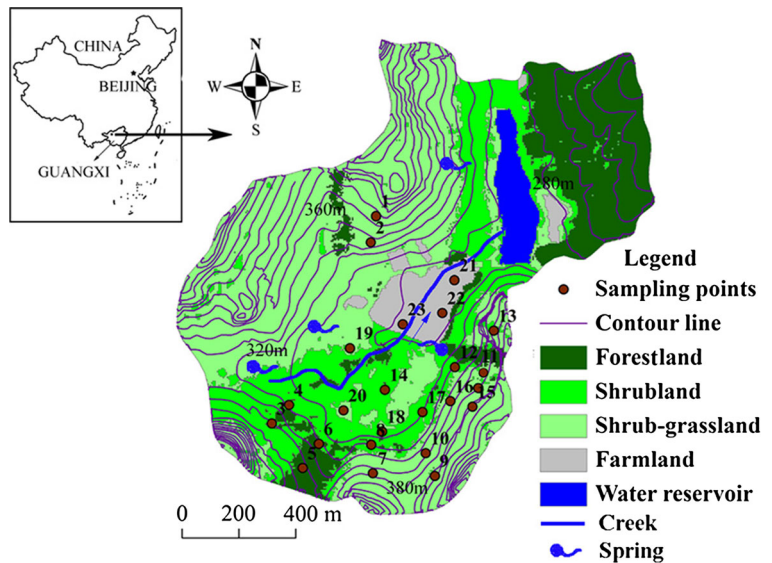
The objectives of our study are (1) to investigate the vertical distribution of  $K_s$  and (2) to analyze the influencing factors of  $K_s$  in different topographical locations and land-use types in a small karst catchment in northwest Guangxi, Southwest China.

## Materials and methods

### Study area

Measurements were conducted in a small catchment used for long-time field research by the Huanjiang Observation and Research Station for Karst Ecosystems under the Chinese Academy of Science, in Huanjiang County of northwest Guangxi, Southwest China (Fig. 1). The study area is a typical karst catchment with elevation ranging from 272 to 647 m and characterized by a flat depression surrounded by mountains on all sides, except an outlet in the northeast (Fig. 1). The slopes are steep, with most gradients greater than 25°. The higher gradients always occur on the upslope, while the lower gradients are located at the foot of the hillslopes. The climate is subtropical monsoon, with an average annual precipitation of 1389 mm, mostly falling

**Fig. 1** Location of the experiment site and the distribution of the sampling profiles



from May to September. Surface infiltration rates are high and exceed most of rainfall rates (Chen et al. 2012a), resulting in negligible surface runoff, with a runoff coefficient of less than 5 % (Chen et al. 2012b). The average annual temperature is 18.5 °C, with the highest average monthly temperature in July and the lowest in January. Soils mainly develop from dolomite containing significant amounts of rock fragments. On average, soil thickness is 50–80 cm in the depression and 10–30 cm on the hillslopes.

The cultivated lands have been abandoned since 1985. However, about half of them have been reused since 2005. Farmland, including mostly corn and pasture, occurs in the depression and the downslope. Shrub-grassland is the dominant land-use type in the hillslopes. Forests often grow in patches where there is a high cover of exposed bedrock. Shrubland occurs mainly in the southwest of the depression and west slope near the catchment outlet. A creek flows from the southwest to the northeast all year long. Four epikarst springs interperse in the catchment (Fig. 1). Two of them flow most time of the year and the other two flow only during the rainy season.

**Soil sampling**

Soils were sampled from 23 profiles scattered in the catchment (Fig. 1). Based on a detailed investigation of land-use type and a DEM map of the small catchment, typical soil profiles were chosen from different topographical locations (upslope, downslope, and

depression) and different land-use types (farmland, shrub-grassland, shrubland, and forestland). For each profile, six soil horizons (0–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm) were chosen to collect soil samples. For the profiles less than 100 cm, soil samples were collected until reaching the bedrock. For each soil horizon, undisturbed soil samples were collected by metal cylinders with two repetitions, and disturbed soils were collected from the entire soil horizon with a shovel. To avoid the large rock fragments in the profile, small cylinders with volume of 100 cm<sup>3</sup> and diameter of 5 cm were used. Both the disturbed and undisturbed soil samples were taken to the laboratory carefully in order to ensure an accurate measurement of Ks and other soil parameters.

**Laboratory measurements of Ks and other soil parameters**

Capillary porosity (CP) and non-capillary porosity (NCP) were measured with water suction method (Li and Shao 2006; Wang et al. 2008b). The cylinder cores were placed in a large plastic container (100 cm×50 cm) with constant water depth of about 5 mm to absorb water until constant weight ( $m_1$ ) was reached. Then, more water was added to the plastic container until the water surface was just below the top of the soil cores. The soil cores were dipped in water for about 24 hours until constant weight ( $m_2$ ) was obtained. Subsequently, the soil cores were connected to a mariotte bottle with hydraulic head of about 3 cm to measure Ks with

constant head method based on Darcy's law (Lado et al. 2004; Gwenzi et al. 2011). The outflow through the soil core was measured in given time intervals until the flow rate became steady. Finally, the cores were dried under 105 °C to get the bulk density (BD). The Ks (m/day), CP (%), NCP (%), and BD (g/cm<sup>3</sup>) were calculated using the following formulas:

$$K_s = \frac{14.4 \times Q \times L}{h \times S} \quad (1)$$

$$CP = \frac{m_1 - m_{\text{dry}}}{\rho_w V_t} \times 100 \quad (2)$$

$$NCP = \frac{m_2 - m_1}{\rho_w V_t} \times 100 \quad (3)$$

$$BD = \frac{m_{\text{dry}}}{V_t} \quad (4)$$

where 14.4 is a unit conversion factor that transferred the unit of Ks from centimeters per minute to meters per day,  $Q$  is the steady-state velocity of the outflow (cm<sup>3</sup>/min),  $L$  is the length of the soil core (cm),  $h$  is the hydraulic head (cm),  $S$  is the cross-sectional area of the soil core (cm<sup>2</sup>),  $\rho_w$  is the density of water (g/cm<sup>3</sup>),  $V_t$  is the volume of the soil core (cm<sup>3</sup>), and  $m_{\text{dry}}$  is the dry soil mass (g). Disturbed soils were air-dried and then sieved by 0.15-mm mesh to measure SOC with potassium dichromate wet combustion method (Zhang et al. 2012). RC (%) was calculated by mass of the rock fragments divided by the total mass of mixed soil and rock fragments.

#### Data analysis

The data were analyzed using Excel 2003 and SPSS 18.0. First, the outliers, which were out of the range of mean $\pm$ 3 times standard deviation, were deleted for Ks and other soil parameters. Partial correlation analysis was used to explore the main influencing factors of Ks in different topographical locations and land-use types. Least significant difference (LSD) method was used to analyze the differences between different categories.

## Results

### Vertical distributions of Ks for different topographical locations

On average of all the profiles in the study area, Ks of surface soil (0–10 cm) was significantly higher ( $p < 0.05$ ) than that of other soil horizons. No significant differences were found among horizons of 10–100 cm (Fig. 2).

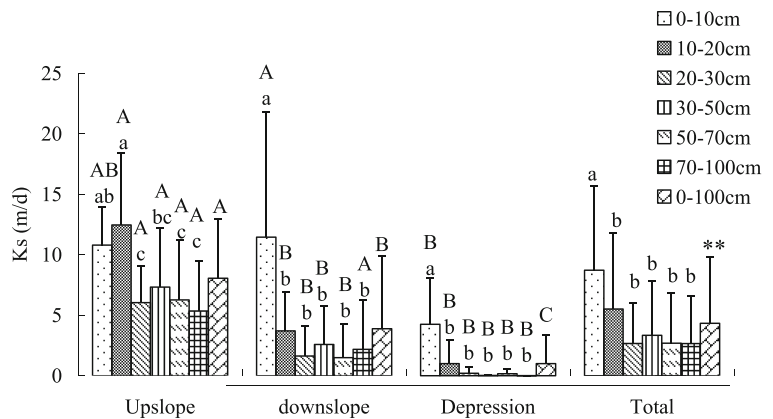
In the upslope areas, the variation of Ks with soil depth could be divided into two sections. The first section was 0–20 cm with relatively higher Ks values, and the second section was 30–100 cm with relatively lower Ks values (Fig. 2). Ks of the subsurface soil (10–20 cm) was the highest and significantly higher than that of 20–100 cm but not significantly higher than surface soil. No significant differences were found among the 30–100-cm depths. In the downslope and depression areas, the variation of Ks could also be divided into two sections with the first section of 0–10 cm and the second of 10–100 cm. Ks of 0–10-cm depth was significantly higher than that of the underlying horizons (Fig. 2), but no significant differences were found among the 10–100-cm soil depths.

For the comparable soil horizons among different topographical locations, surface Ks in the upslope and downslope was significantly higher than that in the depression, but no significant difference was found between upslope and downslope. With the exception of the surface soil, all the other soil horizons showed significantly higher Ks values in the upslope than in the downslope and depression areas, but the difference between Ks values in the downslope and depression areas was not significant. The mean Ks value of the whole profile (0–100 cm) had a significant ( $p < 0.05$ ) decreasing order of upslope > downslope > depression.

### Vertical distributions of Ks for different land-use types

In the forestland, Ks value first decreased and then increased with increasing soil depth, and the variation could be considered as a parabola with the lowest value appeared at 20–30-cm depth. Ks of surface soil appeared to be significantly higher than that of 20–30, 30–50, and 50–70 cm but not significantly higher than 10–20 and 70–100 cm (Fig. 3). In the shrubland and shrub-grassland, Ks showed fluctuation decreasing with increasing soil depth. No significant differences were

**Fig. 2** Vertical distribution of Ks in different topographical locations. The *lowercase letter* means the significant ( $p < 0.05$ ) difference between different soil horizons, and the *capital letter* means the significant ( $p < 0.05$ ) difference between different topographical locations. *Missing letter* means no significant difference among categories. *Double asterisk* means that the Ks was not compared with other categories



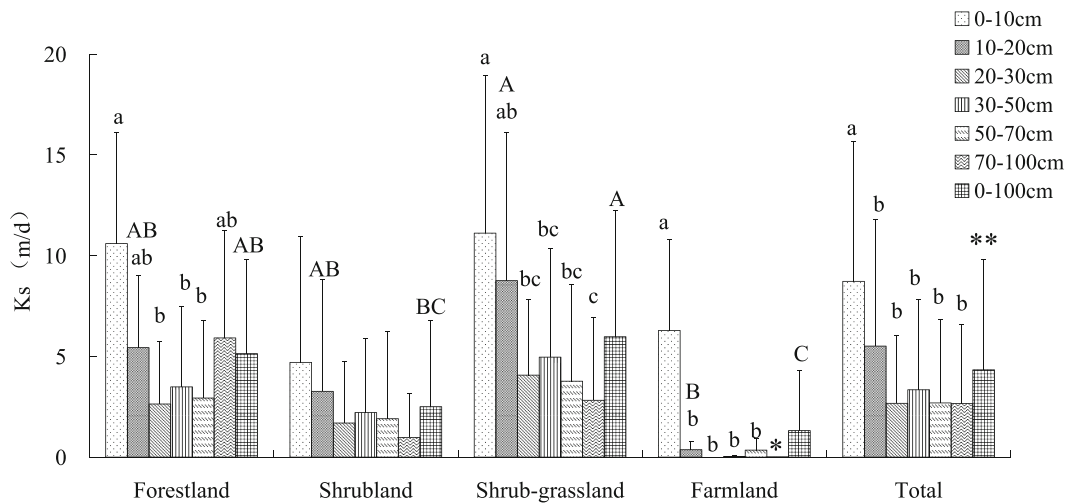
found among the six soil horizons in the shrubland area. However, in the shrub-grassland, Ks of surface soil was significantly higher than that of 20–100 cm, and the subsurface soil had a significantly higher Ks value than 70–100 cm. In the farmland, Ks values could be divided into surface soil with relatively higher value and the underlying soil (10–100 cm) with relatively lower value. Ks of surface soil was significantly higher than that of other soil horizons, but no significant differences were found in 10–100 cm soil horizons.

For comparable soil horizons among different land-use types, only subsurface soil had a significantly higher Ks value in the shrub-grassland than that in the farmland. Considering the whole profile, Ks values had a decreasing order from shrub-grassland to forestland to shrubland to farmland. Ks values were significantly

higher in the shrub-grassland than those in the shrubland and farmland, and significantly higher in the forestland than those in the farmland (Fig. 3).

**Influencing factors for different topographical locations**

In the upslope, NCP was very significantly ( $p < 0.01$ ) positively correlated, but CP was significantly negatively correlated with Ks. Both RC and BD significantly ( $p < 0.05$ ) influenced Ks, but the signal of correlation coefficient was inverse (Table 1). SOC had no significant correlation with Ks (correlation coefficient of  $-0.019$  and significant value of  $0.910$ ). In the downslope, SOC was the only significant factor influencing Ks with significant value  $< 0.01$ . All the other soil parameters had no significant ( $p > 0.05$ ) correlation with



**Fig. 3** Vertical distribution of Ks in different land-use types. The *lowercase letter* means the significant ( $p < 0.05$ ) difference between different soil horizons, and the *capital letter* means the significant ( $p < 0.05$ ) difference between different land-use types.

*Missing letter* means no significant difference among categories. *Asterisk* means that the sampling number was less than 3 without standard deviation. *Double asterisk* means that the Ks was not compared with other categories

**Table 1** The influencing factors of Ks in different topographical locations

Soil properties	Topographical location	Parameter	RC	BD	CP	NCP	SOC
Ks	Upslope	R	0.336*	-0.393*	-0.414**	0.471**	-0.019
		P	0.042	0.018	0.010	0.003	0.910
		N	35	34	36	36	37
	Downslope	R	0.282	0.237	-0.133	0.178	0.476**
		P	0.090	0.177	0.446	0.292	0.004
		N	35	32	33	35	33
	Depression	R	0.242	-0.148	-0.272	0.398**	0.087
		P	0.109	0.354	0.075	0.007	0.576
		N	45	39	42	42	42

Ks saturated hydraulic conductivity, RC rock fragment content, BD bulk density, CP capillary porosity, NCP non-capillary porosity, SOC soil organic carbon, R partial correlation coefficient, P significant value, N number of samples

\* The correlation was significant at 0.05 level

\*\* The correlation was significant at 0.01 level

Ks. In the depression, NCP was the most important factor influencing Ks (correlation coefficient of 0.398). CP and RC also influenced Ks but not significantly, and their significant values were 0.075 and 0.109, respectively.

Among the influencing factors concerned, RC significantly influenced Ks in the upslope. In the downslope and depression, the significant values of RC were closed to 0.1 (0.090 and 0.109, respectively). This indicated the importance of RC in all topographical locations. NCP and CP had opposite effects on Ks, and they had significant correlations with Ks in the upslope but not in the downslope. In the depression, the effect of NCP was significant, but CP was not significant. SOC only influenced Ks in the downslope with a significant value of 0.004 (Table 1).

#### Influencing factor for different land-use types

SOC was the main influencing factor for the forestland (correlation coefficient of 0.447 and significant value of 0.048), while the influence of other soil parameters was not significant ( $p > 0.05$ ). In the shrubland area, Ks had a significantly positive correlation with RC and NCP (correlation coefficients of 0.920 and 0.554, respectively). CP and SOC were also important influencing factors with significant value  $< 0.05$  and correlation coefficients of -0.418 and 0.433, respectively. In the shrub-grassland, RC was the most important influencing factor with significant value of 0.001 and correlation coefficient of

0.440. BD was an important influencing factor with significant value  $< 0.05$ . Other parameters had no significant influence on Ks. In the farmland, only soil porosity significantly influenced Ks (correlation coefficients of NCP and CP were 0.855 and -0.575, respectively) (Table 2).

For all the influencing factors concerned, RC had a significant correlation with Ks in both shrubland and shrub-grassland but not in the forestland and farmland. BD only influenced Ks in the shrub-grassland. Soil porosity influenced Ks in the shrubland and farmland. NCP had a positive effect and CP had a negative effect in the two land-use types. The correlation of SOC and Ks was significant in the forestland and shrubland with significant values of 0.048 and 0.015, respectively, but not significant in the shrub-grassland and farmland (Table 2).

#### Discussions

The vertical distribution of Ks and its effect on hydrological process in different categories

The average Ks value for the profile (0–100 cm) had a significantly decreasing order from upslope to downslope to depression (Fig. 2). This pattern indicates that topographical location has great influence on Ks. Wang et al. (2008a) obtained similar results and reported that Ks increased with increasing elevation in

**Table 2** The influencing factors of Ks in different land use types

Soil properties	Land use types	Parameter	RC	BD	CP	NCP	SOC
Ks	Forestland	R	0.176	0.287	0.176	-0.043	0.447*
		P	0.447	0.234	0.457	0.852	0.048
		N	19	17	18	19	18
	Shrubland	R	0.920**	0.101	-0.418*	0.554**	0.433*
		P	0.000	0.589	0.019	0.001	0.015
		N	31	29	29	31	29
	Shrub-grassland	R	0.440**	-0.372*	0.028	-0.004	0.023
		P	0.001	0.011	0.856	0.979	0.876
		N	48	44	44	47	47
	farmland	R	<sup>a</sup>	0.290	-0.575*	0.855**	0.038
		P	<sup>a</sup>	0.315	0.025	<0.001	0.888
		N	<sup>a</sup>	12	13	13	16

Ks saturated hydraulic conductivity, RC rock fragment content, BD bulk density, CP capillary porosity, NCP non-capillary porosity, SOC soil organic carbon, R partial correlation coefficient, P significant value, N number of samples

\* The correlation was significant at 0.05 level

\*\* The correlation was significant at 0.01 level

<sup>a</sup> Analysis was not done because no rock fragment was found in the farmland

vegetated dunes. The vertical distributions of Ks in the downslope and depression areas were similar in general but different at the upslope (Fig. 2). This may result from distinct vertical distributions of influencing factors. Wang et al. (2008a) found different vertical trends of Ks between highlands and lowlands. They stressed that Ks showed the greatest variability at the depths of 50–150 cm in different positions, which resulted from differences in sedimentation history and soil organic matter content. Bathke and Cassel (1991), however, found that Ks decreased with increasing soil depth at all landscape positions including interfluvial, shoulder, linear, and footslope. They attributed this result to increasing BD, total porosity, and clay content, and decreasing macroporosity, sand content, and percent soil solids.

For the different land-use types in this study, only Ks for subsurface soil showed significant differences (Fig. 3). This may be attributed to the fact that land-use types mainly played their role in shallow soil layers. For example, Halabuk (2006) found significant difference of Ks in 0–5-cm soil depth among different land-use types. However, in karst areas, the surface soil has more complex influencing factors than the subsurface soil, such as rock fragment cover, litter cover, animal activity, etc. (Li et al. 2008; Chen et al. 2009, 2012a). The combination effect of these factors may weaken the

effect of vegetation on values of surface soil Ks. As a consequence, the surface soil was not significantly influenced, but the subsurface soil was significantly influenced by land-use types. The vertical distribution of Ks in the forestland was different from the other land-use types. Yao et al. (2013) also found different distributions of Ks in different land types and attributed this difference to wind erosion, spatial variability of the landscape, and human disturbances. Schwen et al. (2014) found that the vertical distribution of hydraulic soil parameters under farmland differed distinctly from that under forestland. The different distributions of Ks in our study area could be attributed to different structures of the underlying bedrock. Bedrock was fine weathered in the forestland resulting in higher Ks values in the 70–100-cm depths (Fig. 3). Similar results were reported by Coquet et al. (2005) who found the highest Ks value in the C horizon overlying highly fractured substrate and fine weathered limestone.

Different vertical distributions of Ks values were found for different topographical locations and land-use types (Figs. 2 and 3). This result indicates that vertical distributions of Ks must be considered in building hydrological models. Hwang et al. (2012) simply assumed that Ks decreases with increasing soil depth and used a decay rate as a parameter. On the other hand, Chen and Hu (2004) made a hypothesis that Ks

decreases exponentially with soil depth, and the e-folding depth was used in their hydrological model. However, the assumption that  $K_s$  simply decreases with soil depth seems to be inadequate in karst catchments. In this study, the variation of  $K_s$  for the forestland could be represented as a parabola. In the upslope, downslope, depression, and farmland, the variation of  $K_s$  could be divided into two sections. Only in shrubland and shrub-grassland did  $K_s$  values decreased with increasing soil depth.

$K_s$  values of all the soil horizons in the upslope and downslope were higher than the maximum local rainfall intensity which was 67.4 mm/h (1.62 m/day) according to Yang et al. (2012). This result indicates that rainfall may easily infiltrate into the soil and leaked to the epikarst. The runoff generation pattern may be dominant by saturation-excess runoff. The vertical distribution of  $K_s$  plays an important role in soil water movement (Ahuja and Ross 1983). Blanco-Canqui et al. (2002), for example, found that the argillic horizon with lower  $K_s$  was a barrier to vertical flow and created lateral flow. In our catchment, the lower  $K_s$  horizon was not found and interflow would seldom appear on the hillslope. However, in the depression, surface  $K_s$  values were significantly higher than in the underlying layers. The lowest  $K_s$  value (0.004 m/day) in the 70–100-cm depth was much lower than the rainfall intensity. This result indicates that surface runoff generation in the depression could be caused by infiltration excess. In another study, van Tol et al. (2013) grouped 52 hillslopes into six classes including interflow (soil/bedrock interface), shallow responsive, recharge to groundwater, recharge to wetland, recharge to midslope, and quick interflow based on their dominant hydrological response in South Africa. None of the classes were identified in the current study, which indicates a much more complex hydrological process in karst areas. For the different land-use types, no water resistance layer was found in the forestland, shrubland, and shrub-grassland. However, in the farmland,  $K_s$  values for 10–100-cm depth were significantly lower than 0–10-cm, and infiltration can easily occur in the 10-cm depth.

#### Influence of soil parameters on $K_s$ values

$K_s$  had more influencing factors in the upslope than in the downslope and depression (Table 1). This is attributed to different soil parameters in different topographical locations. In karst areas, the upslope always has

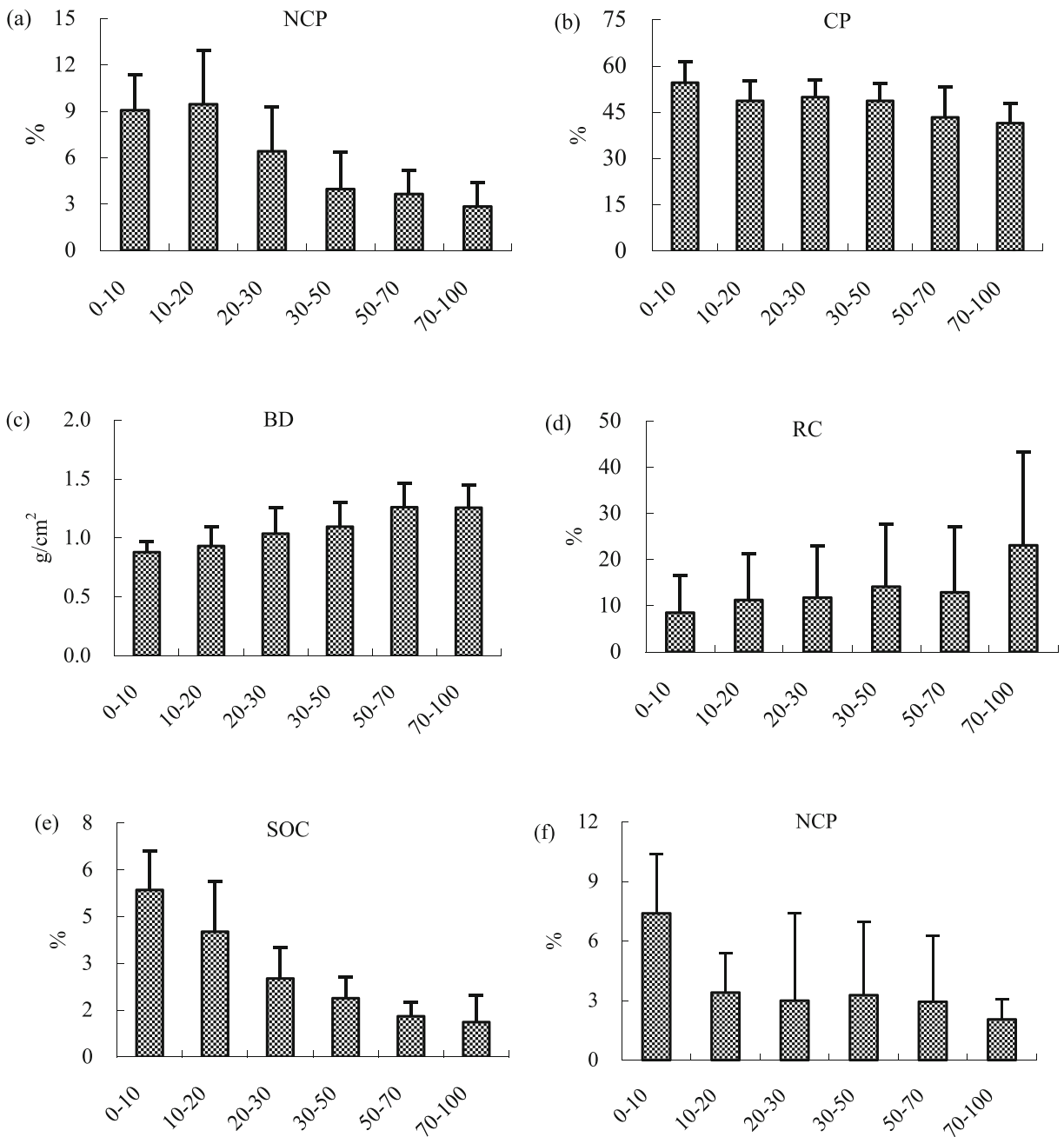
higher RC than the downslope and depression (Li et al. 2007; Chen et al. 2011). Soil porosity and BD were also different between upland and lowland. Fine soils are more easily to be eroded in the upslope and deposited in the downslope and depression. Clay content was much higher in the bottom than in the top of the slope (Chen et al. 2011). Soil sediment in the downslope and depression was compact and soil porosity relatively lower. This discrepancy resulted in different influencing factors for  $K_s$  in varying topographical locations.

Only one parameter seemed to be influential for the forestland (Table 2) because forestland always appeared where there was a high cover of basement rock output (Nie et al. 2011). In these areas, RC was relatively lower and soils were always compact. However, SOC content was relatively higher due to the root and litter of the forest. This resulted in SOC being the main influencing parameter. Unlike the results for forestland, all the considered soil parameters, except BD, had a significant influence on  $K_s$  values in the shrubland area. This may be to the fact that shrubland spreads in the catchment area. Soil parameters always had higher variation. In the farmland,  $K_s$  values were mainly influenced by soil porosity. This may be attributed to the fact that RC and SOC were very low. Soil porosities and infiltration are significantly influenced by tillage (Lipiec et al. 2006). As a result, NCP and CP are the primary influencing factors of  $K_s$  in the farmland.

RC had higher correlation coefficients with  $K_s$  in all categories except for the forestland and farmland, which had little or no rock fragments. Results indicated that RC is an important influencing factor for both topographical locations and land-use types. The effect of RC on  $K_s$  was positive in the study area. Sauer and Logsdon (2002) also found that  $K_s$  increased with increasing RC. However, Novák et al. (2011) found the inverse results. RC had two inverse effects on  $K_s$ . On one hand, it can decrease  $K_s$  values by reduction of the area of flow cross section and by increasing the tortuosity of the water flow. On the other hand, it can increase  $K_s$  by increasing occurrence of macropores in the interface of soil and rock (Zhou et al. 2009). In karst areas, the positive effect seems to override the negative effect, and  $K_s$  values increase with increasing RC. This might be to the fact that rock fragments in karst areas are finely weathered, which may increase soil porosity in the interface between soil and rock fragments.

The influence of SOC on  $K_s$  values was significant in the forestland and shrubland but not significant in the



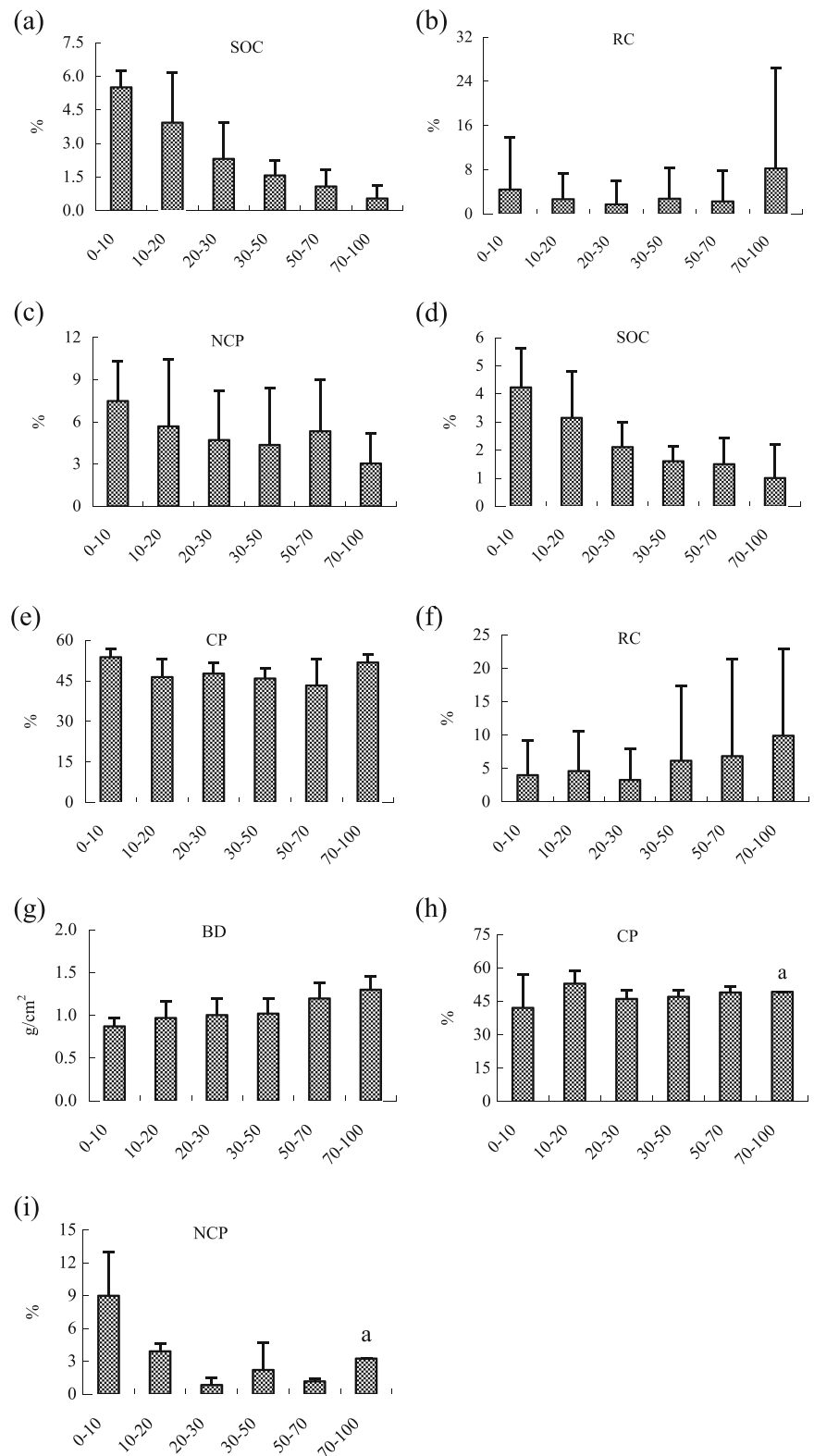


**Fig. 4** The vertical distribution of soil properties (mean + SD) that had significant effect on Ks in different topographical locations: upslope (a–d), downslope (e), and depression (f)

shrub-grassland and farmland (Table 2). SOC may have two opposite influences on Ks. On one hand, SOC can maintain the stability of soil structure, which leads to more leakage of water and increases Ks, as reported by Lado et al. (2004). On the other hand, SOC can absorb up to 20 times of its weight in water, as indicated by Jones et al. (2009). The adsorption tends to slow down

the flow rate and decrease Ks. Nemes et al. (2005) also found the conflicting effects of SOC in Ks. In our study, only the positive effect of SOC has been found. This may be caused by the occurrence of relatively higher macroporosity in karst soils. The existence of SOC protects the porosity structure of the soil and plays its positive role.

**Fig. 5** The vertical distribution of soil properties (mean + SD) that had significant effect on Ks in different land-use types: forestland (a), shrubland (b–e), shrub-grassland (f, g), and farmland (h, i). *a* means that the sampling number was less than 3 without standard deviation



The relationship between the vertical distribution of Ks and the concerned soil parameters

Vertical distributions of soil parameters that significantly correlated to Ks were drawn (Fig. 4) to detect the mechanism of vertical distribution of Ks in different topographical locations. In the upslope, the distribution of Ks was similar to that of NCP (Figs. 1 and 4a). Perhaps, this was because Ks was significantly correlated with NCP (Table 1). However, the distribution of Ks was different with CP and BD which also had significant correlations with Ks. Perhaps, this was because the variations of CP and BD were relatively lower in the whole profile (Fig. 4b, c). Ks was significantly positively correlated with RC (Table 2). However, it is interesting that Ks had an inverse vertical distribution with RC (Figs. 1 and 4d). This may result from the effect of BD which increased with increasing soil depth (Fig. 4c), as indicated by the fact that the soils were compact in the deeper horizons. The presence of compact soil may diminish the occurrence of macropores in the soil-rock interface and decrease Ks. The vertical distribution of Ks was similar with SOC in the downslope and with NCP in the depression (Figs. 1 and 4e, f), because only one influencing factor was significant in the downslope and depression.

SOC was the only soil parameter that significantly positively influenced Ks in the forestland (Table 2). However, the vertical distribution of Ks was different with SOC (Figs. 2 and 5a), especially in 70–100-cm depths which had higher Ks value but lower SOC value. This difference may come from the effect of weathered bed rock which tends to increase Ks significantly (Coquet et al. 2005). Ks was influenced by more parameters in the shrubland (Table 2). What's more, the vertical distributions of these parameters were extremely heterogeneous except for CP (Fig. 5b–e). The combination of these parameters led to larger variation of Ks, and no significant difference was found among different soil horizons (Fig. 3). In the shrub-grassland, the distribution of Ks (Fig. 2) showed a converse distribution with RC (Fig. 5f) which showed a significant positive correlation with Ks. This may be attributed to the fact that BD had a significantly negative effect on Ks and increased with increasing soil depth. In the farmland, the influence of CP on the distribution of Ks was relatively lower for its even distribution in the soil profile (Fig. 5i). However, NCP had a higher influence on the vertical distribution of Ks (Figs. 2 and 5h).

## Conclusion

The vertical distribution of Ks was different for different land-use types but similar for two sections (higher and lower horizons) among different topographical locations. The mean Ks value first decreased and then increased with increasing soil depth in the forestland and erratically decreased in the soil profile in the shrubland and shrub-grassland. In the farmland, Ks was higher in the surface soil layer (0–10 cm) than in the other soil horizons. These results indicate that different vertical distributions of Ks must be considered in hydrological modeling of the study area. The mean Ks value was relatively higher in all horizons in the upslope and downslope but relatively lower at 10–100-cm soil depths in the depression. This result indicates that saturation-excess runoff mechanisms can occur in the slopes and infiltration-excess runoff mechanisms can predominate in the depression. The mean Ks value was higher in the forestland, shrubland, and shrub-grassland than that in the farmland where a water-resistance layer (10–20 cm) was found. This result indicates that surface runoff has a higher probability of occurrence in the farmland than in the other land-use types.

The upslope and shrubland had more parameters influencing Ks than the other categories, indicating their complex hydrological features. RC showed a close relationship with Ks in all the categories except in the forestland and farmland containing little or no rock fragments. However, the influence of other soil parameters on Ks was only significant in specific categories. This suggested that RC might be the most important influencing factor of Ks and it should be considered in hydrological modeling of karst catchments.

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