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Characteristics of soil moisture storage from 1979 to 2017 in the karst area of China

Yuanhong Deng[a,b,c], Shijie Wang[a,d], Xiaoyong Bai[a,e,f], Guangjie Luo[f], Luhua Wu[a,c], Fei Chen[a,g], Jinfeng Wang[a,g], Qin Li[a,c], Chaojun Li[a,h], Yujie Yang[a,h], Zeyin Hu[a,c] and Shiqi Tian[a,h]

[a]State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China; [b]Center for Lunar and Planetary Sciences, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China; [c]University of Chinese Academy of Sciences, Beijing, China; [d]Puding Karst Ecosystem Observation and Research Station, Chinese Academy of Sciences, Puding, China; [e]CAS Center for Excellence in Quaternary Science and Global Change, Xi'an, China; [f]Guizhou Provincial Key Laboratory of Geographic State Monitoring of Watershed, Guizhou Education University, Guiyang, China; [g]College of resources and environmental engineering, Guizhou University, Guiyang, China; [h]School of Geography and Environmental Sciences, Guizhou Normal University, Guiyang, China

ABSTRACT

Soil moisture restricts the ecological restoration in karst, but studies on soil moisture storage (SMS) in karst are lacking. Thus, this study analyzed the characteristics of SMS in the karst area of China (K) and revealed the relationships of SMS with its influencing factors. The main results are as follows: (1) Average SMS in K is higher than that in the non-karst area (N). However, when SMS is below the thresholds 12 mm (0–7 cm) and 563.6 mm (0–289 cm), SMS in K is lower than that in N. (2) SMS in K experienced a decreasing trend in 1979–2017. (3) SMSs of K and N increase with precipitation class, but the SMS in K is more sensitive to precipitation. (4) SMSs of Agriculture and Forest landcovers in K significantly reduced in 1979–2017. Overall, the SMSs in K are high, but the soil water is easily lost due to serious soil erosion.

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KEYWORDS
Karst; soil moisture storage; precipitation; elevation; land cover

1. Introduction

Soil moisture affects soil temperature, soil fertility as well as soil aeration, and effective soil water is one of the basic conditions for plant growth (Tardieu and Katerji 1991; Yan et al. 2018). Meanwhile, soil water is the link between surface water, atmospheric water, groundwater and soil water (Yang and Tian 2005; Fatichi et al. 2016). It is a key parameter in the hydrological and climatic models (Koster et al. 2004). The current research about soil water focuses on characteristics of soil hydrological process, effects of soil moisture on vegetation growth and feedbacks between soil moisture and climate (Akbar et al. 2018; Deng et al. 2018), and studies about soil moisture storage (SMS) are lacking. Under the background of global change and development of modern agriculture, climate and water resources at the regional scale have changed significantly (Vorosmarty et al. 2000).

CONTACT Xiaoyong Bai baixiaoyong@vip.skleg.cn
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Therefore, the study of temporal and spatial characteristics of SMS has been urgent in recent decades, which is conducive to agricultural water resources planning and management, rational allocation and arrangement of irrigation water, and promote the sustainable development of agroforestry, especially in the karst region (Ibrahim and Huggins 2011).

Influenced by the geological background and water chemical dissolution, the typical karst has a unique hydrological and geomorphic structure with a double-layer (surface and underground) hydrodynamic system, and the surface water leakage is severe (Bailly-Comte et al. 2009). Moreover, the terrain in the karst area is rugged, and with the broken surface, barren soil and low vegetation coverage, the ability of karst ecosystem to resist external disturbance is poor. More importantly, coupled with the impact of human activities, soil erosion in karst area is intensified, and leading to the formation of karst rocky desertification landscape (Wang et al. 2004), and special karst drought occurs (Zhang et al. 2006). Therefore, soil moisture has become a limiting factor for the restoration of the karst ecological environment, the study of which plays an important role in the management of water resources and ecological restoration, and agricultural industrialization in karst areas (Hartmann et al. 2014). However, current research scales of soil moisture characteristics in karst areas are confined to slope scale and small watershed scale (Fu et al. 2014; Liu et al. 2017), and distributions of soil and water in karst areas are featured with strong heterogeneity (Bautista et al. 2011; Yin et al. 2013). Thus, the application of previous conclusions in large-scale soil moisture is uncertain and the researchers fail to highlight the unique characteristics of soil moisture in karst areas. Therefore, based on the comparison between karst and non-karst areas, we studied the spatial pattern and temporal evolution of SMS with soil thicknesses of 0–7 and 0–289 cm in the karst area of China. Additionally, soil moisture and its storage are affected by precipitation, topography, and land cover (Chen et al. 2010; Yang et al. 2014; Toohey et al. 2018). Thus, we also revealed the characteristics of SMS in karst area under different precipitation, elevation, gradient classes and land cover types, which can better serve the utilization of agricultural water resources and the restoration of karst areas with fragile ecological environment.

2. Materials and methods

2.1. Data source

The monthly soil moisture dataset (1979–2017) (https://www.ecmwf.int/) comes from ERA-Interim reanalysis with the spatial resolution of 0.125° (Dee et al. 2011). The dataset provides four layers of soil moisture data at soil depths of 7, 28, 100 and 289 cm; the unit is soil volumetric moisture content, m^3/m^3. The soil moisture product has been validated and applied in the analysis of temporal and spatial variations of soil moisture, hydrometeorology, numerical simulation, and other fields. Soil absolute depth to bedrock map (unit: cm) with the spatial resolution of 250 m is generated by using the global compilation of soil ground observations, and its accuracy assessment is available in (Hengl et al. 2017). The multi-year average annual precipitation and elevation maps are obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/) with the spatial resolution of 500 m and 1 km, respectively. The annual land cover maps (1992–2015) are provided by ESA CCI (http://maps.elie.ucl.ac.be/CCI/viewer/) with spatial resolution of 300 m. The shapefiles of karst and non-karst boundaries in China are obtained by the spatial processing of the carbonate rock outcrops

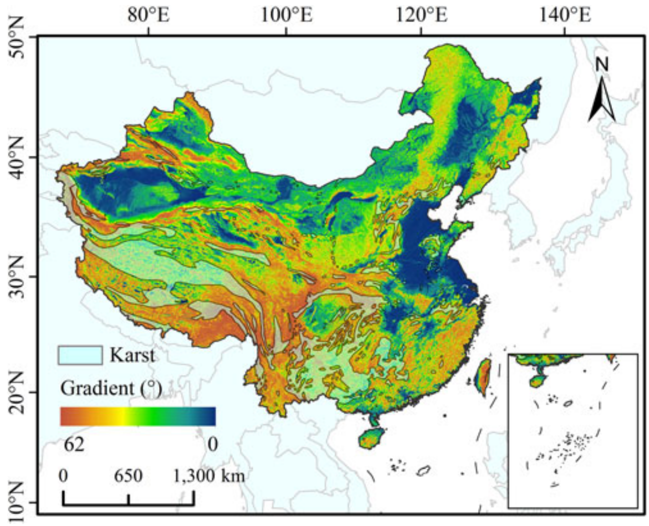

Figure 1. Gradient map and the spatial distribution of the karst area in China.

map provided by Geography and Environmental Science, University of Auckland (http://www.sges.auckland.ac.nz/sges_research/) and Chinese administrative vector boundary provided by Resource and Environment Science Data Center of Chinese Academy of Sciences. The spatial resolutions of the above gridded data are interpolated to 0.125° by the nearest method.

According to the classification of dry and wet zones in China, the multi-year average annual precipitation is divided into 1 (Precipitation < 200 mm), 2 (200 < Precipitation < 400 mm), 3 (400 < Precipitation < 800 mm), 4 (800 < Precipitation < 1200 mm), 5 (1200 < Precipitation < 1600 mm), 6 (1600 < Precipitation < 2000 mm) and 7 (Precipitation > 2000 mm). Referring to Li et al. (2008), the elevation of China is divided into 1 (Elevation < 0), 1 (0 < Elevation < 1000 m), 3 (1000 < Elevation < 2000 m), 4 (2000 < Elevation < 4000 m), 5 (4000 < Elevation < 6000 m) and 6 (Elevation > 6000 m), which are negative terrain, low elevation, middle elevation, sub-high elevation, high elevation and extremely high elevation, respectively. The gradient map in Figure 1 was extracted from DEM data and is classified into 1 (Gradient < 2°), 2 (Gradient < 6°), 3 (6° < Gradient < 15°), 4 (15° < Gradient < 25°) and 5 (Gradient > 25°). In this article, the area with land cover classes unchanged from 1992 to 2015 is selected, and the land cover classes are merged into eight categories: Agriculture, Forest, Grassland, Wetland, Shrubland, Sparse vegetation, Urban and Bare area.

Karst area in China is over 3 million km^2 (including those buried under non-soluble rocks), which is more than one-third of the total land area of China. Particularly, the karst mountainous areas of Yunnan, Guizhou, and Guangxi Provinces in Southwest China have a total area of 320,000 km^2, which is one of the largest karst concentrated distribution areas in the world (Li et al. 2018). The karst area involved in this study belongs to the outcrop type (Figure 1). The multi-year average annual precipitation in the karst area of China is 24.7–2362.2 mm, the multi-year average temperature ranges from –25.2 °C to 24 °C, and the average elevation is 2887 m. In the non-karst area of China, the multi-year average annual precipitation is 8.2–2526.4 mm, the multi-year average temperature is –25.2 °C to 28 °C, and the average altitude is 1572 m. Notably, the carbonate rock background makes the formation rate of soil more than 20 times slower than non-carbonate rock type.

2.3. Methods

Based on soil volume water content, V, and soil depth, H, the calculation method of SMS, S, is as follows:

Calculate the SMS in the soil thickness range of 0–7 cm:

$$S = \begin{cases} 10V_{L1}H & 0 \leq H \leq 7 \\ 70V_{L1} & H>7 \end{cases} \tag{1}$$

Calculate the SMS of the whole soil layer in the thickness range of 0–289 cm:

$$S = \begin{cases} 10V_{L1}H \;\; 0 \leq H \leq 7 \\ 70V_{L1} + 10V_{L2}\;(H–7)\;\; 7<H \leq 28 \\ 70V_{L1} + 210V_{L2} + 10V_{L3}\;(H–28)\;\; 28<H \leq 100 \\ 70V_{L1} + 210V_{L2} + 720V_{L3} + 10V_{L4}(H–100)\;\; 100<H \leq 289 \\ 70V_{L1} + 210V_{L2} + 720V_{L3} + 1890V_{L4}\;\; H>289 \end{cases} \tag{2}$$

V_{L1}, V_{L2}, V_{L3} and V_{L4} in the above formulas represent the soil moisture of 0–7, 7–28, 28–100 and 100–289 cm soil layers, respectively. For the convenience of description, the soil layers with thicknesses of 0–7 and 0–289 cm are referred to as L_S and L_W, respectively.

The Y_i and T_i represent the SMS and the corresponding time, respectively. The linear regression between Y_i and T_i is established. The specific formula is as follows:

$$\hat{Y}_i = \alpha + \beta T_i \tag{3}$$

$T_1 = 1979$, $T_2 = 1980$, $\ldots$, $T_{39} = 2017$. The least square method is used to estimate the regression constant α and regression coefficient β in the formula.

3. Results and analysis

3.1. Spatiotemporal evolution differences of SMS in karst and non-karst areas

3.1.1. Spatial distribution of SMS

Figure 2 shows that the SMSs of karst and non-karst in L_S range from 0 to 29.2 mm, but the average SMS in karst area (17.34 mm) is higher than that in the non-karst area (16.32 mm). The spatial pattern of SMS is similar to that of precipitation in Supplementary Figure S1. The SMSs of karst and non-karst areas with large precipitation are high in the south of China, whereas they are low in the north inland arid areas of China. The SMSs of karst and non-karst area in L_W are 0–1038.5 and 0–1077.3 mm, respectively, and the average SMS in karst area remains higher than that in the non-karst area with a difference of 23.93 mm. The existence of a two-dimensional structure and vertical leakage in karst areas easily lead to soil erosion (Wang et al. 2001; Febles-Gonzalez et al. 2012). Thus, the SMS of the karst area should be lower than that of the non-karst area. However, it is inconsistent with the result of our study, which may be attributed to the influence of the study scale and soil thickness. In Figure 2, the spatial distribution of SMS in L_W (0–289 cm) calculated by cumulative SMSs of four soil layers (0–7, 7–28, 28–100 and 100–289 cm) is similar to that of L_S (0–7 cm), and their spatial correlation coefficient is 0.872 for karst area and 0.896 for non-karst area. In addition, the areas with

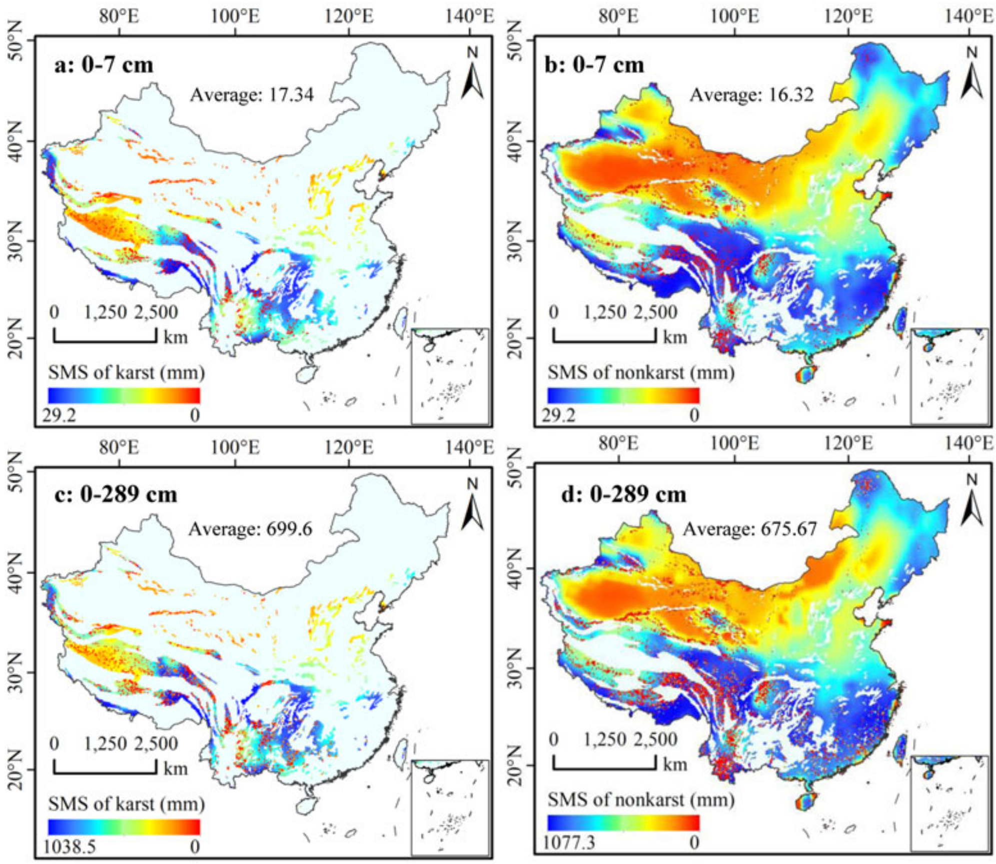

Figure 2. Spatial distributions of multi-year average SMSs of karst and non-karst areas in China.

SMS of 0 mm in L_S and L_W mainly distribute in the arid northwest of China and the eastern edge area with a large topographical gradient of the Qinghai–Tibet Plateau.

Thresholds of 12 mm for L_S and 563.6 mm for L_W in the difference of SMS between karst and non-karst areas were indentified from the cumulative percentage curves in Figure 3. The SMS of the non-karst area is higher than that of karst area when SMS is below the threshold. But, the average SMS of karst area is higher than that of non-karst area, possibly aaffected by the soil volume water content or the soil thickness of 0 cm. From the quartile, SMSs in karst and non-karst areas show a negative skewness distribution with the average annual SMSs less than the median. The spatial variability coefficients of SMSs in karst and non-karst areas are 0.39 and 0.33 in L_S, and 0.43 and 0.34 in L_W, respectively, suggesting that the spatial heterogeneity of SMS in karst area is stronger than that in non-karst area and is enhanced with the increase of soil depth, which is possibly influenced by the strong heterogeneity of soil distribution or the complex topographic structure in karst.

3.1.2. Change trend of SMS

The SMSs in karst and non-karst areas of China experienced a downtrend in L_S and L_W during 1979–2017 (Figure 4), which is consistent with the trend of global soil moisture (Sheffield and Wood 2008; Albergel et al. 2013). The decrease rates of SMSs in karst and non-karst areas are similar within the same soil thickness range, with rates of −0.0097 and

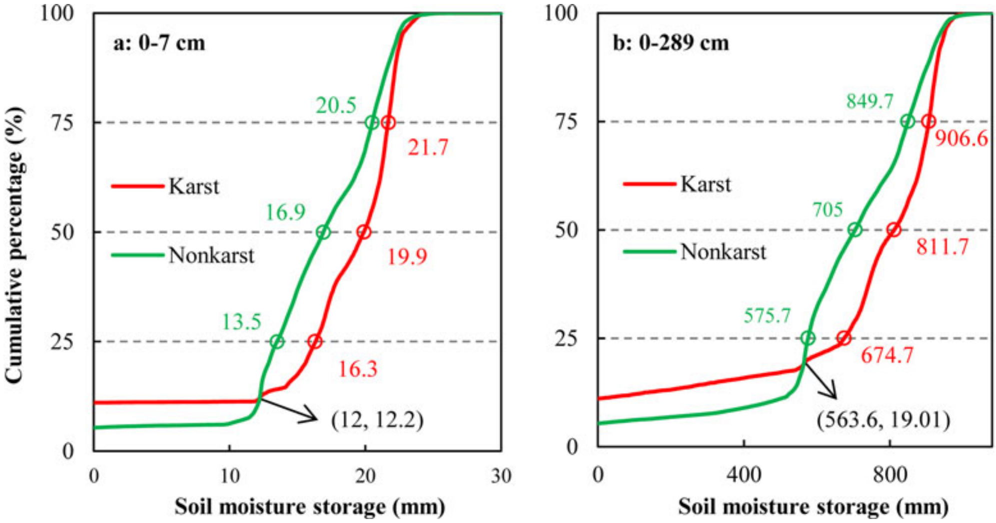

Figure 3. Cumulative percentage curves of SMS in karst and non-karst areas. Hollow circles and data labels in Figure 3 represent 1/4, 1/2 and 3/4 quantiles and corresponding SMSs.

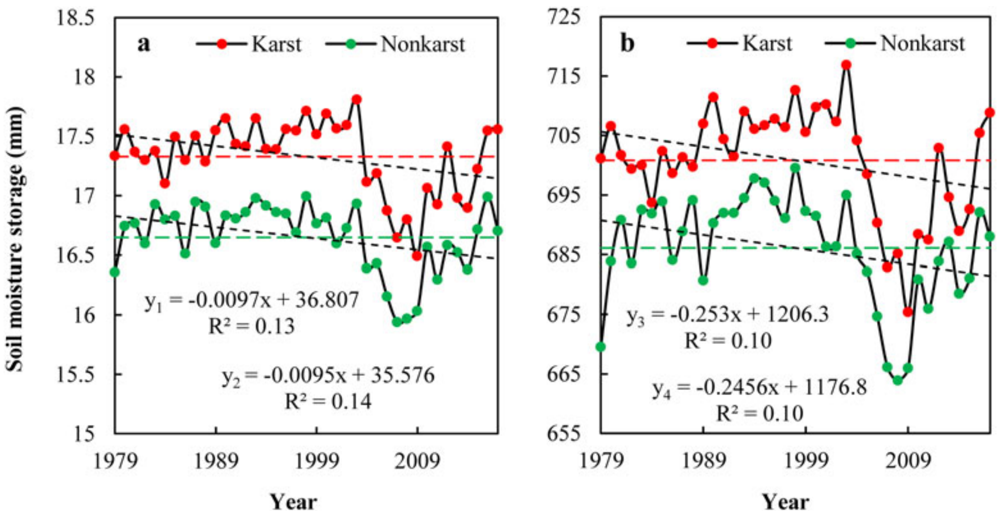

Figure 4. Interannual variations and changing trends of SMS anomalies in karst (a) and non-karst (b) areas with different soil thicknesses. Red dashed line and green dashed line represent the mean SMS of annual series in karst and non-karst areas, respectively; y_1 and y_2 in Figure 4a represent linear equations of SMS at 0–7 cm in karst and non-karst areas, respectively; y_3 and y_4 in Figure 4b represent linear equations of SMS at 0–289 cm in karst and non-karst areas, respectively.

–0.0095 mm/yr in L_S as well as –0.253 and –0.02456 mm/yr in L_W, respectively. These rates indicate that the current trend of SMS may have adverse effects on agriculture and ecology, and corresponding measures for water management and regulation should be put forward. From 2004 to 2015, the SMSs in karst and non-karst areas were lower than the multi-year average SMSs, and the soil was in a dry state. Overall, the interannual variations in karst and non-karst areas are similar, but the fluctuation directions are different in some years. For example, in Figure 4(a,b), the interannual variations of SMSs in karst and non-karst areas in 1989–1997 exhibit significant difference.

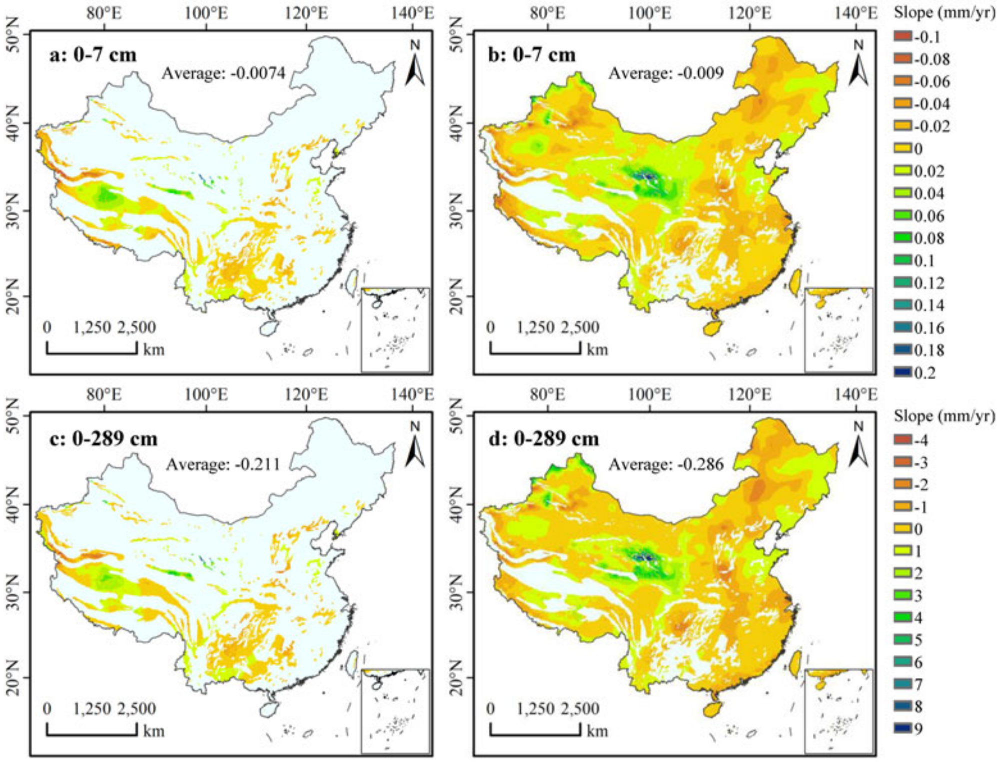

Figure 5. Spatial distributions for variation trends of SMS in karst (a and c) and non-karst areas (b and d) at soil thicknesses of 0–7 and 0–289 cm from 1979 to 2017.

At the pixel scale (Figure 5), the variation trends of SMS in L_S and L_W in karst and non-karst areas are dominated by the decrease, but the significant regional difference is also observed. Spatially, the mean rates of SMS change in karst and non-karst areas in L_S are –0.0074 and –0.009 mm/yr, respectively, whereas those in L_W are –0.211 and –0.289 mm/yr, respectively. These rates disclose that the decrease rate of SMS in the non-karst area is faster than that in the karst area at the pixel scale. In the karst area of China, the decreased areas in L_S and L_W account for 68.88% and 68.12%, respectively, and the average change rates of corresponding areas are –0.02 and –0.702 mm/yr, respectively. In the non-karst area of China, the decreased areas in L_S and L_W account for 60% and 58.28%, respectively, and their average change rates are –0.019 and –0.702 mm/yr, respectively. Furthermore, areas with SMS increasing were also observed in the karst and non-karst areas of China. For example, the SMSs in karst areas of the central Qinghai–Tibet Plateau show an increasing trend. The SMSs in the non-karst areas of Western China, centred on the Qilian Mountains, also show an increasing trend, and the increasing rate decreases to the periphery.

3.2. Difference of SMS between karst and non-karst areas based on precipitation class

Precipitation is a critical factor affecting soil moisture. Figure 6(a) shows that SMSs in karst and non-karst areas increase with precipitation class, but the SMS of the non-karst area under the highest precipitation class is relatively low, which may be due to the wide coverage of the non-karst area and the thinner soil thickness of precipitation class 7. In L_S, SMS of karst area

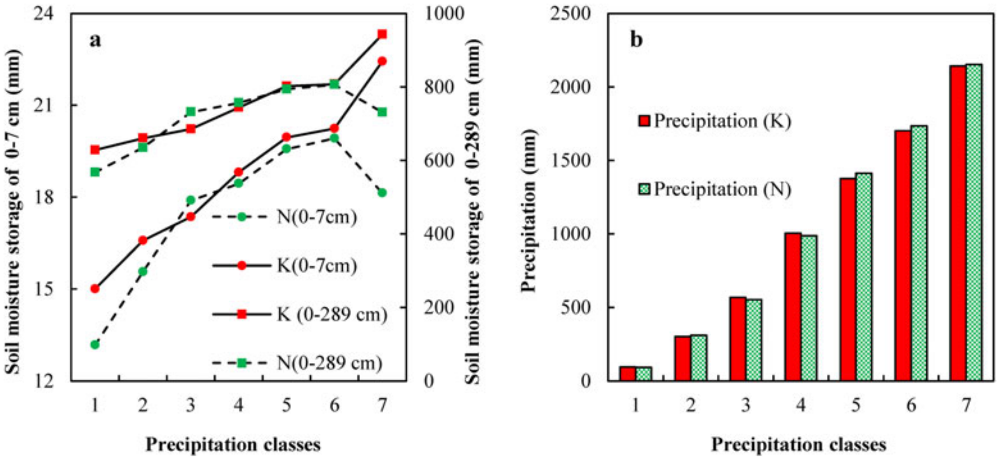

Figure 6. Average SMSs and average precipitation at different precipitation classes in karst and non-karst areas. K and N denote the karst area and non-karst area.

is higher than that in non-karst area for all precipitation classes, except for precipitation class 3, and the SMS of non-karst area (17.89 mm) is slightly higher than that in karst area (17.35 mm). In L_W, SMSs at precipitation classes 3 and 4 in karst area are higher than those in non-karst area. The variation curve of SMS with precipitation class tends to be steeper in karst area than in non-karst area for two soil thickness ranges, indicating that the response of SMS to precipitation in the karst area is more sensitive than that in the non-karst area. It suggests that the SMS of the karst area is more susceptible to extreme precipitation events. Figure 6(b) shows that the average annual precipitation of non-karst area is higher than those in karst area at precipitation classes 2, 5, 6 and 7 with differences of 7.62–36.16 mm. This finding is opposite to the differences in the average SMSs of the corresponding precipitation classes between karst and non-karst areas, suggesting that other factors cause differences in SMSs between karst and non-karst areas.

3.3. Difference of SMS between karst and non-karst areas based on elevation class

The relationship between SMS and elevation in karst and non-karst areas is quite different (Figure 7). The SMS of karst area decreases with the increase of elevation class and reaches the minimum at high elevation (elevation class 5) in L_S and sub-high elevation (elevation class 4) in L_W, respectively, which are 16.62 and 652.51 mm, respectively. The SMS of non-karst area increases with the elevation class; within two soil thickness ranges, the SMS is lowest at middle elevation (elevation class 3), which are 14.36 mm for 0-7 cm and 606.01 mm for 0-289 cm. Comparing the SMSs between karst and non-karst areas at the same elevation class, the SMS in karst area is higher than that in non-karst area overall, but the SMS of non-karst area is higher than that in karst area at high elevation (over 4000 m) and extremely high elevation (over 6000 m) areas. When compared with the lower elevation class, the SMSs in both karst and non-karst areas decrease at middle elevation class and increase at very high elevation.

3.4. Difference of SMS between karst and non-karst areas based on gradient class

Significant differences in the relationship between SMS and gradient class are observed in karst and non-karst areas (Figure 8(a)). In L_W, the SMS decreases with the increase of

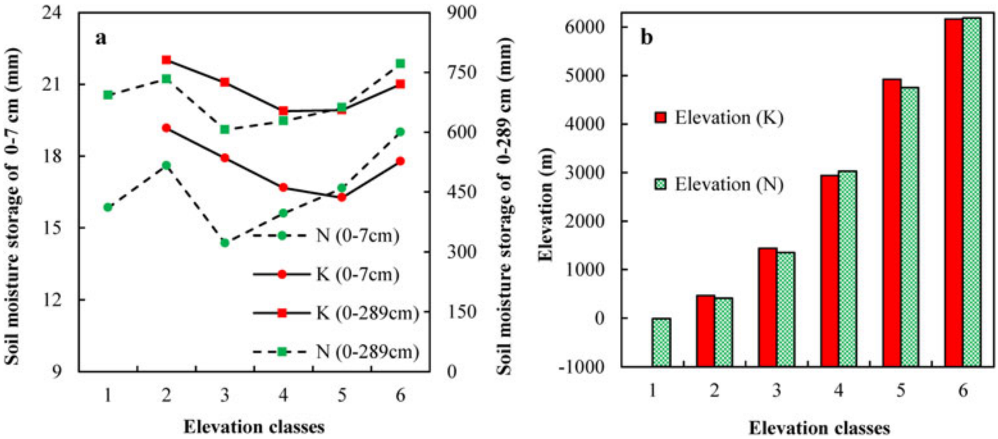

Figure 7. Average SMSs and average elevations at different elevation classes in karst and non-karst areas. K and N denote the karst area and non-karst area.

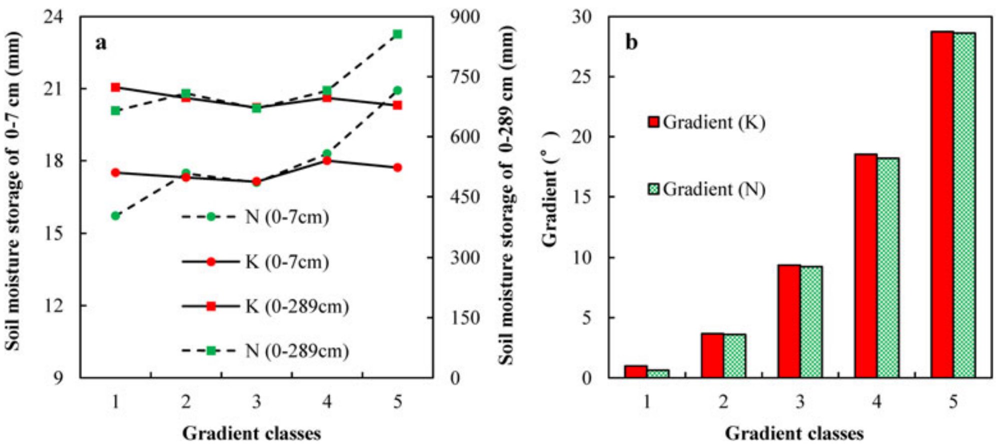

Figure 8. Average SMSs and average gradients at different gradient classes in karst and non-karst areas. K and N denote the karst area and non-karst area.

gradient class, which is possibly caused by the serious soil erosion and thin soil layer. However, in L_S, the SMSs of karst areas increase slightly with the increase of gradient class, which is inconsistent with the findings of Yang et al. (2014). The SMS in the karst area is the least at gradient class 3. The SMSs of non-karst areas in L_S and L_W increase with the gradient class.Under the same gradient class and different soil thicknesses, the SMS in karst area at class 1 is higher than that in non-karst area, butthe SMSs at gradient classes 2, 4 and 5 are lower than those in non-karst area; and the SMSs in karst and non-karst areas at gradient class 3 are similar. Figure 8(b) demonstrates that the average gradient of karst area is slightly higher than that of non-karst area in different classes.

3.5. Difference of SMS between karst and non-karst areas under land cover classes

For various land cover classes (Figure 9), the maximum SMS of karst area in L_S is 19.02 mm for Forest, followed by Wetland, Agriculture, Grassland, Sparse vegetation,

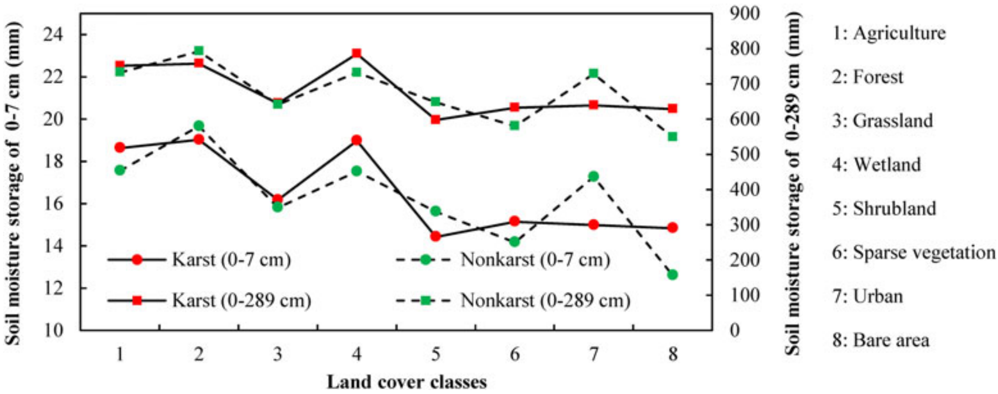

Figure 9. Average SMSs of different land covers in karst and non-karst areas.

Table 1. SMS trends (mm/yr) under different land cover classes and soil thicknesses in karst and non-karst areas.

Soil depth	1	2	3	4	5	6	7	8
K (0–7 cm)	−0.012*	−0.01*	0	0.005	−0.002	−0.005	0.012	−0.014
N (0–7 cm)	−0.013*	−0.011*	−0.003	−0.012*	−0.006	−0.013*	−0.015*	−0.007*
K (0–289 cm)	−0.458*	−0.347*	0.085	0.487*	−0.033	−0.068	1.52*	−0.398
N (0–289 cm)	−0.451*	−0.394*	−0.003	−0.329	−0.069	−0.434*	−0.510*	−0.249***

Note: In table, K and N denote the karst area and non-karst area, and 1, 2, 3, 4, 5, 6, 7, 8 represent Agriculture, Forest, Grassland, Wetland, Shrubland, Sparse vegetation, Urban and Bare area, respectively.
*, ** and *** indicate significance at $p < .01$, $p < .05$ and $p < .001$, respectively.

Urban, and Bare area; Shrubland has the least SMS of 14.43 mm; in L_W, the maximum SMS in Wetland is 785.57 mm, followed by Forest, Agriculture, Grassland, Urban, Sparse vegetation and Bare area; the SMS of Shrubland remains the lowest 597.42 mm. In the non-karst area, SMSs of L_S under different land cover classes are similar to those of L_W. Concretely, the average SMS of Forest is the largest with 19.66 mm in L_S and 792.55 mm in L_W, whereas those of Bare area are the smallest with 12.61 mm in LS and 549.21 mm in LW. In two soil thicknesses, the average SMSs of Agriculture, Wetland, and Sparse vegetation in karst area are higher than those in non-karst area. From Agriculture to Bare area, the vegetation approximately declines, and the SMSs in karst and non-karst areas decrease in both L_S and L_W.

Table 1 shows that in 1979–2017, the SMSs of Agriculture and Forest in karst area exhibited a significant decreasing trend in L_S, and those of Shrubland, Sparse vegetation and Bare area experienced a non-significant decreasing trend, with Bare area decreasing fastest, followed by Agriculture, whereas the SMSs of Wetland and Urban showed a non-significant increasing trend. In L_S, SMSs of eight land covers in non-karst area went down in 1979–2017 overall. Among them, the SMS of Urban decreased the fastest, followed by Agriculture, and Sparse vegetation,and the SMS of Grassland decreased the slowest. Comparing the changing trends of SMS in karst and non-karst areas under the same land cover, the reduction rate of SMS in non-karst area was faster than that in karst area except Bare area. In L_W, the average SMS trends of different land cover types in karst and non-karst areas were consistent with those in L_S, but the increase trends of SMSs in L_W of Wetland and Urban in karst were significant. The SMSs of Agriculture and Forest in karst and non-karst areas declined significantly in L_S and L_W, and their rates were relatively faster than those of other land covers, which reveals that agricultural water resources from the soil itself are reducing and may affect agricultural production, especially in ecologically fragile karst areas.

4. Discussion

4.1. Differences in SMS between karst and non-karst areas in China

Figure 10(a) displays that the average soil moisture in karst and non-karst areas of China rises with the increase of soil depth, and the soil moisture in karst area is higher than that in non-karst area. Figure 10(b) shows that the soil in non-karst area is thicker than that in karst area; the average soil thickness in karst area is 11.96 m, whereas that in non-karst area is 27.10 m. It illustrates that the SMS in karst area is larger than that in non-karst area overall due to the influence of higher soil water content. The cumulative percentage curves of SMS in Figure 3 shows that the threshold is 12 mm in L_S and 563.6 mm in L_W, respectively. When the SMS is less than the threshold, the SMS in karst area is lower than that in non-karst area. Supplementary Figure S2 shows that these areas are located in the western part of China, where the terrain is undulating, and the climate is dry, such as the Taklimakan Desert.

Table 2 shows that when SMS $\leq$ 12 mm in L_S, the SMS in karst area is lower than that in non-karst area because of the thinner soil thickness in karst area; when SMS is over 12 mm in L_S, the SMS in karst area is higher than that in non-karst area because of the higher soil moisture and thicker soil in karst area. In L_W, the reasons are similar. The

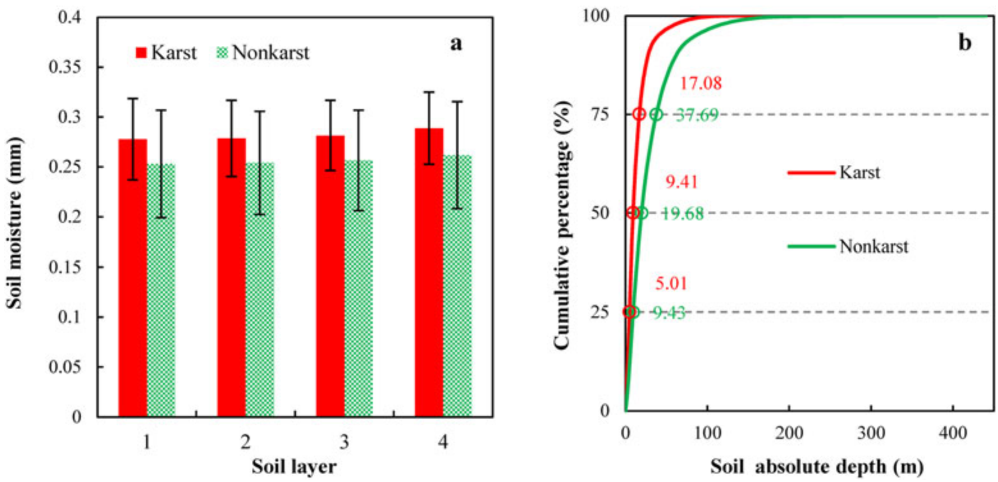

Figure 10. Average soil moisture at different thicknesses (a) and cumulative percentage curves of the absolute soil depths in karst and non-karst areas (b). In Figure 10(a), 1, 2, 3 and 4 of abscissa axis denote 0–7, 7–28, 28–100 and 100–289 cm soil layer, respectively. In Figure 10(b), hollow circles and data labels represent 1/4, 1/2 and 3/4 quantiles and corresponding soil depths.

Table 2. Average soil moisture and average soil depths in karst and non-karst areas calculated with SMS thresholds as the breakpoints.

Soil thickness (cm)	SMS range (mm)	Karst					Non-karst				
		SM1	SM2	SM3	SM4	Depth (m)	SM1	SM2	SM3	SM4	Depth (m)
0–7	0–12	0.280	–	–	–	0.002	0.218	–	–	–	0.032
	>12	0.280	–	–	–	0.07	0.249	–	–	–	0.066
0–289	0–563.6	0.277	0.279	0.282	0.290	0.504	0.216	0.218	0.220	0.224	1.777
	>563.6	0.281	0.282	0.286	0.294	2.863	0.253	0.254	0.257	0.263	2.879

Given the actual participation of soil depth in the calculation of SMS, the soil layer thickness over 7 cm is changed to 7 cm in L_S, and the soil thickness over 289 cm is changed to 289 cm in L_W; SM1, SM2, SM3 and SM4 represent soil moisture at 0–7, 7–28, 28–100 and 100–289 cm, respectively.

above results show that the karst area has advantages in terms of soil water content compared with non-karst. However, soil water resources in the karst area are easily lost due to serious soil erosion (Drew 1983; Febles-Gonzalez et al. 2012), leading to a high risk of water shortage. In particular, karst rocky desertification landscapes have occurred in karst areas in southwestern China where there is no enough soil to erode (Bai et al. 2013).

4.2. Reasons for differences in SMS between karst and non-karst areas in different environmental factors

In L_S and L_W, the SMSs of different precipitation/elevation/gradient classes in the karst area of China are different; furthermore, differences of SMSs between karst and non-karst areas are found under the same soil depth range, elevation, or gradient class, which seems to indicate that SMSs are affected by geological background, precipitation, elevation, and gradient. We observed that the SMS in the non-karst area increased with the gradient class. This observation contradicts the conventional understanding that the steeper the gradient, the more easily soil and water are lost, and the less SMS is (Yang et al. 2014). For the similar performance of SMSs in L_S and L_W, this article takes L_W (0–289 cm) as the representative to analyze the reasons. Precipitation can directly recharge soil water. Figure 11 shows that the annual precipitation and soil thickness in karst and non-karst areas decrease with the increase in elevation class. In elevation classes 2–4 and 6, the average annual precipitation in karst is higher than that in non-karst background, but the average soil thickness in corresponding elevation class is thinner than that in non-karst area. At elevation class 5, it is the opposite . Combined with Figure 7, the average SMS in karst area is higher than that in non-karst area due to the influence of annual precipitation at sub-high elevation and below. At extremely high elevation, the soil thickness determines that the average SMS in non-karst area is higher than that in karst area.

In Figure 11(b), the average annual precipitation in karst and non-karst areas increase with gradient class, which is more significant in non-karst areas, whereas the average soil thickness decreases with the increase of gradient class. Moreover, precipitation leads to the increase of SMS with gradient class in the non-karst area of China, revealing that the influence of gradient on SMS is weakened by precipitation at the mesoscale or regional scale, and the relationship between SMS and gradient at the slope scale is not applicable to the mesoscale scale. At gradient class 1, the annual precipitation in karst area is

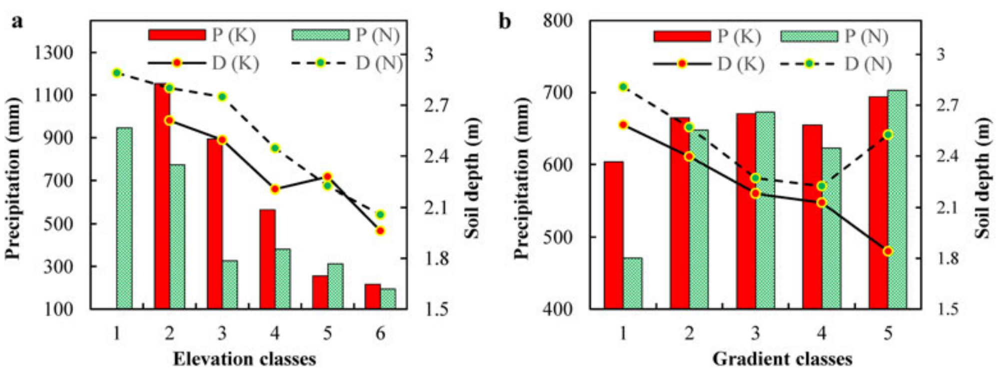

Figure 11. Average soil depths and corresponding precipitation in karst and non-karst areas at the same elevation (a) or gradient (b) class with soil thickness ranging from 0 to 289 cm. P and D represent precipitation and soil depth, respectively; K and N denote the karst area and non-karst area.

132.79 mm more than that in non-karst area, which makes the SMS in karst area higher than that in non-karst area. At gradient class 5, the average annual precipitation and average soil thickness in non-karst area are 9.04 mm and 0.68 m greater than that in karst area, respectively, causing higher SMS in non-karst area than that in karst area at this gradient class.

5. Conclusion

Using ERA-Interim soil moisture data, this article calculated the SMSs in karst and non-karst areas of China, revealed the spatial characteristics and changing trend of SMS in karst area by comparing with non-karst area, and analyzed the characteristics, differences, and reasons of SMSs under different precipitation, elevation, gradient classes, and land cover types for karst area. Our findings are as follows:

1. Influenced by soil moisture, the average SMSs at soil thicknesses of 0–7 and 0–289 cm in the karst area of China are higher than those in the non-karst area of China. However, due to the effect of soil thickness, the SMS in karst area of China is lower than that in non-karst area when the SMS is below the threshold of 12 mm for 0–7 cm and 563.6 mm for 0–289 cm, respectively.
2. Overall, the SMSs of 0–7 and 0–289 cm decreased in karst and non-karst areas of China from 1979 to 2017, and the reduction rates in different geological backgrounds are similar. However, at the pixel scale, the regional difference of SMS trends is significant, and the average decrease rate of non-karst area is faster than that of karst area.
3. SMSs in karst and non-karst areas increase with the precipitation class. The SMSs of karst areas with precipitation below 400 mm and above 2000 mm are larger than those in non-karst areas. The SMS of karst area is more sensitive to precipitation, indicating that SMS in karst area is more vulnerable to extreme precipitation events.
4. The SMS in the karst area decreases with the increase of the elevation class, whereas that in the non-karst area shows the opposite result. At elevation classes below 4000 m, the SMS of karst area is greater than that of non-karst area due to more precipitation. In areas with an elevation over 6000 m, the SMS of karst area is lower than that of non-karst area due to thinner soil thickness.
5. The SMS in karst area decreases with the increase of gradient class overall at the soil depth of 0–7 cm. However, the non-karst area generally shows an increasing trend because, at the regional scale, precipitation conceals the law applied to small scales that the SMS decreases with the increase of the gradient class.
6. The SMSs of various land covers are different in karst and non-karst areas. At soil thicknesses of 0–7 and 0–289 cm, SMSs of Agriculture and Forest are higher than that of other land covers, and their SMSs in 1979–2017 experienced a significant decreasing trend, which is not conducive to agricultural production and vegetation restoration.

The calculation of SMS used in this article is simple, which neglects some details, such as the difference in soil water content in the same soil layer (e.g. 0–7 cm). However, this study revealed the spatial pattern and changing trend of SMS in karst area on a relatively large scale, and identified its particularities compared with the non-karst area, which is unable to be found by studying soil moisture only.

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