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Spatial association between landslides and environmental factors over Guizhou Karst Plateau, China

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Abstract Guizhou Karst Plateau is located at the center of the karst region in Asia, where landslides are a typical disaster. Affected by the local karst environment, the landslides in this region have their own characteristics. In this study, 3975 landslide records from inventories of the Guizhou karst plateau are studied. The geographical detector method is used to detect the dominant casual factor and predominant multi-factor combinations for the local landslides. The results show that landslides are prone to areas on slopes between 10° and 35°, of clay rock, in close proximity to gullies, and especially in areas of moderate vegetation, dryland, and mild rocky desertification. Continuous precipitation over 10 days has a great effect on landslide occurrence. Compared with the individual factors, the impact of two-factor interaction has greater explanatory power for landslide volume. The volume of earthquake-induced landslides is predominantly controlled by the interactions of faults and slopes, while that of human-induced landslides is affected by the interactions of land cover and hydrological conditions. For rainfall-induced landslides, the dominant interactions vary in different regions. In the central karst basin, the interactions between faults and precipitation can explain over 90% of the variations in landslide volumes. In the southern hilly karst region, the interactions between lithology and slope can explain over 71% of the variations in landslide volume and those between fault and land-use can explain 50% of the variations of the landslide volumes in the northeastern mountainous karst region.

Keywords: Landslides; Karst; Combined impact; Geographical detector method; Environmental factor; Guizhou

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Introduction

Landslides affect both people and infrastructure and cause social, economic and geomorphologic problems around the world (Zhuang and Peng 2014; Haque et al. 2016). In China, landslides have become a frequent hazard, causing approximately 1000 fatalities per year and significant damage to infrastructure over the past several decades (Duan 1999; Jiang 2000; Yin 2001). Identifying landslide distribution and the driving factors behind landslide occurrence provides a scientific basis for the reduction of disasters associated with landslides.

Many qualitative and quantitative analyses of the relationships between causative factors and landslide occurrence have been conducted over the past 20 years. For instance, the distribution and abundance of earthquake-triggered landslides are related to the types of large faults (reverse fault, normal fault, and strike-slip fault) and match the pattern of local historical seismicity (Xu et al. 2014a; Bucci et al. 2016). Seismic landslides affected by normal or reverse faults are prone to occurring on the hanging wall of faults but also have a relationship with slope (Has et al. 2012; Xu et al. 2014b; Xu et al. 2018). Land-use changes can considerably affect landslide behavior (Glade 2003), and those landslides caused by anthropogenic disturbances most commonly occur in populated hilly landscapes and are always limited in size (Van et al. 2006). Even forested regions can be landslide-prone (Ost and Eeckhaut 2003), where both forest structure and terrain can significantly influence landslide susceptibility (Rickli and Graf 2009; Moos et al. 2015).

Although topographical, geomorphological and hydrological features are generally seen as primary factors controlling landslides (Pun et al. 2003; Ayalew and Yamagishi 2005; Miller and Burnett 2007; Westen et al. 2008; Crozier 2009; Guo et al. 2015), the characteristics and mechanisms of landslides remain difficult to identify, especially in areas with significant environmental heterogeneity. Many efforts have been undertaken to study the characteristics of landslide occurrence (Lan et al. 2004; Xu et al. 2014b; Hong et al. 2016) and landslide susceptibility in China (Xu 2001; Bai et al. 2011; He et al. 2012; Peng et al. 2014; Guo et al. 2015). However, the environmental factors and mechanisms that control landslides vary regionally due to the complexity of landslide mechanisms. Meanwhile, rapid socio-economic development has led to an unsustainable ecosystem, increasing the complexity of the landslide mechanism (Gutiérrez et al. 2014).

The Guizhou karst plateau, located at the uplift edge of the Qinghai-Tibet Plateau, is the center of the Asian karst region. Due to the bedrock geology being mainly domestic carbonate and dolomite, the karst landscape accounts for approximately 70% of the total area, covering the entire region with the exception of the southeast *(*Bai et al. 2009; Guo et al. 2013*)*. A number of studies concerning landslide characteristics in Guizhou have been conducted and have mainly focused on landslides occurring in a county or a small area (Wang et al. 2004; Li et al. 2015; Li et al. 2016). Huang et al. (2012) reported the spatial distribution of 321 mountain landslide events throughout Guizhou, but the authors did not perform further analysis. The role played by that combination of karst and environmental factors in suppressing or favoring landslides is always not clear.

In this study, we used 3975 landslide inventory records that cover almost the entire karst region of Guizhou and span from 1952-2005 to 1) study the spatiotemporal distribution of landslides in Guizhou karst Plateau and 2) understand the impacts and combined effect of environmental factors on the occurrence of landslides. The ultimate objective of this work is to understand the characteristics and controlling factors of karst landslides to provide information for further studies in similar karst areas.

1 Study Area

Guizhou is located in southwestern China at latitudes between 24°37′N-29°13′N and longitudes between 103°36′E-109°35′E, of which the west, the north, the northeast and the central are karst region (Figure 1). As the monsoon moves from south to north, extreme rainfall is usually concentrated in the southwest of Guizhou (Chen 2015). To facilitate analysis, we divide Guizhou karst plateau into six regions based on a karst landform map (Department of Agriculture of

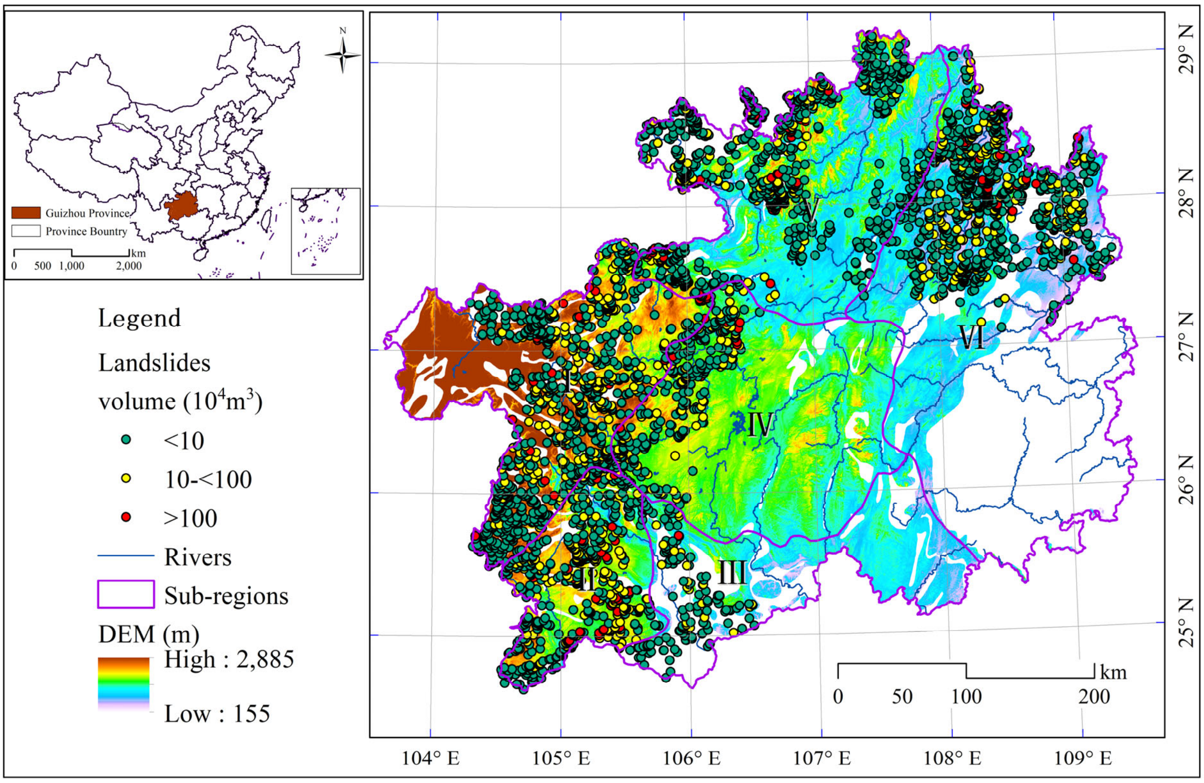

Figure 1 Spatial distribution of landslides in the Guizhou Karst Plateau. The area with white background is non-karst region. Numbers Ⅰ to Ⅵ represent the sub-regions of the western plateau, the southwestern plateau, the southern valley, the central basin, the northeastern mountainous region and the eastern hilly regions, respectively.

Guizhou Province 1995), which classified Guizhou into several sub-regions according to the types of karst landforms. The six sub-regions are the western plateau, the southwestern plateau, the southern valley, the central basin, the northeastern mountainous region and the eastern hilly regions (Figure 1).

2 Data Sources and Methods

2.1 Landslide dataset

The landslide data are obtained from the Geology and Environment Monitoring Bureau of Guizhou Province. According to the classification of Cruden and Varnes (1996), the landslide type is slides. The data include 3975 detailed landslide records that contain the time, place, and volumes for landslides. The triggering factors, such as rainfall, earthquakes, and human activity, are also recorded.

Figure 1 shows the locations of landslides of the karst Guizhou, the investigatory landslides covered almost the mountainous karst region except the central Guizhou where are less likely to occur landslides. The eastern hilly sub-region has the highest number of landslide records, 1072, which is approximately 27% of the total landslide records (3975) used in this study. In order of regional record abundance, the eastern hill sub-region is followed by the 1009 records from the western plateau sub-region, which account for approximately 25% of the total records, and by the 858 records in the northeastern mountainous region, which account for approximately 22% of the total records. There are 581, 275 and 161 landslide records from the southwestern hilly plateau, the central basin and the southern valley, which account for 15%, 7% and 4% of the total records, respectively.

Figure 2 shows the distribution of landslide events along the yearly and monthly coordinates. The annual total landslide events show an increasing trend from 1952 to 2005. Most of the landslides (73%) occurred in the summer from June to August, while 22.5% landslides occurred in the spring from March to May, and only 4.5%

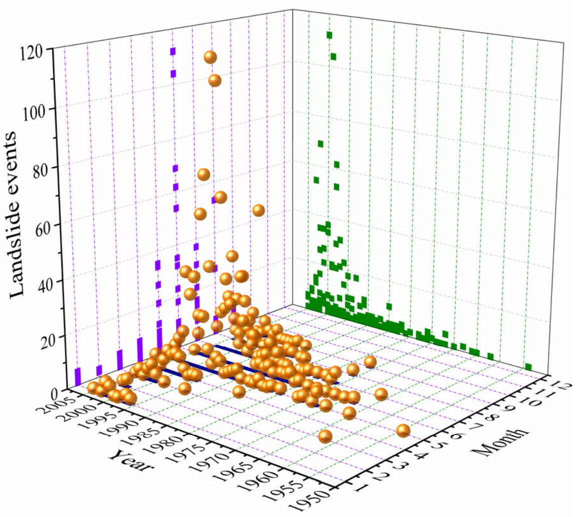

Figure 2 Distribution of landslide events along the yearly and monthly coordinates for all recorded landslide events.

landslides occurred in other seasons.

According to landslide volumes, if the landslides are less than 10^5 m^3, between 10^5 and 10^6 m^3, between 10^6 and 10^7 m^3 or greater than 10^7 m^3, then the landslides are classified as small, medium, large or huge landslides, respectively. According to this classification, most of the landslides that occurred in Guizhou are small and medium landslides. The small landslides account for 72.71% of the rainfall-induced events, 86.94% of the human activity-induced events, and 89.04% of the earthquake-induced events, while the medium landslides account for 22.53%, 12.1%, and 9.59% of the rainfall-induced, human activity-induced, and earthquake-induced landslide events, respectively (Figure 3). The records of large and huge landslide events are relatively rare. Large landslides account for 4.17%, 0.96% and 1.37% of the rainfall-induced, human-induced, and earthquake-induced landslide events, respectively. There are 21 huge landslide events that were triggered by rainfall, accounting for 0.59% of the recorded landslide events.

2.2 Environment factor data sources

The digital elevation model (DEM) with a spatial resolution of 90 m used in this study was derived from the Shuttle Radar Topography Mission (SRTM) (CGIAR-CSI 2012). The Normalized Difference Vegetation Index (NDVI) from May to August with a spatial resolution of 8 km was obtained from the Global Inventory Monitoring and Modeling Studies (GIMMS) group (http://glcf.umd.edu/data/gimms/). The land-use map of 2005 with a spatial resolution of 250 m, the geological map with a scale of 1:500000, and the road map with a scale of 1:100000 were obtained

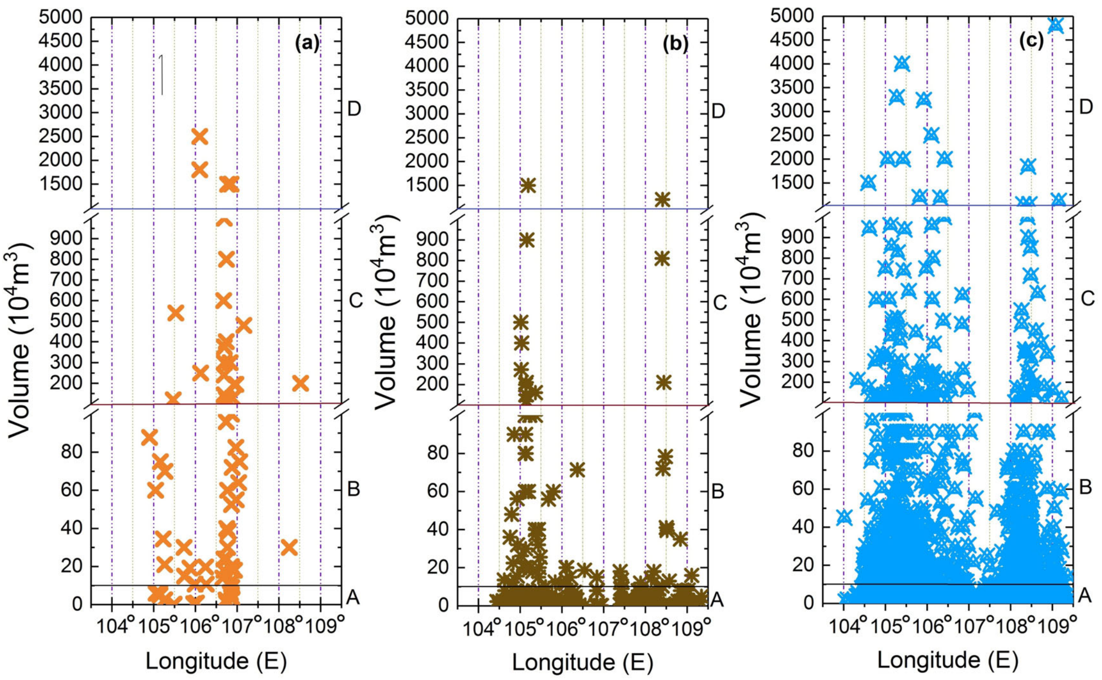

Figure 3 Longitudinal distribution of the landslide volumes for (a) earthquake-induced landslides; (b) human activity-induced landslides and (c) rainfall-induced landslides. A, B, C and D represent small, medium, large and huge landslides, respectively.

from the Data Center of the Institute of Geographical Sciences and Natural Resources Research at the Chinese Academy of Sciences. The degree of rocky desertification, measured at a spatial resolution of 100 m, was obtained from the Institute of Guizhou Mountain Climate and Environment. The daily precipitation data from 87 stations were obtained from the Meteorological Bureau of Guizhou Province, which covers the entire Guizhou. All of the data were resampled to a spatial resolution of 100 m using a simple linear interpolation method in ArcGIS version 10.0.

2.3 Methods

We use an equal interval and Jenks natural breaks classification method to classify the spatial patterns of environmental factors into several strata on the ArcGIS version 10.0 plat-form. As the landslide density is more common and useful to explain where easily prone to landslides (Lan et al. 2002; Bai et al. 2005; Xu et al. 2014b), beside the landslide frequency, the landslide density is dominant used for analyzing the landslides distribution characteristic. Here, the landslide frequency in category *i*, F_i, is calculated as follows:

$$F_i = \frac{N_i}{\sum_i N_i} \tag{1}$$

where N_i is the number of landslides that occurred in category *i*, i is the number of specific category of one environmental factor.

The landslide density is defined as that the landslide number in each equal spacing unit, it is calculated as follows:

$$D_i = \frac{N_{L_i}}{A_i} \tag{2}$$

where D is landslide density, N_L is the number of landslides, N_{Li} is the total number of landslides in the category *i*, A_i is the area of a specific category *i*.

A chi-square test was used to test whether the differences in categories were significant.

For the factors of fault, road, and gully, as their contributions to landslides are dependent on distances (Lin et al. 2006; Wang 2008; Broothaerts 2012; Guo et al. 2015), areas within 5 km or a1 km buffer zone were analyzed. For the lithology factor, as the lithologic map lacks lithologic descriptions of some rocks, these areas must be excluded.

Cumulative precipitation affects landslides occurrence a lot, in the represent paper, the cumulative precipitation is calculated using

$$C_i = \sum_{i=0}^{i} P_i \tag{3}$$

where C_i is the cumulative precipitation for the i^{th} day, and P_i is the precipitation of the i^{th} day before the occurrence of the landslide.

We used the geographical detector method to analyze the relationship between the landslide volume, *V*, and environmental factors, *X*. The geographical detector method is a spatial variation analysis method based on geographic category (Wang et al. 2010). It includes four parts: risk detector, factor detector, ecological detector, and interaction detector. The factor detector indicates the dominant factors responsible for the objective risk. Then, the interactive detector identifies how the interactions of factors enhanced or weakened landslide occurrences. The detailed descriptions of this method are found in Wang et al. (2010). The geographical detector method is based on, when the *V* and *X* spatial distributions are identical, the variable *V* is associated with variable *X*. If factor X explains the pattern of *V* in a better manner, the value of *V* will be uniform across each strata of *X*, and the spatial variance of *V* within all strata will be 0. *X* and *V* are the accumulations of X_i and V_i in all strata, respectively. Therefore, we defined the association between *V* and *X* (factor detector) as the power of the determinant (q):

$$q(X) = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h \sigma_h^{\ 2} \tag{4}$$

where σ^2 is the global variance of *V* across the entire study area, *N* is the total number of sample units across the whole study area, σ_h^2 is the variance of *V* within strata *h* of environmental factor *X*, N_h is the sample units of strata *h*, and *L* is the number of strata (or categories) of factor *X* (*h*=1,2,3…,*L*). The value of *q* indicates to what extent *V* is interpreted by *X*. If *q* [0, 1]=0, there is no association between *V* and *X*. If *q*=1, *V* is completely determined by *X* (*i.e., V* is perfectly spatially stratified heterogeneous).

The definitions of σ^2 and σ_h^2 are as follows:

$$\sigma_h^{\ 2} = \frac{1}{N_h - 1}\sum_{i=1}^{N_h}(V_{h,i} - \overline{V_h})^2 \tag{5}$$

where $V_{h,i}$ is the value of the i^{th} sample unit of *V* in strata h and V_h is the mean of V in strata h. Furthermore,

$$\sigma^2 = \frac{1}{N-1}\sum_{j=1}^{N}(V_j - \bar{V})^2 \quad (6)$$

where V_j is the value of the jth sample unit of the entire study area, and $\bar{V}$ is the mean of V over the entire study area.

The interactions between two different environmental factors X_1 and X_2 are represented by the symbol ∩. The variable $q_{X_1 \cap X_2}$ indicates the power of the determinant of factor for X_1 and X_2, where the value of $q_{X_1 \cap X_2}$ represents a new factor created by overlaying two factors.

3 Results

3.1 Individual causal factor

3.1.1 Slope and aspect

Previous studies have shown that slope gradients have a considerable influence on landslide occurrence (Dai and Lee 2002). Figure 4a

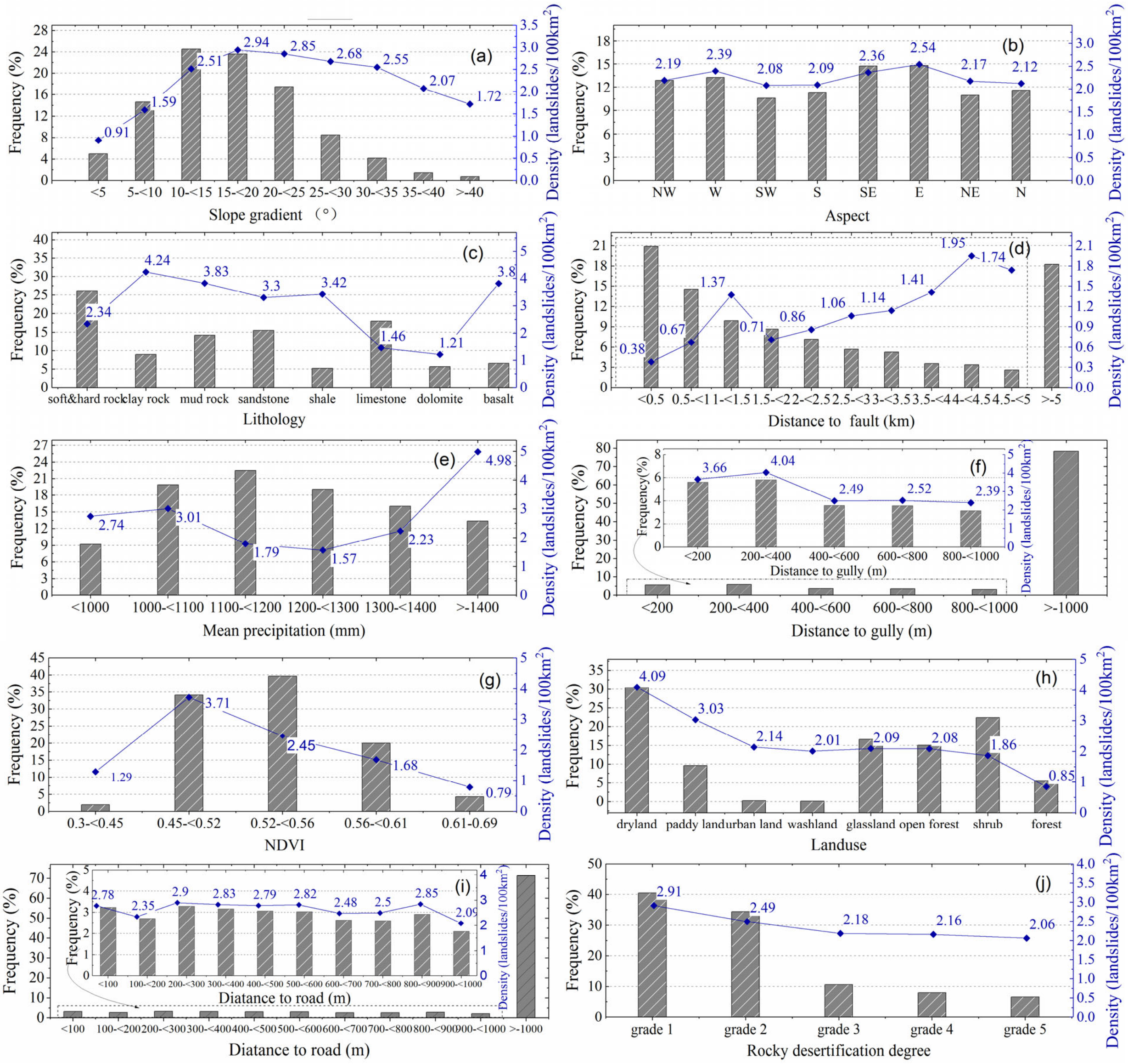

Figure 4 Landslide frequency (shaded bars) and density (blue dots) distributions for each factor strata of the Guizhou Karst Plateau, China: a) slope, b) aspect, c) lithology, d) fault proximity, e) mean precipitation, f) gully proximity, g) Normalized Difference Vegetation Index (NDVI), h) land use, i) road proximity, and j) rocky desertification. f) and i) have given enlarged view of landslide distributed in 1km.

shows that 65.5% of the total landslides distribute within slope gradients between 10°–25°. As high landslide density concentrate on slope gradients ranging from 10° to 35°, with the density of which are all larger than the average value 2.25 events per 100 km², the slope gradients between 10° and 35° is the main environment prone to landslides in the studied karst area. Chi-square tests confirm that the differences in slope gradients are significant (P< 0.001).

Aspect influences both soil moisture retention and vegetation, which in turn affect soil strength and the susceptibility of landslides. Previous studies have shown that areas with south-facing slopes are landslide-prone in the Northern Hemisphere (Qi et al. 2010; Guo et al. 2015). In Guizhou, we found that the eastern facing slopes are relatively landslide-prone. The southeast and east facing slopes have higher landslide frequencies, reaching 14.77% and 14.73%, respectively. Meanwhile, the eastern facing slope has relative high density, which exceeds 2.5 events per 100 km² (Figure 4b). However, chi-square tests show that the differences in aspect are insignificant over the entire area.

3.1.2 Lithology and fault

The lithology is related to the properties of the slope-forming materials, such as strength and permeability; thus, lithology is an important factor that influences the occurrences of landslides (Dai and Lee 2002). In the study area, the lithological types include interbedded soft and hard rock, clay rock, mud rock, sandstone, shale, limestone, dolomite and basalt. The interbedded soft and hard rocks have the highest landslide frequencies, reaching 26.10%. However, the clay rock, mud rock, sandstone, shale, and basalt have higher landslides density, which are larger than 3 events per 100 km². Among them, the clay rock is the dominant rock type prone to landslides (with a density of 4.24 events per 100 km²) (Figure 4c). Chi-square tests confirm that the differences in lithology are significant (P< 0.01).

Faults, which destroy rock structure and reduce slope stability, are densely distributed across the study area. Figure 4d shows that 81.8% of the landslide events occurred within 5 km of faults. Within the 5 km range, the frequencies of landslides decrease as the distance from the faults increase, while the density of landslide keeps increasing trend. Unlike other studies, landslides in the presented karst region are not affected by faults a lot, because the density of landslide near faults is obvious lower than the average value. Chi-square tests confirm that the differences in slope gradient are significant (P< 0.001).

3.1.3 Precipitation and gully

Precipitation increases soil water content and pores water pressure, which increase the probability of landslides. Figure 4e shows that areas with annual total precipitation exceeding 1000 mm have the higher landslide frequencies, and the areas with heavy rainfall (precipitation over 1400 mm) have the highest landslide density, reaching 4.98 events per 100 km², much larger than the average value of the study area. Based on the correlation analysis of the average monthly precipitation and landslide events, we found that the landslide events are highly associated with the number of days with more than 50 mm of precipitation (R^2=0.8, P<0.01). This result shows that precipitation plays a key role in causing slope instability.

Areas near gullies are usually unstable because of water incision and bank erosion (Lin et al. 2006; Broothaerts et al. 2012). In the study area, the statistic result shows that only 21.72% of landslides occurred within 1 km of gullies, while 79.28% of landslides occurred more than 1 km away from gullies. Though a low frequency near gullies, the landslide densities are obvious in high value, ranging from 3.66 events per 100 km² in 200m away from gullies to 4.04 events per 100 km² in 200-400m away from gullies (Figure 4f).

3.1.4 NDVI and land-use

Previous studies have shown that vegetation with strong and large root systems helps improve the stability of slopes (Imaizumi et al. 2008; Kim et al. 2013). NDVI reflects the growth and coverage of vegetation, with higher values representing more mature vegetation systems. In the study area, the highest frequencies of landslides occurred in areas with NDVI values between 0.52-0.56, accounting for 39.63% of the total landslides, and the landslide density has a larger value in area with NDVI between 0.42-0.56 (Figure 4g). Therefore, landslides are infrequent in both higher and lower NDVI areas but are more common in moderately vegetated areas. Chi-square tests confirm that the differences in NDVI are significant ($P< 0.001$).

Unlike the NDVI value, which reflects the greenness and vegetation cover in an area, land use indicates the long-term conditions of the land surface. In particular, human activities related to soil and rock transportation increase the probability of landslide occurrence (Glade 2003). In the study area, dry land is the most landslide-prone, with landslide frequencies of 30.43% and landslide density of 4.09 events per 100 km^2 (Figure 4h), followed by paddy land with density of 3.03 events per 100 km^2. The forest is where landslides are least likely to occur, the landslide frequency and density is only 5.56% and 0.85 events per 100 km^2, respectively. Chi-square tests confirm that the differences in land use are significant ($P< 0.01$).

3.1.5 Road

The development of transportation infrastructure (e.g., roads, railways, and highways) always weakens slope stability (Wang 2008). In the study area, zones within 1 km of roads account for 28.7% of the total landslides (Figure 4i), the landslide density near roads are just slight larger than the average value, indicating that road construction has no much influence on landslide occurrence. Meanwhile, Chi-square tests show that the differences in road within 1 km are insignificant.

3.1.6 Rocky desertification

Rocky desertification, which covers 35% of the land surface of Guizhou, is a typical landscape in the Guizhou Karst Plateau (Bai et al. 2009). Statistical analysis results show that with the degree of rocky desertification increase from grades one (light degree) to five (heavy degree), both the landslide frequency and landslide density decrease, which indicates that landslides are likely occur at light rocky desertification region (Figure 4j). This is reasonable because higher degrees of rocky desertification indicate less material, which is required for a landslide. Chi-square tests confirm that the differences in rocky desertification are significant ($P< 0.001$).

3.2 Combined effect of environment factors

Geographical detector analysis is used to detect the single and combined effects of environmental factors on landslide volumes. The results show that the explanatory powers for combined factors are much higher than those for individual factors, indicating that the landslide volumes are obvious controlled by the interactions of multiple factors (Table 1). We use the word “dominant” hereafter to indicate that a factor or interaction has the largest q value.

Previous studies found that distances to faults and slope gradients are important factors for earthquake-induced landslides (Has et al. 2012; Xu et al. 2014b). In Guizou karst plateau, the distance to faults is also very important and is identified as the dominant single factor (q=0.137), followed by NDVI (q=0.12). Although slope and lithology each have low q values, they are also important because of the interactions of faults and slope, and those of lithology and NDVI can explain over 79% of the variations in earthquake-induced landslide volumes. This indicates the small variations of interactions between faults proximity and slope gradients, and that NDVI and lithology can cause large variations in landslide volumes. Specifically, the area that 1-1.5km away from faults with 10°-20° slope is most prone to large-scale landslides.

For human activity-induced landslides, NDVI and land use are important factors associated with landslide volumes. The dominant interaction is between gully and aspect (q=0.5), followed by that between NDVI and land-use (q=0.44) and that between NDVI and annual total precipitation (0.41). The environment that 1km away from the river with north facing slope and that covered shrubs with low vegetation coverage are more likely occur large landslides. As human-induced landslides are usually accompanied by land-use change, NDVI and land-use are important factors. Other interaction factors, such as gullies proximity, aspect and precipitation, indicate that the size of human-induced landslides is also related to hydrological conditions.

For rainfall-induced landslides, the geographical detector analysis did not capture any significant single factor associated with the landslide volumes for the entire Guizhou, likely because of the higher heterogeneity of landforms in Guizhou. Therefore, to facilitate analysis, we divided Guizhou into six regions according to a karst landform classification map (Department of

Table 1 Factor and factors interaction

Region	Dominant factor	*q* of single factor	Dominant interaction	*q* of two-factor interaction	Concentrated environment for large-scale landslides
Earthquake-induced landslides					
Entire region	Fault NDVI	0.137 0.122	Fault ∩ slope NDVI ∩ lithology	0.82 0.79	*1-1.5km away from faults with 10°-20°slope NAN
Human activity-induced landslides					
Entire region	NDVI Land-use	0.081 0.052	Gully ∩ aspect NDVI ∩ land-use NDVI ∩ precipitation	0.5 0.44 0.41	*North facing slope 1km away from the river Shrubs with low vegetation coverage NAN
Rainstorm-induced landslides					
Region 1	Aspect Road Lithology	0.011 0.010 0.009	Fault ∩ aspect Lithology ∩ precipitation	0.21 0.17	East and north facing slope near faults Clay rock, sandstone and limestone areas with annual precipitation of 1100-1300mm
Region 2	Aspect Fault	0.028 0.021	Lithology ∩ aspect Slope ∩ aspect Fault ∩ aspect	0.17 0.16 0.14	Sandstone area with north facing slope NAN NAN
Region 3	Fault Land-use	0.077 0.051	Lithology ∩ slope Rocky desertification ∩ slope	0.71 0.70	*20°-25°slope with interbedded soft and hard rock *15°-25°slope with low rocky desertification
Region 4	Fault	0.136	Fault ∩ precipitation Fault ∩ NDVI Fault ∩ lithology	0.90 0.87 0.86	*0.5-1.5km away from faults with annual precipitation over 1100mm *0-4km away from faults with medium vegetation coverage 3-3.5km away from faults interbedded soft and hard rock
Region 5	Lithology Gully	0.023 0.018	Fault ∩ land-use Fault ∩ lithology	0.50 0.34	*Shrubbery area 4.5-5km away from the faults NAN
Region 6	Precipitation Fault NDVI	0.020 0.019 0.018	Fault ∩ precipitation Fault ∩ NDVI	0.37 0.25	*0.5-3.5km away from faults with annual precipitation between 1100-1200mm NAN

Notes: All q values in this table are significant at the 0.05 confidential level. Regions 1 to 6 indicate the sub-regions of the northwestern plateau, the southwestern hilly plateau, the southern valley, the central basin, the northeastern mountainous region and the eastern hilly region. * indicates that landslides are significant concentrated. NAN means that there is no obvious concentrated environment for large-scale landslides.

Agriculture of Guizhou Province 1995) and found that the six regions have different dominant individual and interaction environmental factors.

In the northwestern plateau region (sub-region 1), the dominant individual factor is aspect, with a q value of 0.011. The dominant interaction factor is that between fault and aspect (q=0.21), followed by that between lithology and precipitation (0.17). The environment of east and north facing slope near faults are particularly prone to large landslides. In the southwestern hilly plateau region (region 2), aspect is the dominant single factor (q=0.028), and its interaction with lithology is the dominant interaction factor (q=0.17). Other important interactions include those between aspect and slope (q=0.16) and between aspect and fault (q=0.14). Large landslides in this sub-region prone environment are sandstone area with north facing slope. The q values for the above two regions are relatively low, probably because of the higher heterogeneity of the landforms in western Guizhou.

In the southern hilly region (sub-region 3), the dominant individual factor is faulting. Although lithology, slope and rock desertification alone each have low q values, the interactions between lithology and slope and between rocky desertification and slope explain over 70% of the variations in the landslide volumes. This high association reflects that slope, lithology and rocky desertification are the main characteristics of the terrain; the slight variations in these interactions make a noticeable difference in landslide volumes. Meanwhile, the 20°-25°slope with interbedded soft and hard rock are prone to large landslides.

The central basin region (sub-region 4) is a relatively flat area located in the center of the study area. Faulting is the dominant single factor associated with landslide volumes, with a q value of 0.136. The interactions of faults with other factors, including precipitation, NDVI and lithology, can explain over 86% of the variations in landslide volumes. This implies that landslide volumes are overwhelmingly affected by faults and their interactions with other environmental factors in this region. We interpret the high association between landslide volumes with faulting and its interaction with precipitation, NDVI and lithology as follows: in the absence of other strong factors that affect the instability of the slope, slight changes in the interactions of faults with precipitation, NDVI or lithology could lead to significant differences in landslide volumes in the basin region.

The northeastern Guizhou region is a mountainous region (sub-region 5) with mature forest covered by many dissolved valleys. The lithology and gullies are important factors and are associated with landslide volumes in this area. The interactions between fault and land use and that between fault and lithology can explain 50% and 34% of the local variations in landslide volumes, respectively. This indicates that the variations of land-use type and fault proximity greatly influence the landslide volumes. Specifically, the area 4.5-5km far away from the faults covered shrub is fragile to landslides.

The eastern hilly region (sub-region 6) has an annual total precipitation between 1000–1300 mm. Here, with significantly different spatial rainfall, precipitation is the dominant single factor (q=0.02). The important interactions are those between faults and precipitation (q=0.37) and between faults and NDVI (q=0.25). The area 0.5-3.5km far away from faults with annual precipitation between 1100-1200mm is prone to large landslides.

3.3 Triggering factor analysis

3.3.1 Seismicity

Earthquakes are not an important triggering factor for landslides in the karst region of Guizhou. Earthquake-induced landslides account for only 1.8% of the total recorded landslides. Figure 3a shows that earthquake-induced landslides occurred mostly at approximately 107°E, which is near the Longmenshan Fault and is an earthquake-prone zone.

3.3.2 Human activity

The human-induced landslides accounted for 8.1% (321 out of 3975) of the total landslides recorded, and they are mainly distributed along 105°E and between 108°-109°E (Figure 3b). Statistical analysis shows that 45.5% of the human activity-induced landslides occurred in urban village, industrial and mining areas, while the other 54.5% of the human-induced landslides were distributed over forests and grasslands. This result implies that agricultural activities the main reason causing landslides.

3.3.3 Heavy rainfall

The rainfall-induced landslides account for 90.1% (3581 out of 3975) of the total landslides recorded. The rainfall-induced landslides are widely distributed between 104.5°-107°E and 108°-109°E (Figure 3c). We used 233 landslide records with detailed information on landslide occurrence time and location and the daily precipitation measured by the meteorological stations near the landslide locations to study whether the rainfall-induced landslides are triggered by simultaneous precipitation or by accumulated precipitation.

The results show that accumulated precipitation before landslide occurrence is very important for landslides in Guizhou. Approximately 79.6% of landslides occurred with simultaneous daily precipitation of less than 50 mm, and only 11.8% of landslides are related to simultaneous rainstorms (precipitation over 50 mm) while 8.6% are related to simultaneous heavy rainstorms (precipitation over 100 mm) (Figure 5a). If we take 50 mm precipitation as the threshold, it is found that the percentage of landslides increased from 20.4% to 41.9%, 50.5% and 100% as the accumulated days increased from one to three, to five and to ten days. A clear logistic curve exists between the 10-day accumulated precipitation and the probabilities of landslide occurrence (P<0.01) (Figure 5b). Hence, continuous precipitation over 10 days has a decisive effect on landslide occurrence.

4 Discussion

Karst plays an important role on predisposing

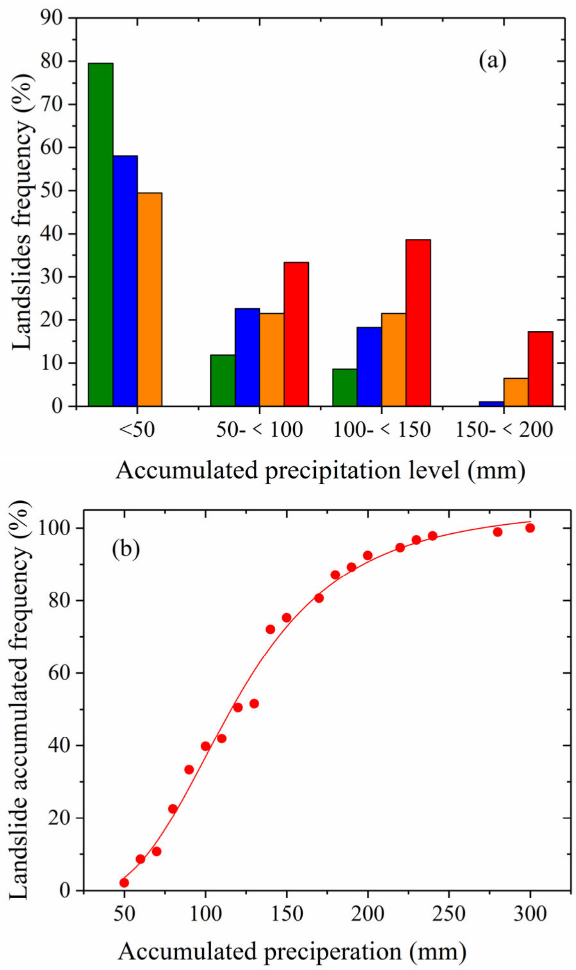

Figure 5 (a) Landslide frequency and precipitation. Green, blue, orange and red bars represent simultaneous, 3-day, 5-day and 10-day cumulated precipitation, respectively. (b) 10-day cumulated precipitation and the accumulation frequency.

and/or favoring landslides. In the karst region, dissolution and expansion increased with groundwater activity enhancing, which weakened the stability of the sliding surface, cracks or layers and the integrity or ruggedness of the rock. Its active weathering processes promotes lack of basal support, breakdown processes in the underground environment, progressive rock mass weakening, and instability at the surface (Gutiérrez et al. 2014). Therefore, the large area of carbonate is the main body for landslides (Figure 4c). While the failure of geotechnical structures caused by the faults further be wakened and result in the stability of slopes, large areas far from faults also keep strong instability due to karstification, therefore, the effect of faults is not so obvious on the landslides occurrence (Figure 4d) as other areas studied by Su (1995) and Xu (2014b).

In terms of the precipitation-induced landslides, we found that only 11.8% related to simultaneous rainstorms, while nearly 100% of these landslides related to the 10-day cumulative rainfall (Figure 5). This can be interpreted by that dissolution widens discontinuities most heavily in the rock masses before water reaches saturation or with continuous milt rainfall. With the groundwater system developed in karst region, water circulation in karst conduits favor instability inducing high fluid pressures with the consequent decrease in the normal effective stress and shear strength on failure planes (Gutiérrez et al. 2014). Landslides thus likely occurred gullies proximity with a large hydraulic gradient and a higher intensity (Figure 4f), however, spatial differences in surface hydrological conditions is not a restriction for landslides because of karst groundwater system. Just as the result of this paper shows that there are still large amount of landslides occurred far away from rivers (Figure 4f).

Due to the structure between carbonates and soil is relative weak, the karst is easy to suffer soil erosion and resulting to rocky desertification. While steep slopes are generally rocky landforms, gentle slopes with light rocky desertification could provide enough material for landslide occurrences. Hence, the lower slope and the light rocky desertification region are prone to landslides (Figure 4a, j). Vegetation has a certain inhibitory effect on landslides because of its closing effect and slope stabilization. However, in the karst region of Guizhou, the moderate NDVI region shows frequently occurring landslides (Figure 4g). We interpreted that lower NDVI always indicates lack of vegetation and loose materials, while the area with higher NDVI is always covered by mature forests with strong root systems and hydrological regulation, which is positive on landslides. Just as shown in the result of Imaizumi et al. (2008) and Moos (2015), the effect of vegetation on landslides are closely related to the vegetation structure. Taking all of these into account, therefore, material plays an important role for landslides in the Guizhou karst Plateau.

According to the result of Geographical detector, fault and slope are the dominant multi-factors for the earthquake-induced large landslides, this is consistent with other research such as Has et al. (2012) and Xu et al. (2014b). High-intensity human activities undoubtedly increased the shear stress of rocks and therefore weakened the stability of slopes. When under appropriate hydrological conditions with decreasing in the normal effective stress and shear strength on failure planes, landslides then are easily to occur.

Rainfall-induced landslides have different formation mechanism in different sub-regions. In the western plateau, the combination of fault and slope is the dominant for large-scale landslides. This is because that the local geological stratum is in the same direction as the aspect. With rivers eastern-orient, the landslides are affected by traceability-cracking effect (Wu 1994), and are mostly concentrated on the environment of east and north facing slope near faults. The southwestern plateau is a region suffered extreme precipitation as well as heavy rocky desertification. With south-facing slope strongly affected by rainfall, north facing slopes have much more material for landslides. The interaction of lithology and slope thus control the magnitude of landslide. The carbonate does not cover throughout the southern valley region, then interbedded soft and hard rocks plays important role instead for sliding (Wu 1994). With the weak interface of geological stratum easily changes to sliding surface, the combination of lithology and slope are dominant for large-scale landslides. All the environmental factors in the central basin have no apparent spatial heterogeneity, the landslides then are dominant controlled by fault and its interaction. The northeastern mountainous region covered mature forest system, landslides seldom occurred in the forest. But the shrubbery area near faults, affected by the underdeveloped root systems, mild hydrological regulation, and progressive rock mass weakening, are the area prone to landslides. The eastern hilly region has great spatial heterogeneity in precipitation, hence, the stronger pore water pressure and weaker adhesion in heavier rainfall area near faults promotes the occurrence of large-scale landslides. Taking all of these into account, the occurrence of large landslides is affected by the comprehensive effect of karst, faults, and lithology. However, with the spatial significant heterogeneity of some environmental factors, there are regional differences in the dominant multi-factors for landslide occurrence.

5 Conclusions

The Guizhou Karst Plateau is a fragile area prone to landslides, which are controlled by a complex combination of environmental factors. In this study, we use 3975 landslide records to investigate the effects of environmental factors on landslides in karst region. Most of the landslides (90.1%) in the studied area were induced by rainstorms, while 8.1% were induced by human activities, and only 1.8% were induced by earthquakes. The one-factor statistical analysis results show that landslides in the studied karst area are most common on slopes between 10° and 35°, in areas of clay rock, in close proximity to gullies, and especially in areas of moderate vegetation, dryland, and mild rocky desertification. The cumulative frequency of landslides shows a clear logistic distribution along with the 10-day cumulative precipitation. Continuous precipitation over 10 days has a great effect on landslide occurrence.

Geographical detector analysis reveals that the explanatory power of individual factors is weak but that of two factor interactions is strong when explaining a factor's influence on landslide volumes. The interaction between fault and slope and that between NDVI and lithology can explain over 79% of the variations in earthquake-induced landslide volumes. Meanwhile, the interactions between gully and aspect and that between NDVI and land use can explain 50% and 44% of the variations in human-induced landslide volumes, indicating that volume of human-induced landslides are affected by not only human activities but also by hydrological conditions.

Rainfall-induced landslides are predominant controlled by geological conditions. However, with different terrain, the dominant multi-factors significantly differ with each other. In the central karst basin of Guizhou, the interactions between faults and precipitation and between faults and NDVI can explain over 86% of the variations in landslide volumes. In the southern karst hilly region of Guizhou, the interactions between lithology and slope and between rocky desertification and slope can explain over 70% of the volume variations. Meanwhile, the interactions between faults and land can explain 50% of the variations in landslide volumes in the northeastern mountainous karst region of Guizhou.

The Guizhou Plateau is a typical karst environmental. Additionally, this region has significant environmental heterogeneity. The results of this study could provide valuable information and a scientific basis for local ecological environmental management and future disaster research concerning karst landforms.

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