The interactive effects of elevation, precipitation and lithology on karst rainfall and runoff erosivity

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ABSTRACT

Soil erosion, which is the prominent ecological and environmental problem in the karst regions of southwestern China, has seriously affected the region’s ecological conservation and economic development. Quantifying rainfall erosivity and runoff erosivity, can be a means to identify the dominant environmental factors involved in these processes and provide a theoretical basis for mitigating soil and water loss. This aids determination of the measures required to control rocky desertification and promote the ecological restoration of karst areas. Accordingly, this study simulated the rainfall erosivity in the Sancha River Basin (SRB) between 1985 and 2014 using an adopted daily rainfall model according to the karst erosive rainfall standard. Based on the degree of rocky desertification in the karst areas, correction coefficients were applied to improve runoff erosivity calculation and estimate the runoff erosivity of the basin between 1993 and 2014. In addition, the dominant and interactive factors affecting rainfall/runoff erosivity of the diverse geomorphological types in the SRB were quantitatively identified using the geographical detector. Results showed that the rainfall erosivity between 1985 and 2014 averaged 6913.73 MJ-mm-ha⁻¹-h⁻¹, with an average runoff erosivity of 1121.37 mm·km⁻²·s⁻¹ between 1993 and 2014. Precipitation and elevation were found to be the dominant factors shaping the spatial distributions of rainfall/runoff erosivity in the SRB. Precipitation explained over 90% of the spatial distribution in rainfall erosivity, and the q value of precipitation for runoff erosivity had no direct relationship with time. Furthermore, the interactions of elevation and precipitation, elevation and lithology type had prominent effects on rainfall erosivity and runoff erosivity in the SRB, respectively. Among them, the compound effects of elevation and precipitation could explain more than 80% of rainfall erosivity. These findings should be essential for managing soil and water loss in the karst areas.

1. Introduction

The karst ecosystem develops through atmosphere–water–rock–bi-ology interactions based on carbonate rock, and has a unique composition, structure, and function. Due to the distinct geochemical processes in the karst areas of the Guizhou Province, the thickness of soil layer in this region is generally thin (Wang et al., 2019). Under equal erosion intensity, the damage caused by soil erosion in the region is far greater than in non-karst areas with thicker soil layers (Zeng et al., 2017). Considering the extensive potential damage caused by erosion, rainfall and runoff are determined as the main driving factors leading to soil erosion. Karst rainfall erosivity characterizes the impact of precipitation on soil erosion in karst areas, and is mainly affected by rainfall volume, intensity, pattern, and frequency. Karst runoff erosivity is one of the major driving forces of soil erosion processes on slopes or in watersheds and can be responsible for the erosion of slopes, gullies and valleys in karst areas by dislodging soil and transporting sediment. One approach for quantifying such damage is the universal soil loss equation (USLE) model, in which the rainfall factor of soil erosion is expressed as rainfall erosivity (Jelinski and Yoo, 2016), and estimation of sediment loss on the slope scale is characterized by runoff erosivity. Thus, accurate assessments of rainfall erosivity, runoff erosivity, and identification of the

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dominant environmental factors affecting erosivity are of great importance for predicting soil erosion (Guo et al., 2019).

The temporal and spatial variability in rainfall erosivity and runoff erosivity are affected by multiple factors and their interactions. However, existing research has mainly focused on the evaluation of erosivity and the identification of their driving forces (Gu et al., 2019; Shin et al., 2019; Zhao et al., 2017). Although many of these studies have identified single or multiple factors influencing rainfall/runoff erosivity, quantitative analysis of the interactions between influencing factors is lacking. Ignoring the interactions of multiple influencing factors makes it difficult to fully understand the influence of rainfall erosivity and runoff erosivity mechanisms, and reduces the potential for soil and water loss. In addition, multiple studies have emphasized the importance of the temporal dynamics on runoff erosivity, which is strongly affected by the frequency, intensity, and variability of climatic events, and the compounding of these factors leads to substantial uncertainty in estimation runoff erosivity (Liu et al., 2017). Additionally, due to the difficulty of obtaining measured runoff data and the complexity of simulation experiments, studies on runoff erosivity have been focused on limited time periods (Xu et al., 2016; Zhang et al., 2015; Zhang et al., 2016). These studies cannot accurately reflect the long-term dynamic characteristics of this phenomenon. Hence, the interaction of factors influencing erosivity should be further examined and long-term dynamic simulations of runoff erosivity should be performed, to better understand how these factors influence soil erosion, especially in karst regions.

Current research on the calculation of rainfall/runoff erosivity has led to different conclusions due to the variety of available data sources and methods in karst area (Zhu et al., 2021). For example, by observing the runoff plot data of Guizhou karst area, Zhang et al. (2014) concluded that the erosive rainfall index of karst bare land on yellow soil should be calculated with the maximum rainfall intensity of 30 min. However, Chen et al. (2016) reported that $E_{RI}$ as the composite index of rainfall kinetic energy and rainfall intensity, cannot effectively reflect the relationship between rainfall and soil erosion of yellow soil in southwest China. In addition, while research on rainfall erosivity and runoff erosivity has been largely independent of each other, there is a paucity of research that comprehensively analyses both factors (Liu et al., 2018). Collectively, rainfall/runoff erosivity are the measurement of soil erosion potential, and the joint consideration of both factors is key to accurately predicting soil loss (Nearing et al., 2017).

The karst processes within the geological and climatic environment of the Guizhou Province in southwestern China have resulted in the formation of special geomorphological features, which distinguished by complex geological conditions and the fragile landform (Huang et al., 2016). Geomorphology has played a key role in the formation and development of the natural environment (Zongning et al., 2007). The scale-dependent differentiation of various landforms in karst areas directly affects the surface water and light intensity, thereby controlling the distributions and changes of rainfall erosivity and runoff erosivity. The factors affecting rainfall/runoff erosivity are thus expected to differ slightly among different geomorphological types (Kim and Mohanty, 2016). To date, research on rainfall/runoff erosivity has mostly focused on administrative regions or watersheds as a whole, neglecting the differences among subareas with different geomorphological types (Kim et al., 2020; Wu et al., 2016). Hence, the understanding of the dominant environmental factors affecting rainfall/runoff erosivity in karst areas with different geomorphological types remains incomplete. This study therefore conducted a comprehensive analysis on the factors influencing rainfall erosivity and runoff erosivity, characterizing their dominant and interactive factors in the basin and diverse geomorphological types.

The aim of this study was to determine the dominant factors affecting both rainfall erosivity and runoff erosivity for diverse geomorphological types in a typical karst basin. The objectives were to: (1) optimize rainfall erosivity and runoff erosivity models for karst areas and to explore the spatial distribution of rainfall/runoff erosivity in SRB. (2) identify the dominant influencing factors and their interactions affecting the spatial distributions of rainfall/runoff erosivity over a long-term period for diverse geomorphological types within the basin. The findings of this study are expected to provide a new scientific basis for informing the management of soil and water loss and ecosystem restoration in karst areas.

2. Material and methods

2.1. Study area

The study area of SRB is located in the Guizhou Province, southwestern China (104°18′–106°18′ E, 26°10′–27°00′ N), encompass 7061 km$^2$ (Fig. 1). As a small watershed typical of China’s karst regions, the SRB is a primary tributary of the Wujiang River Basin, with a total length of 325.6 km (Zhong et al., 2018). The area features typical karst landscapes with strong rocky desertification and a fragile ecological background, as well as serious soil erosion. The geomorphology of the basin is characterized by early and middle stages of karst geomorphological development and evolution. Additionally, the geomorphology is fragmented and has been violently incised, consequently developing an extensive abundance of peak cluster depressions.

2.2. Data

The data included spatial distribution data on environmental factors, meteorological data, and runoff data from hydrological stations (Table 1). The meteorological data which used for erosivity calculations included precipitation, temperature, sunshine duration, and wind speed. There are two hydrological stations in the SRB, Yangchang and Longchangqiao Hydrological Stations. We obtained the 1993–2014 daily average runoff data for the calculation of runoff erosivity from both stations. Based on the geomorphological classification system, the diverse geomorphological types in the SRB could be classified into five geomorphological types: middle elevation plain, middle elevation terrace, middle elevation hill, small relief mountain, and middle relief mountain (Table S1).

2.3. Methods

2.3.1. Generation of spatio-temporal basin rainfall erosivity

For the calculation of rainfall erosivity in SRB from 1985 to 2014, the rainfall erosivity of 24 meteorological stations in the SRB and surrounding areas was calculated firstly, and then the rainfall erosivity in SRB was obtained by co-kriging interpolation. Although precipitation data at the annual and monthly resolutions are commonly used for calculations (Chen et al., 2017; Luo et al., 2019), daily precipitation data can provide valuable rainfall information (Qin et al., 2016). Therefore, this study adopted the model of Zhang et al. (2002) to calculate rainfall erosivity based on the karst erosive rainfall standard and daily precipitation data, for more reliable estimations of rainfall erosivity (Cui et al., 2020; Xin et al., 2011). Notably, the model performance is more stable and accurate where there is abundant annual precipitation (Chen and Zha, 2018). Karst surface soil is a discontinuous, shallow soil layer, and large areas of rocky desertification landscape are exposed to the bedrock, and its underground structure is developed by the dissolution of carbonate rocks, cracks, karst pipes, funnels, karst caves and so on (Qian et al., 2018). The process of soil erosion on the slope in karst area is complicated and the runoff is not only lost with surface, but also leaked underground along karst fissures and sinkholes. Peng et al. (2017) used artificial rainfall experiments to simulate the effect of rainfall intensity on karst runoff and sediment yield, and found that erosive rainfall would be formed when the daily rainfall is $≥30$ mm in karst areas. Therefore, the erosive rainfall standard in karst areas should be higher than that of non-karst areas. As such, in the adopted rainfall erosivity model, $30$ mm of rainfall was set as the standard for karst erosive rainfall rather than the $12$ mm standard previously established.
for erosive rainfall in general. The equations used for calculations are described below:

$$R_i = \alpha \sum_{j=1}^{k} (P_j)^{\beta}$$  \hspace{2cm} (1)$$

where $R_i$ is the rainfall erosivity value of the $i$th half-month for the year (MJ-mm-ha$^{-1}$-h$^{-1}$), $k$ is the number of rainfall days in the half-month period, and $P_j$ represents the daily rainfall of the $j$th day in the half-month period (mm). With an erosive rainfall standard in the karst area at 30 mm, the daily rainfall value is $\geq$30 mm, otherwise $P_j$ is set to 0. Both $\alpha$ and $\beta$ are model parameters, estimated as follows:

$$\alpha = 21.586 \beta^{-7.199}$$ \hspace{2cm} (2)$$

$$\beta = 0.8363 + \frac{18.144}{P_{d30}} + \frac{24.455}{P_{y30}}$$ \hspace{2cm} (3)$$

where $P_{d30}$ denotes the average daily rainfall (mm) for the cases of daily rainfall $\geq$30 mm, and $P_{y30}$ is the average value of the annual erosive rainfall.

Considering the diverse topography of the basin, the distribution of precipitation in the SRB was expected to be greatly affected by topography. The co-kriging method can interpolate between neighboring data points, thereby obtaining more appropriate data for daily rainfall erosivity calculations (Liu et al., 2020a). Therefore, the co-kriging method was used to interpolate rainfall erosivity across the rainfall erosivity calculated for each of the 24 meteorological stations, to incorporate elevation as a factor in the spatially explicit rainfall erosivity calculations for the SRB.

### 2.3.2. Generation of spatio-temporal basin runoff erosivity

For the calculation of runoff erosivity, the runoff erosivity factor in the modified universal soil loss equation (MUSLE) was calculated from the Soil and Water Assessment Tool (SWAT) (Michalec et al., 2017). Because the SRB includes both karst and non-karst areas and clastic rock is the only non-carbonate rock in the study area, the unmodified runoff erosivity model was used to calculate the distribution area of clastic rock in the SRB, representing the non-karst areas. The modified model was used to calculate runoff erosivity for the distribution of carbonate rock in karst areas. Owing to the unique phenomena of rocky desertification and complex terrain conditions in the study area, the direct use of runoff...
erosivity factor for MUSLE model calculation was expected to introduce bias into the simulation results. According to Dai et al. (2017), who investigated the relationship between soil erosion and bedrock bareness rate, artificial rainfall experiments in a karst area revealed that the correlation coefficient between surface sediment and bedrock bareness rate was –0.076. In another related study on soil erosion in karst areas of the SRB (Gao and Wang, 2019), the correction coefficient (Table 2) changes depending on the conditions of rocky desertification to modify the runoff erosivity, which was expected to improve the accuracy of the simulation in the karst areas. The final equations of runoff erosivity are:

\[
R_E^1 = 11.8 \times (Q_{surf} \times q_{peak})^{0.56}
\]

\[
R_E^2 = 11.8 \times (1 - 0.076\alpha) \times (Q_{surf} \times q_{peak})^{0.56}
\]

where \(R_E^1\) and \(R_E^2\) are the runoff erosivity values (\(m^3 s^{-1} km^{-2}\)) in non-karst areas and karst areas, respectively. \(\alpha\) is the correction coefficient for rocky desertification. \(Q_{surf}\) is the total surface runoff (\(mm-hm^{-2}\)), and \(q_{peak}\) is the peak runoff rate (\(m^3 s^{-1}\)).

In this study, the elevation data were loaded into the SWAT model, and 27 sub-basins were generated after division. Afterward, the thresholds of land use type, soil data and slope were set to 5%, 5%, and 5%, respectively, and 1260 hydrological response units (HRUs) were delineated.

Finally, the meteorological data were input for simulation, wherein the data for 1985–1992, 1993–2003, and 2004–2014 were considered as warm-up, calibration, and validation periods, respectively. The coefficient of determination (\(R^2\)) and Nash–Sutcliffe efficiency (NSE) were selected to evaluate model performance. Specifically, when NSE > 0.6 and \(R^2 > 0.6\), the simulation results were considered satisfactory (Morigais et al., 2015).

2.3.3. Geographical detection of the dominant environmental factors and their interactions

In this study, the geographical detector was used to explore the explanatory power of environmental factors for spatial heterogeneity of rainfall/runoff erosivity. It is a tool for detecting spatial heterogeneity and can objectively quantify the influence of geographical elements on the natural environment (Wang et al., 2010b). Thus, it can quantitatively reveal the explanatory power of the impact factors to the dependent variables, and can detect the interaction of two influencing factors to the dependent variables. An effective tool for identifying and analyzing the driving factors of the spatial heterogeneity of geographical phenomena (Wang et al., 2016), it has been applied in studies on landscape ecological patterns (Li et al., 2020), urban carbon emissions (Zhang and Feng, 2020), and the ecological environment (He et al., 2015), as well as health risk assessment (Wang et al., 2018).

**Factor detector:** The core concept behind this feature is to determine if the changes in specific environmental factors and geographical phenomena are significantly consistent across space. The \(q\) value is used to quantify how much a factor \(X\) explains the spatial differentiation of attribute \(Y\) (Liu et al., 2020b), and can be expressed as follows:

\[
q = 1 - \frac{\sum_{i=1}^{N_h} N_i \sigma_i^2}{N \sigma_Y^2}
\]

where \(h = 1, \ldots, L\) is the stratification of variable \(Y\) or factor \(X\), and \(N_h\) and \(N\) are the numbers of units in layer \(h\) and the entire area, respectively. \(\sigma_X^2\) and \(\sigma_Y^2\) are the variances in the \(Y\) values of layer \(h\) and the entire area, respectively. The range of \(q\) is \([0, 1]\), such that a larger value of \(q\) corresponds to a stronger explanatory power of the independent variable \(X\) for attribute \(Y\).

**Interaction Detector:** This feature identifies the interaction between different influencing factors (Ju et al., 2016) by evaluating whether the interaction between factors \(X_1\) and \(X_2\) will strengthen or weaken the explanatory power of the dependent variable \(Y\), or whether the effects of these factors on \(Y\) are independent. Detected interactions can be divided into several categories: nonlinear weakening, single factor nonlinear weakening, double factor enhancement and independent and nonlinear enhancements.

In the geographical detector, the values of rainfall/runoff erosivity and their variability (annual variation) were used as \(Y\) attributes, respectively, whereas the vegetation coverage, land use type, precipitation, slope, elevation and lithology type served as the \(X\) factors. In this study, factor and interaction detectors were used to explore the driving factors of rainfall/runoff erosivity and variability based on different geomorphological types.

3. Results

3.1. Model validation of rainfall/runoff erosivity

According to the model calculations, the average annual rainfall erosivity in the SRB for 1985–2014 ranged as 4351.45–8632.20 MJ-mm-ha\(^{-1}\)-h\(^{-1}\), with an overall mean of 6913.73 MJ-mm-ha\(^{-1}\)-h\(^{-1}\). This result is consistent with the findings of Dai et al. (2013), who simulated rainfall erosivity in the Guizhou Province. Zhu et al. (2019) obtained a rainfall erosivity of 2150–9250 MJ-mm-ha\(^{-1}\)-h\(^{-1}\) for the Guizhou Province, which is also close to the simulated rainfall erosivity found in this study.

The calibration and verification results of the SWAT model were shown in Table 3. With the \(R^2\) and NSE values of the calibration period (1993–2003) and validation period (2004–2014) at both Yangchang and Longchangqiao stations all being greater than 0.65, the simulation results achieved the accuracy requirements. The \(R^2\) and NSE were slightly lower during the verification period than during the calibration period, likely due to uncertainty in the model parameter values and the complexity of runoff patterns during the long-term verification period (Hoang et al., 2018). In general, the SWAT model performed well in simulating runoff erosivity in the SRB and was suitably applicable to this basin.

3.2. Spatial distribution of rainfall/runoff erosivity

The spatial distribution of rainfall erosivity from 1985 to 2014 was shown (Fig. 2). Between 1985 and 2014, the rainfall erosivity exhibited strong spatial heterogeneity, with an overall increasing trend from west to east and higher rainfall erosivity in the downstream areas of the basin than in the upstream areas. In 2008, the rainfall erosivity of the SRB reached the highest in 30 years, 12313.97 MJ-mm-ha\(^{-1}\)-h\(^{-1}\), likely due to higher rainfall and severe flooding in the Guizhou Province that year. The rainfall erosivity in the SRB was lowest in 2013, at 3428.47 MJ-mm-ha\(^{-1}\)-h\(^{-1}\), but the rainfall erosivity exceeded 4000 MJ-mm-ha\(^{-1}\)-h\(^{-1}\) in all other years.

### Table 2
Correction coefficients for different rocky desertification conditions.

<table>
<thead>
<tr>
<th>Rocky desertification</th>
<th>None</th>
<th>Potential</th>
<th>Light</th>
<th>Moderate</th>
<th>High</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock bareness rate</td>
<td>%</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>less than 20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>greater than 90%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\alpha)</td>
<td>10</td>
<td>25</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>95</td>
</tr>
</tbody>
</table>

### Table 3
Evaluation of the runoff simulation results from 1993 to 2014.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(R^2) (\text{NSE})</td>
<td>(R^2) (\text{NSE})</td>
</tr>
<tr>
<td>Yangchang</td>
<td>0.78 0.66</td>
<td>0.68 0.67</td>
</tr>
<tr>
<td>Longchangqiao</td>
<td>0.72 0.70</td>
<td>0.66 0.65</td>
</tr>
</tbody>
</table>
The runoff erosivity of karst areas (Fig. 3, Fig. S2) and non-karst areas (Fig. 4, Fig. S3) in the SRB was simulated for 1993–2014. Runoff erosivity ranged as 0.05–11733.60 m$^4$s$^{-1}$km$^{-2}$, with an average value of 1121.37 m$^4$s$^{-1}$km$^{-2}$. Similar to rainfall erosivity, runoff erosivity in the SRB presented strong spatial heterogeneity, where it was lower in the upper and middle reaches of the basin and considerably higher downstream. Furthermore, runoff erosivity changed considerably over time. The largest average runoff erosivity of 2737.43 m$^4$s$^{-1}$km$^{-2}$ was observed in 2014, whereas average runoff erosivity was less than 2000 m$^4$s$^{-1}$km$^{-2}$ in other years. These results are readily explained by the continuous heavy rainfall that occurred in the Guizhou Province in 2014. Specifically, severe, heavy, and continuous provincial-wide rainstorms caused serious soil and water loss, resulting in unusually high runoff erosivity in 2014, and playing an important role in sediment transport in the basin. In contrast, the runoff erosivity of SRB was generally low (<500 m$^4$s$^{-1}$km$^{-2}$) in 2003, 2006, and 2013.

3.3. Quantitative attribution of rainfall erosivity and variability

3.3.1. Identification of the dominant factors for rainfall erosivity and variability

The q values of the influential factors for rainfall erosivity were shown in Fig. 5a. Generally, the dominant factors determining rainfall erosivity from 1985 to 2014 were precipitation and elevation. From 1990 to 2014, precipitation was the dominant factor driving the spatial distribution of rainfall erosivity, for which all q values exceeded 0.70. Moreover, precipitation explained more than 90% of the spatial distribution for rainfall erosivity from 1990 to 1999. Elevation had its highest q value with 0.72 from 1985 to 1989, and the values were all greater than 0.55 from 1990 to 2014. The explanatory power of vegetation coverage was at least 20% from 1985 to 2004, and q values were less than 0.10 from 2005 to 2014. Lithology type was the fourth greatest factors of rainfall erosivity for 30 years, with relatively stable q values between 0.10 and 0.15. In addition, land use type and slope had little impact on rainfall erosivity, both explaining less than 10%.

The dominant factors for rainfall erosivity variability from 1985 to 2014 were identified (Fig. 5b). Elevation could explain up to 49.76% of the spatial distribution for rainfall erosivity variability from 2010 to 2014, which was higher than those of other periods. The variability in rainfall erosivity was negative for both periods of 1995–1999 and 2005–2009. Overall, precipitation and elevation were the main factors affecting rainfall erosivity variability, accounting for more than 25% of its spatial distribution. In the 30-year study period, no direct relationship was identified for the changes of q value for rainfall erosivity.

![Fig. 2. Spatial distribution of rainfall erosivity (MJ-mm-ha$^{-1}$-h$^{-1}$) in SRB.](image)

![Fig. 3. Spatial distribution of runoff erosivity (m$^4$s$^{-1}$-km$^{-2}$) in karst areas.](image)
variability over time.

3.3.2. Interaction effects between environmental factors
The interaction of factors impacting rainfall erosivity and variability were shown in Fig. 6. From 1985 to 2014, the combination of environmental factors greatly increased the explanatory power of spatial distribution in terms of rainfall erosivity and variability, revealing the strongest interactive effects between precipitation and elevation from

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Fig. 4. Spatial distribution of runoff erosivity (m^4 s^{-1} km^{-2}) in non-karst areas.

Fig. 5. The q values of rainfall erosivity (a) and variability (b) in the SRB.

Fig. 6. Interactive factors of rainfall erosivity (a) and variability (b) in the SRB.
1985 to 2014. For the period from 1985 to 1989, the strongest interaction factors were interaction of precipitation and elevation, elevation and lithology type, elevation and geomorphological type, indicating that topography played an important role in rainfall erosivity. After 1989, the three strongest interaction combinations were between precipitation and elevation, precipitation and geomorphological type, precipitation and lithology type, with the dominance of each compounding interaction changing over time. These results indicated that the interaction between precipitation and topography has been the main combination of factors driving rainfall erosivity in the SRB since 1989.

Compared with the relatively consistent pattern of interaction effects on rainfall erosivity, the strongest interactions for rainfall erosivity variability changed conspicuously over time (Fig. 6b). From 1985 to 1989, the dominant pairwise interactions driving variabilities in rainfall erosivity were elevation and precipitation, elevation and vegetation coverage, elevation and lithology type, all with explanatory powers greater than 70%. However, from 2000 to 2004, the three strongest pairwise interactions were between precipitation and lithology type, precipitation and elevation, precipitation and vegetation coverage. During other periods, the dominant interactions between the factors affecting rainfall erosivity variability were the same as those of rainfall erosivity.

3.3.3. Detection of dominant and interactive factors on diverse geomorphological types

The dominant factors driving rainfall erosivity for diverse geomorphological types were identified (Fig. 5a). For the middle elevation plain, elevation explained over 95% of the spatial distribution of rainfall erosivity. This is because the middle elevation plain has the lowest terrain relief, and thus subtle changes in elevation had a large impact on rainfall erosivity. Both land use type and slope had low explanatory power for rainfall erosivity in the middle elevation plain, with q values less than 10%. For the middle elevation terrace, the order of explanatory power during the study period (30 years) was precipitation > elevation > lithology type. In mountainous areas, the explanatory power of precipitation for rainfall erosivity had no direct relationship with terrain relief, which were ranked as small relief mountain > middle relief mountain > middle elevation hill. In relatively flat areas, the effect of lithology type on rainfall erosivity decreased with increasing terrain relief, and its explanatory power followed as middle elevation plain > middle elevation terrace. The lithology types of the middle elevation plain were more diverse than those of the middle elevation terrace. Hence, the changes in the lithology type of middle elevation terrace had a greater impact on rainfall erosivity.

The dominant factors influencing the variability in rainfall erosivity and their explanatory powers for the different geomorphological types differed over the study period of 30 years (Fig. 5b). Lithology type had strong explanatory power for the middle elevation plain, exceeding 60% for the spatial distribution of rainfall erosivity variability. In relatively flat areas, the q values of lithology type increased with increasing on terrain relief, in the order of middle elevation plain < middle elevation terrace. For mountainous areas, the explanatory power of precipitation for rainfall erosivity variability was not directly related to the terrain relief.

Overall, it was found that the combined interactions of different natural environmental factors increased the explanatory power of rainfall erosivity and its variability for the different geomorphological types (Tables S2–S6). From 1990 to 2014, the combination precipitation and vegetation coverage explained more than 90% of the spatial distribution for rainfall erosivity in the middle elevation plain. However, the change in q values was not significantly related to time. For the middle relief mountain, the explanatory power of the combination of precipitation and elevation for rainfall erosivity exceeded 80%. From 1990 to 2014, the top three interactive pairs were the superposition of precipitation and elevation, precipitation and lithology type, precipitation and vegetation coverage. In mountainous areas, over 1990–1999 and 2005–2014, the explanatory power of the combination of precipitation and elevation for the spatial heterogeneity of rainfall erosivity decreased with decreasing on terrain relief, which had increasing q values in the order of middle elevation hill < small relief mountain < middle relief mountain. In mountainous areas, the combination of precipitation and elevation explained more than 20% of the rainfall erosivity variability from 1985 and 2014, with an explanatory power for the middle relief mountain up to 55% (Tables S7–S11).

3.4. Quantitative attribution analysis of runoff erosivity and variability

3.4.1. Identification of dominant factors of runoff erosivity and variability

In the SRB, for runoff erosivity from 1993 to 2014, the dominant factors were precipitation, elevation, and lithology type, with the q values changing over time (Fig. 7). Among the influencing factors, precipitation had the largest explanatory power for the spatial heterogeneity of runoff erosivity from 1993 to 1994. Moreover, the q values for precipitation from 1995 to 2014 all exceeded 0.10 and declined over time. From 1995 to 2014, the spatial distribution of runoff erosivity was primarily determined by elevation (explanatory power > 10%), while the change in q values did not show a temporal trend. From 1993 to 2014, lithology type was ranked third among the environmental factors, and its influence on the spatial heterogeneity of runoff erosivity was generally stable. In addition, slope had the weakest power (q < 0.10) for explaining the spatial distribution of runoff erosivity. The explanatory powers of geomorphological type, land use type, and vegetation coverage all varied over time. From 1993 to 2004, the explanatory powers of environmental factors were ranked as vegetation coverage > geomorphological type > land use type. However, the order of explanatory power from 2005 to 2014 was geomorphological type > land use type > vegetation coverage.

In the SRB, the runoff erosivity variability exhibited a negative trend from 1995 to 2009. Elevation was the dominant factor affecting the spatial distribution of runoff erosivity variability from 2000 to 2014, with the explanatory power of 24.94%. In other periods, precipitation was the dominant factor affecting runoff erosivity variability, with the q value for precipitation from 1995 to 1999 at 0.37. Over time, the power of vegetation coverage for explaining the spatial distribution of runoff erosivity variability declined.

3.4.2. Interaction of environmental factors on runoff erosivity and variability

From 1993 to 2014, the interactive factors that most greatly affected runoff erosivity in the SRB were the combination of precipitation and elevation, elevation and lithology type, precipitation and lithology type, elevation and geomorphological type (Fig. 8a). For 1995–2004 and 2009–2014, the order of interactions was as follows: elevation and lithology type > elevation and geomorphological type > precipitation and lithology type, all with explanatory powers higher than 20%. From 1993 to 2009, the explanatory power for the combination of elevation and precipitation increased over time. From 1993 to 2014, more than 15% of the spatial distribution on runoff erosivity variability could be explained by the combination of precipitation and elevation. However, the change in q values had no direct relationship with time (Fig. 8b). From 2000 to 2014, the interaction of elevation with other environmental factors greatly improved the power to explain runoff erosivity variability, for which the interactive q value between elevation and lithology type was 0.35.

3.4.3. Analysis of dominant and interactive factors on diverse geomorphological types

From 1993 to 2009, the dominant factor influencing runoff erosivity in the middle elevation plain was lithology type, with the q values greater than 90% (Fig. 5a). From 2010 to 2014, lithology type explained 80.28% of the spatial distribution for runoff erosivity, because rock properties can directly affect runoff erosivity through the effects of...
infiltration and evaporation. From 1995 to 2014, the explanatory power of vegetation coverage for runoff erosivity in relatively flat areas decreased with increasing in terrain relief, for which $q$ values were ranked as middle elevation terrace < middle elevation plain. Additionally, in mountainous areas for which increasing $q$ values followed the order of middle elevation hill > small relief mountain > middle relief mountain. For the middle elevation terrace, the interactions between precipitation and other factors greatly affected runoff erosivity. Among all the combinations of factors, the interaction between precipitation and elevation was the most significant during 1993–2014, with $q$ values $> 0.9$ (Tables S12–S16).

For the middle elevation terrace and middle elevation hill, precipitation was the dominant factor affecting the spatial distribution of runoff erosivity variability between 1993 and 2014, with the $q$ values of
precipitation on the middle elevation terrace exceeding 0.55 (Fig. S5b). For the middle elevation hill, the change in the explanatory power of the various environmental factors for runoff erosivity variability had no direct relationships with time. In relatively flat areas, the combination of precipitation and lithology type decreased with increasing in terrain relief between 1993 and 2014, in the order of middle elevation plain > middle elevation terrace (Tables S17–S21).

4. Discussion

For this study, we optimized the model of rainfall erosivity based on the karst erosive rainfall standard and the model of runoff erosivity according to bedrock bareness rate. Moreover, the dominant and interactive factors of rainfall/runoff erosivity and variability in the SRB and diverse geomorphological types were quantitatively identified, to provide relevant policy recommendations for controlling the soil and water loss in karst areas.

4.1. Dominant factors of karst rainfall/runoff erosivity

This study confirmed that precipitation, elevation, vegetation coverage, lithology type, land use type and slope all have important effects on rainfall/runoff erosivity and variability in the SRB and different geomorphological types. In particular, precipitation and elevation were clearly significant for determining the spatial distribution of rainfall/runoff erosivity, which precipitation is a prerequisite for rainfall erosivity and an indispensable source of water for surface runoff mechanisms (Xin et al., 2011). Meanwhile, the high relief terrain causes the adiabatic expansion and cooling of rising air masses, which in turn increases relative humidity, leading to cloud formation and precipitation that ultimately affect rainfall/runoff erosivity (Meshesha et al., 2015).

The interaction of environmental factors was found to enhance the explanatory power of rainfall/runoff erosivity. In particular, the combinations of precipitation with various other environmental factors had the strongest interactive impact on the rainfall erosivity. For the middle elevation plain, the interaction between vegetation coverage and precipitation had greater explanatory power for the spatial distribution of rainfall erosivity than any single factor. This is because vegetation can effectively reduce the kinetic energy of rainfall and prevent the soil surface from being directly impacted by raindrops, thus leading to promotion of rain infiltration, and reduction runoff energy (Xu et al., 2018). The pairwise combinations of precipitation and lithology type (1993–1999), precipitation and elevation (2000–2014) were dominantly influenced the distribution of runoff erosivity in the middle relief mountain. This is because lithological conditions in watersheds often determine the infiltration and evaporation of water and the maximum underground water storage capacity. Moreover, these factors also affect the spatial distribution of evaporation, infiltration, and groundwater (Li et al., 2019).

4.2. Characteristics of karst rainfall/runoff erosivity variability

In the SRB, climate change and geological conditions have resulted in pronounced changes in rainfall/runoff erosivity (Amanambu et al., 2019). The results of this study revealed that precipitation, elevation, and lithology type were the main driving factors of rainfall/runoff erosivity variability in the karst areas. Although the combined effect of precipitation and elevation had the greatest initial impact on rainfall erosivity (1995–2009), the interaction between precipitation and geomorphological types showed dominance in 2010–2014, demonstrating the growing influence of terrain relief. The explanatory power of vegetation coverage for spatial distribution on runoff erosivity variability declined from 1993 to 2014. In recent years, the NDVI value of SRB has been steadily increasing, with the value of 0.685 and 0.740 in 2000 and 2005, respectively. In 2010, the NDVI of SRB was 0.762 and value in 2014 was 0.824. With the advancement of ecological management projects in China’s karst areas including the ChangZhi Project and the Natural Forest Protection Project, the overall ecological and vegetation conditions in the karst areas are improving significantly, which may explain the decrease in q values for vegetation coverage in runoff erosivity variability over time. The interaction between precipitation and elevation dominated runoff erosivity variability, with the q values exceeding 0.15. The middle elevation hill was more sensitive to changes in elevation, which agrees with previous research findings wherein the stratification of elevation was found to reflect comprehensive differences in climate, vegetation, and topography related to the geomorphological type (Kotlarski et al., 2015).

4.3. Uncertainty analysis and future perspectives

The average annual rainfall erosivity in the SRB for 1985–2014 ranged from 4351.45 to 8632.20 MJ·mm·ha$^{-1}$·h$^{-1}$, with the average value of 6913.73 MJ·mm·ha$^{-1}$·h$^{-1}$. In addition, Xu et al. (2005) used a monthly rainfall erosivity model to calculate the rainfall erosivity in the Guizhou Province, where the average rainfall erosivity for 1951–2001 was 4383.34 MJ·mm·ha$^{-1}$·h$^{-1}$. Zhu et al. (2019) also simulated rainfall erosivity in the Guizhou Province for the period between 1960 and 2017, and obtained average values of 5825.60 MJ·mm·ha$^{-1}$·h$^{-1}$. The average value of rainfall erosivity found in this study was higher than the previous studies because the Guizhou Province includes karst and non-karst areas. The rainfall erosivity of non-karst areas is lower than that of karst areas, and the calculation methods of previous studies for rainfall erosivity did not distinguish in karst and non-karst areas. This study promoted the rainfall erosivity model, to calculate rainfall erosivity in karst areas more accurately.

Runoff is one of the main driving forces of soil erosion, which erodes surfaces, slopes and valleys by dislodging and separating soil and initiating sediment transport (Dai et al., 2018). Currently, related research is mostly limited to empirical inferential statistics, which generates uncertainty in the estimation of runoff erosivity. In this study, the SWAT model was used to simulate changes to runoff erosivity in the SRB. The model had good accuracy and applicability, making it a strong foundation for future studies on runoff erosivity in the SRB and similar karst areas. However, the SWAT method has some limitations that merit further investigation. For a hydrological model, minimizing uncertainty is critical for the verification of model accuracy. Therefore, future work should focus on expanding the number of iterations of the SWAT model to reduce uncertainty and improve the accuracy of model calibration and validation.

Rainfall/runoff erosivity and variability were affected by various environmental factors that may affect the spatial distribution of erosivity. In this study, natural environmental factors were analyzed to identify the dominant and interactive factors affecting rainfall/runoff erosivity and variability. As the geographical detector is based on stratified variance, it can eliminate collinearity between independent variables and effectively overcome the limitations of traditional statistical analysis in processing categorical variables.

5. Conclusion

In this study, long-term rainfall erosivity (1985–2014) and runoff erosivity (1993–2014) in the karst basin of the SRB in the Guizhou Province, southwestern China were evaluated. Modified rainfall erosivity and runoff erosivity calculation were applied in this study, along with the geographical detector, which was employed to quantitatively identify the dominant and interactive factors influencing rainfall/runoff erosivity in the SRB according to diverse geomorphological types. The main findings are as follows.

The average rainfall erosivity in the SRB from 1985 to 2014 was 6913.73 MJ·mm·ha$^{-1}$·h$^{-1}$, while the average runoff erosivity from 1993 to 2014 was 1121.37 m$^3$·km$^{-2}$·s$^{-1}$. Both rainfall erosivity and runoff
erosivity were strongly spatially heterogeneous in the SRB and varied greatly over time. The areas with high rainfall/runoff erosivity were mainly distributed in the lower reaches of the SRB, whereas low rainfall/runoff erosivity was generally observed in the western part of the basin.

Precipitation and elevation were the dominant factors affecting the distribution of rainfall/runoff erosivity in the SRB. The dominant factor influencing rainfall erosivity from 1985 to 1989 was elevation, with q values greater than 0.70, whereas the dominant factor from 1990 to 2014 was precipitation. The pairwise interactions among precipitation, elevation and lithology type were the dominant factors affecting the spatial distribution of runoff erosivity in the SRB, and the corresponding q values changed over time.

Precipitation and elevation have remained the dominant factors affecting the rainfall/runoff erosivity variability throughout the SRB. From 1985 to 2014, the explanatory power of each influencing factor for the spatial heterogeneity of rainfall erosivity variability had no direct relationship with time. However, the q value of vegetation coverage for the spatial distribution of runoff erosivity variability decreased over time. In mountainous areas, the q values of slope increased with decreasing in terrain relief, whose q values followed the order of middle elevation hill > small relief mountain > middle relief mountain.

In this study, the geographical detector was used to quantitatively analyze the explanatory power of natural factors on the spatial distribution of rainfall/runoff erosivity in karst areas, and explore the driving factors. Due to the availability and effectiveness of data, the selected factors are relatively limited in spatio-temporal change pattern of erosivity. In further studies, ecological protection projects, social economy factors and other related indicators can be incorporated to improve the indexing of impact factors and carry out a more comprehensive factor analysis. This will ensure a better understanding of the mechanisms driving the spatial distribution of rainfall/runoff erosivity in karst regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2021.105588.

References


