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Quantitative Analysis of the Influencing Factors and Their Interactions in Runoff Generation in a Karst Basin of Southwestern China

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Abstract: The unique geological conditions of karst regions create highly heterogeneous habitat characteristics, and the addition of human disturbance results in rocky desertification. Water and soil loss are the core questions, and moreover, runoff is the key factor in this process. To further investigate these problems, a typical karst peak cluster depression in southwestern China was selected for this study. Based on the optimal simulation of the runoff yield and flow in this area, the factor detectors and interaction detectors in the geographical detector method were used to quantitatively analyze the factors influencing runoff and their interactions for different geomorphic types. The results show that: (1) the three main factors influencing the total river runoff, surface runoff, and groundwater are landscape fragmentation, land use type, and precipitation, but the ranking of these main influencing factors in each geomorphic type region exists different; (2) the dominant factor in the relatively higher elevation regions is precipitation; (3) the interaction detector results reveal that the interactions between factors enhance the overall influence of a single factor on the runoff generation in all of the geomorphic type regions, including two interaction types of nonlinear enhancement and bifactor enhancement; and (4) the interactions between the factors in the middle elevation plain, middle elevation terrace, and middle relief mountain regions are stronger than those in the middle elevation hill and small relief mountain regions. Quantitative analysis of the factors influencing runoff in karst areas cannot only promote optimization of the water and soil services, but it also provides a scientific basis for improving the comprehensive treatment of rocky desertification.

Keywords: runoff generation; single factor influence; factor interactions; different geomorphic type; Karst basin

1. Introduction

The ecological environment has suffered serious damage, affected by global change and human activities in recent decades, with the decline of ecosystem services [1]. The comprehensive millennium ecosystem assessment program report points out that in the second half of the 20th century, ecosystem regulation services, which sustain human life [2,3], including water conservation, have significantly declined [4,5]. Furthermore, the degeneration of water conservation services further aggravated environmental degradation [6]. In particular, the vulnerable karst ecosystem, with its special geological conditions [7], has been affected by external environmental impact and has suffered serious vegetation degradation, and gave rise to rocky desertification [8–10]. Among them, water and soil loss are the core problem of rocky desertification formation [11]. Runoff not only provides water resources for human beings [12,13], but it also plays an important role in affecting water and soil loss and conservation [14].

Therefore, based on simulations and influence analysis of the geographical environment on runoff generation in a karst watershed, we provide a theoretical basis that is useful not only for ecological restoration and reconstruction but also for improving the comprehensive control of rocky desertification in karst regions.

In consideration of a physical environment with highly heterogeneous and landform with sharp relief, the spatial relationship analysis between the geographical environment and runoff generation in a karst watershed, containing different geomorphic type regions, is of great significance to the research of the impact mechanism of water and soil conservation. It also promotes the research of restoration mechanisms of soil and water services. Previous studies have done a great deal of work on the spatial heterogeneity of runoff and its influencing factors. Using statistical and clustering analysis, Peng et al. [15] found that runoff and soil loss showed significant variations among different precipitation regimes, and limestone fissures play an important role in surface runoff on karst limestone slopes, which is attributed to their large storage capacity and high infiltration rate. Using cumulative anomaly, wavelet analysis, the Mann–Kendall trend test, and the Hurst exponent, Wu et al. [16] explored runoff change and its responses to climate change and human activities in the Yinjiang River watershed during 1984–2015. Zhang et al. [17] used a Budyko framework to identify the factors influencing karst catchments in Guizhou Province and showed that the primary factors are the geology, slope, land use, and land cover. Dai et al. [18] found that the bedrock bareness rate and the degree of underground pore fissuring were the dominate factors causing the uneven distribution of runoff on soil surfaces and underground. Yan et al. [19] used the standard statistical technique to determine that in order of importance, the factors contributing to runoff are the rainfall intensity, slope angle, and the degree of underground pore fissures. In general, most studies of the relationship between the factors influencing runoff generation in karst areas have mainly used traditional statistical analysis or spatial analysis.

However, these above analysis methods have difficulty in quantifying the extent of the influence of each factor on the runoff. Furthermore, comprehensive comparison of these factors and their combinations is still lacking, and the quantitative attributes of multi-factor effects and their interactions have also received little attention [20]. The geographical detector method can be used to determine the driving force behind geographical phenomena by detecting the heterogeneity of the spatial stratification. The core assumption is that if an independent variable has an important influence on a dependent variable, the spatial distributions of the independent variable and the dependent variable are highly consistent [21]. Especially for karst areas, which have a high spatial heterogeneity, the geographical detector method is beneficial for the advanced study of the spatial pattern and influence mechanism of runoff generation. Based on these considerations, a typical karst basin distributed with peak-cluster depression was selected as the study area. With the help of karst basin runoff and the related variables simulation by the soil and water assessment tool (SWAT), including total river runoff, surface runoff, and groundwater as dependent variables, and the land use types, vegetation cover, lithologic types, geomorphic types, landscape fragmentation, precipitation, elevation, and slopes were investigated as the analysis factors, which are independent variables. The geographical detector method was applied to analyze the dominant factors and the interactions of the factors for different geomorphic types.

2. Materials and Methods

2.1. Study Area

A typical karst peak-cluster depression was selected as the study area (Figure 1). The study area is located in southwestern China between 104°54′–106°24′ E and 26°06′–27°00′ N, and it has a drainage area of 4681 km². The area has special geological and hydrological characteristics, such as unique hydrogeological structures (surface and underground binary hydrological structure), discontinuous and thin surface soils, and uneven distributions of water and land resources [22]. Vulnerable eco–geological

environments and the interference of human activities have resulted in severe rocky desertification in the area. The elevation ranges from 932 to 2277 m, and it grows from east to west.



Figure 1. Map of the basic environmental elements of the study area in northwestern Guizhou Province, China.

2.2. Simulation and Optimization of Runoff Generation

2.2.1. Soil and Water Assessment Tool

Based on the soil and water assessment tool (SWAT) model, the total river runoff, the surface runoff, and the groundwater are obtained. Detail simulation process and results were shown in our previous studies [23]. Thus, here, we present a brief introduction to the SWAT model and simulation result. The SWAT model is a semi-distributed hydrological model of a watershed, with a strong physical mechanism, which can use spatial data provided by GIS (geographic information system) and remote sensing to simulate various hydro–physical processes in large, complex basins [24]. Compared with distributed and conceptual hydrological models, the SWAT model is hydrological process-based [25], provides easy access to input data, and a high operation efficiency [26].

The hydrological cycle simulated by the SWAT model is based on the processes of each hydrological variable.

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right)$$
(1)

where SW_t is the final soil moisture content (mm); SW_0 is the initial soil moisture content on the *i* th day (mm); *t* is the time (d); R_{day} is the rainfall on the *i* th day (mm); Q_{surf} is the surface runoff on the *i* th day (mm); E_a is the evapotranspiration on the *i* the day (mm); W_{seep} is the water seepage from the soil profile into the vadose zone (mm); and Q_{gw} is the baseflow returned on the *i* th day (mm).

The runoff simulation of the SWAT model includes several different modules of surface runoff, groundwater, and concentration of channels. The surface runoff simulation uses the soil conservation service (SCS) curve number (empirical models), which is a function of the soil permeability, land use, and antecedent soil moisture conditions, and the level of the soil infiltration capacity is mainly based on the physical and chemical attribution of the different soil types. Different land use types affect the runoff production by changing the surface evaporation, soil moisture status, and the interception by the land cover. The groundwater is simulated according to the water balance equation of shallow and deep aquifers, and calculation of every variable is based on its flow process. Generally speaking, the simulation of the underground runoff in karst region is greatly affected by parameters such as base-flow retreat constant (ALPHA_BF, the direction indicator of the groundwater's response to

the change in the recharge amount) and the water level threshold (GWQMN) of shallow aquifers when the groundwater enters the main channel.

2.2.2. Model Simulation and Verification

Based on the soil, meteorological, and land use data, the preliminary simulation results can be obtained using this SWAT model. To further improve the accuracy of model simulation, data of observed runoff from some hydrological stations, such as Yangchang, and Longchangqiao, will be utilized for parameter calibration and model validation. According to the parameter sensitivity results and hydrological processes, the adjustable parameters of CN₂, SOL_AWC, ALPHA_BF, CH_K₂, and GWQMN are chosen to do calibration, which reflects the processes of surface runoff, soil moisture, groundwater, groundwater, and interflow respectively.

The Nash–Sutcliffe efficiency, E_{NS} , and coefficient of determination, r^2 based on observed monthly data from 2008 to 2010 were used to evaluate the model effect and validate the calibration results. Values of E_{NS} closer to 1 indicate simulation values that are closer to the observed values. It is generally recognized that ENS in the range of 0.5–0.65 indicates simulation results are credible. E_{NS} values in the range of 0.65–0.75 and above 0.75 is relatively better and excellent simulation, respectively [27]. The results (Table 1) show that the simulation effect performs good and excellent in the Yangchang and Longchangqiao stations, including calibration and validation period.

Hydrological	Calibration Per	riod (2008–2010)	Validation Perio	od (2011–2013)
Stations	E _{NS}	R ²	E _{NS}	R ²
Yangchang	0.70	0.84	0.73	0.93
Longchangqiao	0.82	0.92	0.90	0.95

Table 1. E_{NS} and R^2 of model performance at different monitoring stations.

2.3. Geographical Detectors

In this study, the geographical detector method [28,29] was used to quantify the relationships between the runoff and influencing factors. This model uses the spatial variance analysis method developed in the field of medical geography [30]. It is a method of revealing the driving forces behind elements by detecting their spatially stratified heterogeneity. It is a geographical phenomenon in which the sum of the intra-layer variances is less than the total inter-layer variances [28], which is represented by the *q* value of the geographical detector. It is mainly applied to identify the mechanisms of the factors influencing the spatial differentiation, and the influencing factors are usually categorical variables.

This model consists of four parts: factor detector, ecological detector, risk detector, and interactive detector. The basis of the model [21] is that if the sum of the variance of the subareas is less than the variance of the entire region, spatial heterogeneity exists in the area. This method is skilled at calculating categorical data.

The factor detector calculates the explanatory power of the independent variables over the dependent variables, which is represented by q value. The equations are:

$$q = 1 - \frac{\sum\limits_{h=1}^{L} N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST}$$
(2)

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2, \quad SST = N\sigma^2, \tag{3}$$

where *h* is the layers' number of independent variables; N_h is the sample units' number in the zone; N is the all samples' number in the entire study area; and *L* is the zones' (categories) number of the factor. σ_h^2 is the variance within the zone; and σ^2 is the global variance in the unit. *SSW* is the total variance

within a zone; and *SST* is the global variance in the entire study area. q is the explanatory power of the independent variables over the dependent variables, with a range of 0–1. The closer that the q value is to 1, the stronger the explanatory power is.

The ecological detector estimates if the impacts of two factors on the runoff are significantly various, and it uses F-tests to compare the calculated variance within a sub-region attributed to one factor with the variance and attributed to another one. The interaction detector is very representative of the geographical detector, compared with other statistical methods. It can determine the integrated impact of two individual factors on the runoff. It can assess whether these two factors weaken or enhance each other, or whether they affect the runoff by oneself. The criterion of the interaction results is presented in Table 2.

Table 2. Categories of in	nteractions	between	two o	covariates.
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Criterion	Interactions
$q(X1 \cap X2) < Min(q(X1), q(X2))$	Nonlinear weakening
$Min(q(X1), q(X2)) < q(X1 \cap X2) < Max(q(X1), q(X2))$	Nonlinear weakening of a single factor
$q(X1 \cap X2) > Max(q(X1), q(X2))$	Bifactor enhancement
$q(X1 \cap X2) = q(X1) + q(X2)$	Independence
$q(X1 \cap X2) > q(X1) + q(X2)$	Nonlinear enhancement

Annotation: X1 and X2 is the independent variables of interacions, and they are influencing factors in this study.

2.4. Data

Eight factors were used in the impact analysis of the runoff using geographical detectors: lithology type (http://www.resdc.cn), geomorphic type, land use type, landscape fragmentation, precipitation (http://data.cma.cn/), vegetation cover (250 m, https://glovis.usgs.gov), elevation, and slope. The lithology and geomorphic data were from the Resource and Environment Data Cloud Platform of the Chinese Academy of Sciences (http://www.resdc.cn). According to the study of Zhou et al. [31] on geomorphic classification, there are five geomorphic types in this region: middle elevation plain, middle elevation terrace, middle elevation hill, small relief mountain, and middle relief mountain. The lithologic types include limestone, dolomite, clastic rocks, limestone with clastic rocks, dolomite with clastic rocks, interbedded limestone and dolomite, interbedded limestone and clastic rocks, interbedded dolomite and clastic rocks, and clastic rocks with carbonates. The land use data was from the United States Geological Survey (https://glovis.usgs.gov/), which was interpreted from 30 m resolution Landsat thematic mapper images using the supervised classification method and the ENVI software and was validated using field sampling points collected using GPS (global positioning system). The kappa coefficient was determined to be 0.81 through verification, which shows that the land use remote sensing data is reliable. The land use types include cultivated land, woodland, grassland, water area and land for water conservancy facilities, residential land, and other land. The landscape fragmentation was calculated using FRAGSTATS software, which was represented in our previous study [32].

The above data then need to be partially processed before it can be effectively applied by the geographical detector. Using the method of data discretization from the research of Wang and Xu [21] and priori knowledge [33], the continuous datasets (e.g., elevation, precipitation, and vegetation cover) were categorized as follows. We divided the precipitation and elevation data into nine categories applied the natural break method. The vegetation cover data were divided into eight categories: < 0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–0.9, and 0.9–1. The slope data were divided into eight categories: < 5° , 5–10°, 10–15°, 15–20°, 20–25°, 25–30°, 30–35°, > 35°. The raster data of the factors were extracted to point data using *ArcGIS*, with a sampling interval of 500 m, which was used as the operation data for the geographic detector. In regions with different geomorphic types, consistent

stratification methods were adopted for the influencing factors to construct the same conditions for the factors analysis in order to ensure the comparability of the results.

3. Results Analysis

3.1. Variation Analysis of the Dominant Factors of the Hydrological Variables

Overall, the primary factors influencing the total river runoff, surface runoff, and groundwater are precipitation, land use type, and landscape fragmentation, but the ranking of factors of each variable is different (Table 3). For the total river runoff and the surface runoff, precipitation is the most influential factor, with explanatory powers reaching 21% and 11%, respectively, followed by land use type and landscape fragmentation. For groundwater, the explanatory power of landscape fragmentation and land use type rank first and second, respectively, and the third leading factors are elevation and precipitation. Runoff is caused by atmospheric precipitation. For most rain-fed rivers, rainfall is the most important factor influencing runoff generation [34], especially for the total river runoff. In addition, previous studies have shown that surface runoff is mainly affected by the rainfall capacity [35,36]. Total runoff covers surface runoff and groundwater, and impact of precipitation on it is much greater spatially, with a higher q value than others. The second most important factor affecting both the total river runoff and the surface runoff is land use type. Different land use types have significantly different water consumptions, which affect the hydrological process [37]. For example, the water conservation capacity of forestland soil is relatively stronger, and the runoff interception of forestland is more significant [38,39]. Thus, the total river runoff of forestland is lower. The most significant factors affecting groundwater is landscape fragmentation. Due to the strong development of karst landforms, rainfall quickly becomes groundwater in rock exposed areas with a high degree of landscape fragmentation. Therefore, landscape fragmentation has a distinct impact on groundwater [40].

Influence Factor		
Element of Hydrological Cycle	Dominant Factor	q
	precipitation	0.21
Total River Runoff	land use type	0.16
	landscape fragmentation	0.14
	precipitation	0.11
Surface Runoff	land use type	0.06
	landscape fragmentation	0.04
	landscape fragmentation	0.13
Groundwater	land use type	0.09
	precipitation	0.08

Table 3. The dominant factors and *q* values of the different element of hydrological cycle.

3.2. Single Factor Analysis of the Hydrological Variables for the Different Geomorphic Types

Total river runoff. The explanatory power of these factors on the total river runoff was different for the five geomorphic types (Figure 2). One specific point of view is that there is a similar law among the different regions of geomorphic types, concerning the explanatory power of land use type and landscape fragmentation on the total river runoff. That is, the *q* value increase as the topographic relief increases within a certain range, and then, they reach their maximum values in the middle elevation hill region, with values of 23% and 19.8%, respectively. It decreases even further later. For precipitation, the explanatory power is weak in the middle elevation plain region, with a *q* value of 3.3%. In the other four geomorphic type regions, the influence of precipitation on the total river runoff is more significant, with a *q* value of 22.7% in the small relief mountain region. Based on the ecological detector, compared with the other factors, the influences of landscape fragmentation, land use type, and precipitation on

the spatial distribution of the total river runoff are more significant in the small relief mountain region. Lithologic type and precipitation are significant in the middle relief mountain region. The influence of elevation on the total river runoff is significantly different from the other factors in the middle elevation hill region. In short, the significant influencing factors on total river runoff are different in different geomorphologic regions.



Figure 2. The q values of the factors influencing the total river runoff in the different geomorphic regions.

Surface runoff. The explanatory power of precipitation displayed a nonlinear relationship with the different geomorphic types (Figure 3). The *q* values initially increase and then decrease as the topographic relief increases, and finally, they reach the maximum in the middle elevation hill region. The explanatory power of the land use types on the surface runoff is relatively stronger in the middle elevation terrace and middle elevation hill regions, with *q* values of 21% and 12%, respectively. The *q* values of vegetation cover and landscape fragmentation reach their maximum values in the middle elevation terrace region. The results of the ecological detector revealed that the influence of precipitation on surface runoff is significantly different from that of the other factors in the small relief mountain and middle elevation hill regions, not land use type and landscape fragmentation. This may be related to the weakened influence of natural elements is gradually strengthened.



Figure 3. The q values of the factors influencing the surface runoff in the different geomorphic regions.

Groundwater. The explanatory powers of the different influencing factors on the spatial distribution of the groundwater vary significantly for the different geomorphic type regions (Figure 4). The influences of landscape fragmentation on groundwater are relatively significant in the different geomorphic type regions, except for the middle elevation mountain region. The *q* value of the middle elevation plain region reaches 18.5%. The influences of the land use types on the groundwater decrease as the relief terrace increases. The greatest influence on the groundwater occurs in the middle

elevation plain region, with a *q* value of 18.1%. Land use types and landscape fragmentation are the dominant factors in the middle elevation plain, middle elevation terrace, and middle elevation hill regions. In the small relief mountain and middle relief mountain regions, landscape fragmentation is the prominent factor. Moreover, according to the ecological detector, the influence of landscape fragmentation on groundwater is more significant than the other factors. Its significant impact may be due to the hydrological structure of overground and underground connections in karst region.



Figure 4. The *q* values of the factors influencing the groundwater in the different geomorphic regions.

3.3. Interaction Analysis of the Factors Influencing Runoff in Different Geomorphic Types

Total river runoff. In view of the interaction between factors, the effects of different factor combinations were also investigated in this study using the interaction detector. The results show that pairwise interactions between factors enhance the explanatory power of the factors on the total river runoff (Table 4). Land use types, landscape fragmentation, and precipitation are the dominant factors based on the results of the interaction study, that is, the main interaction in the different geomorphic type regions is the superposition of any two of these three factors. In the middle elevation plain and middle elevation hill regions, the top three interactions are the compositions between land use type and the other factors. For example, land use type combined with vegetation cover or precipitation produce the strongest effects in these two geomorphic type regions, with *q* values of 28.1% and 36.9%, respectively. Precipitation is the common factor in the top three interaction pairs in both the small relief mountain and middle relief mountain regions. The superposition of precipitation and landscape fragmentation and that of precipitation and elevation have the greatest impact on the total river runoff. In the middle elevation terrace region, landscape fragmentation is the common factor in the top three interaction pairs. The dominant interaction is from the synergy of landscape fragmentation and land use type, with a *q* value of 37.1%. Compared to the single factor effect, the interaction between land use type and landscape fragmentation on the total river runoff is stronger than those of the two individual factors. This also indicates that under certain conditions, there will be interaction between the two factors to enhance or weaken the influence extent.

Surface runoff. Based on the interaction detector, land use types, landscape fragmentation, and precipitation are the three dominant factors affecting surface runoff, and the same is true for total river runoff. For the five different geomorphic types, the top three interaction modes of the results of the interaction detector all show the superposition of these three factors with others (Table 5). Specifically, in the middle elevation terrace and middle relief mountain regions, the dominant interactions affecting surface runoff are the combinations of landscape fragmentation with the other factors. In the middle elevation terrace region, the explanatory power of the interaction of landscape fragmentation and vegetation cover reaches 60.3%, which is more than the sum of the *q* values of the two individual factors (Figure 3). This also indicates that these two factors promote each other, and their interaction significantly enhances the influence of the two individual factors. In the middle relief mountain region, the first dominant interaction is landscape fragmentation with precipitation (*q* = 19%). In

the middle elevation hill and small relief mountain regions, precipitation is the dominant factor, and its interactions with the other factors all produce the largest effects. Among the five geomorphic types, the explanatory power of the interaction between precipitation and land use on surface runoff reaches to 40.6%, which is the strongest; and the interaction between precipitation and landscape fragmentation is 38.8%. Moreover, there is an interesting result in the middle elevation plain region. Although the *q* values of these three top interactions are not very large (24.6%, 21.6%, 20.5%), they are also increased by 89.2%, 98.2%, and 454% compared to the sum of the *q* values of the individual factors, especially the mode between landscape fragmentation and lithology type. This may attribute to the related mechanism of these two factors on the surface runoff. For instance, in a limestone region, the more fragmented the landscape is, and the faster surface water will be converted to other forms of water.

Geomorphic Type Region	Middle Elevation Plain	Middle Elevation Terrace	Middle Elevation Hill	Small Relief Mountain	Middle Relief Mountain
1st Dominant Interaction	land use type ∩ vegetation coverage	landscape fragmentation ∩ land use type	land use type ∩ precipitation	precipitation ∩ landscape fragmentation	precipitation ∩ elevation
<i>q</i> value	0.281	0.371	0.369	0.317	0.249
2nd Dominant Interaction	land use type ∩ landscape fragmentation	landscape fragmentation ∩ vegetation coverage	land use type ∩ landscape fragmentation	precipitation ∩ land use type	precipitation ∩ vegetation coverage
<i>q</i> value	0.275	0.36	0.346	0.305	0.224
3rd Dominant Interaction	land use type ∩ slope	landscape fragmentation ∩ precipitation	land use type ∩ elevation	precipitation ∩ lithology type	precipitation ∩ lithology type
<i>q</i> value	0.263	0.334	0.315	0.302	0.213

Table 4. The effects of the dominant interactions of two covariates on the total river runoff of the different geomorphic types.

Table 5. The effects of the dominant interactions of two covariates on the surface runoff of the different geomorphic types.

Geomorphic Type Region	Middle Elevation Plain	Middle Elevation Terrace	Middle Elevation Hill	Small Relief Mountain	Middle Relief Mountain
1st Dominant Interaction	land use type ∩ vegetation coverage	landscape fragmentation ∩ vegetation coverage	precipitation ∩ land use type	precipitation ∩ landscape fragmentation	landscape fragmentation ∩ precipitation
q value	0.246	0.603	0.406	0.213	0.19
2nd Dominant Interaction	land use type ∩ slope	landscape fragmentation ∩ precipitation	precipitation ∩ landscape fragmentation	precipitation ∩ land use type	landscape fragmentation ∩ lithology type
q value	0.216	0.507	0.388	0.145	0.118
3rd Dominant Interaction	landscape fragmentation ∩ lithology type	landscape fragmentation ∩ land use type	precipitation ∩ vegetation coverage	precipitation ∩ lithology type	landscape fragmentation ∩ elevation
<i>q</i> value	0.205	0.496	0.372	0.141	0.116

Groundwater. The top three interactions on groundwater in these five different geomorphic regions are also centered on land use types and landscape fragmentation. There are also differences in the dominant interaction modes of the different geomorphic types (Table 6). In the middle elevation plain region, the land use type has a significant influence on the groundwater (q = 18.5%). For a given performance, the top three interactions are interactions between land use type and landscape fragmentation, vegetation coverage, and slope. The explanatory power of the superposition of land use type and landscape fragmentation is up to 30.7%, which is the strongest. In the small relief mountain region, the top three dominant interactions are landscape fragmentation combined with precipitation, lithology types, and land use type. The combination with the greatest explanatory power is landscape fragmentation and precipitation, which has a q value of 22.8%. In the middle elevation terrace region, the dominant interactions are pairwise combinations of landscape fragmentation, vegetation coverage, and land use type. The combination of landscape fragmentation and land use type achieves the greatest explanatory power (q = 32.4%). In the middle elevation hill region, the main interactions are related to landscape fragmentation, precipitation, and land use type. In the middle relief mountain region, only the q value of landscape fragmentation is greater than 10% (12.8%), but the explanatory power of the pairwise combinations of elevation, landscape fragmentation, and precipitation are up to 22.8%. However, for different geomorphic types, the first dominant interaction is the combination of landscape fragmentation with land use type and precipitation respectively. This may because high fragmentation of landscape also embodies a kind of hydrogeological conditions that rainfall can be quickly converted into groundwater.

Geomorphic Type Region	Middle Elevation Plain	Middle Elevation Terrace	Middle Elevation Hill	Small Relief Mountain	Middle Relief Mountain
1st Dominant Interaction	land use type ∩ landscape fragmentation	landscape fragmentation ∩ land use type	landscape fragmentation ∩ precipitation	landscape fragmentation ∩ precipitation	landscape fragmentation ∩ precipitation
	0.307	0.324	0.227	0.228	0.186
2nd Dominant Interaction	land use type ∩ vegetation coverage	landscape fragmentation ∩ vegetation coverage	land use type ∩ precipitation	landscape fragmentation ∩ lithology type	precipitation∩ elevation
<i>q</i> value	0.286	0.262	0.216	0.203	0.155
3rd Dominant Interaction	land use type ∩ slope	land use type ∩ vegetation coverage	landscape fragmentation ∩ land use type	landscape fragmentation ∩ land use type	landscape fragmentation ∩ elevation
<i>q</i> value	0.278	0.252	0.208	0.182	0.145

Table 6. The effects of the dominant interactions of two covariates on groundwater for the different geomorphic types.

4. Discussion

4.1. Comprehensive Analysis of the Dominant Factors and Interactions for the Different Geomorphic Types

Middle elevation plain region. In the middle elevation plain region, land use type and landscape fragmentation are more important than the other factors in controlling the spatial distribution of the total river runoff and groundwater, with q values concentrated in the range of 12–18.5%. In addition to these two dominant factors, vegetation cover, precipitation, and slope also play roles in the dominant interactions. The interaction modes were further explored according the interaction criteria (Table 7). In this area with low elevation and gentle topography, the high q values of land use types and landscape fragmentation reflect the significant of human activities on runoff [41]. The results show that the interaction modes of the hydrological variables are also pair-wise among the dominant

factors (land use type and landscape fragmentation) and vegetation cover, slope, and precipitation, with primarily nonlinear enhancement, which indicates that the mutual effect of two factors strengthen their individual influences on the spatial variation. The impact of interaction between these two key elements further confirms the dominant influence of them. Only the second dominant mode of total river runoff, and the first dominant mode of groundwater exhibit bifactor enhancement, which is rather weak compared to nonlinear enhancement. Furthermore, the bifactor enhancement mode of these three conditions is the interaction between land use type and landscape fragmentation, that is, the effect of the interaction between these two factors is less than the sum of the two completely individual factors. Landscape fragmentation is calculated using the land use type, so they may have the same effect as their partial overlap, which also illustrates that the different mode of interaction mainly depends on the mechanism of action of two interaction factors.

Table 7. Interaction modes of the factors on runoff in the middle elevation plain region.

	Total river runoff	Surface Runoff	Groundwater
1st Dominant Interaction	nonlinear enhancement	nonlinear enhancement	bifactor enhancement
2nd Dominant Interaction	bifactor enhancement	nonlinear enhancement	nonlinear enhancement
3rd Dominant Interaction	nonlinear enhancement	nonlinear enhancement	nonlinear enhancement

Middle elevation terrace region. In this geomorphic type region, land use type, vegetation cover, landscape fragmentation, and precipitation are the dominant factors, with q values in the range of 11.4–25.1%. Further, it is still land use type that has the greatest impact. In addition, according to the interaction criteria, we found that the effects of the interaction modes among these dominant factors on the total river runoff, surface runoff, and groundwater are all nonlinear enhancement (Table 8). This indicates that the effects of the interactions between the factors are greater than the sum of the two individual factors. Under this geomorphologic condition, the two elements promote each other to affect runoff. What stands out is that landscape fragmentation superimposed with vegetation cover, precipitation, and land use type on surface runoff have interaction degrees of up to 60.3%, 50.7%, and 49.6%, respectively, which is 18.7%, 9.2%, and 11.9% more than the sum of the individual factors. This also indicates that in the middle elevation terrace region, it is more conductive to the interactions between these elements, which will further have a more significant impact on surface runoff.

Table 8. Interaction modes of the factors on runoff in the middle elevation terrace region.

	Total River Runoff	Surface Runoff	Groundwater
1st Dominant Interaction	nonlinear enhancement	nonlinear enhancement	nonlinear enhancement
2nd Dominant Interaction	nonlinear enhancement	nonlinear enhancement	nonlinear enhancement
3rd Dominant Interaction	nonlinear enhancement	nonlinear enhancement	nonlinear enhancement

Middle elevation hill region. There are several different results for the middle elevation hill region. In addition to the three key factors of land use types, landscape fragmentation, and precipitation, which are similar to the results for the middle elevation plain and middle elevation terrace regions, elevation is an important factor. The *q* values of these factors are in the range of 12.2–31.9%. Among them, the influence of precipitation on surface runoff reaches 31.9%. In hilly regions with fluctuations, the influence of human activities is weakened, while objective environmental conditions begin to play an important role, such as precipitation, and elevation. For the pairwise interactions of the above leading factors, the interaction modes, which is different from the previous two geomorphic types, are mainly bifactor enhancement, and the third dominant mode of surface runoff and the first and second dominant modes of groundwater exhibit nonlinear enhancement (Table 9). Furthermore, this also shows that the interaction between the two factors will be weakened in the middle elevation hill region.

	Total River Runoff	Surface Runoff	Groundwater
1st Dominant Interaction	bifactor enhancement	bifactor enhancement	nonlinear enhancement
2nd Dominant Interaction	bifactor enhancement	bifactor enhancement	nonlinear enhancement
3rd Dominant Interaction	bifactor enhancement	bifactor enhancement	bifactor enhancement

Small relief mountain region. In the small relief mountain region, precipitation, landscape fragmentation, and land use type are the main factors, with q values in the range of 11–22.7%. We found that based on the q values, the effect of precipitation is larger compared to the geomorphic type regions discussed above. In addition to these three factors, lithology becomes an important fact in the top three interactions, which is different from the middle elevation regions. For example, the third interaction for total river runoff is a combination of land use type and lithologic type, with a q value of 30.2%. However, the individual explanatory power of land use type is 11%, and that of lithologic type is only 5.2%. This also confirms that the interaction between factors can significantly enhance the effects of the factors. According to the interaction criteria, of the interaction between two factors can strengthen the influences of the two individual factors. Half exhibit bifactor enhancement, and half exhibit nonlinear enhancement (Table 10). In small relief mountain region, precipitation and lithology began to play an important role. On the one hand, it is possibly influenced by weaken human activities; on the other hand, the mountain microclimate changes frequently and changeable [42], and the lithology condition are relatively complex.

Table 10. Interaction modes of the factors on runoff in the small relief mountain region.

	Total River Runoff	Surface Runoff	Groundwater
1st Dominant Interaction	bifactor enhancement	nonlinear enhancement	nonlinear enhancement
2nd Dominant Interaction	bifactor enhancement	bifactor enhancement	nonlinear enhancement
3rd Dominant Interaction	nonlinear enhancement	nonlinear enhancement	bifactor enhancement

Middle relief mountain region. In the middle relief mountain region, the influence of each factor on the runoff distribution is weaker than in the other geomorphic type regions. Precipitation and landscape fragmentation are the dominant factors. Precipitation, lithology, and elevation become more important on runoff, which may due to frequent and complex microclimate changing. The factor combinations of the top three interactions are also different. The interactions between precipitation and elevation, precipitation and lithologic type, landscape fragmentation and precipitation, and landscape fragmentation and elevation have larger effects on the spatial distribution, rather than the interaction between land use type and landscape fragmentation being the main factor. The interaction modes of the different factor combinations are primarily nonlinear enhancement (Table 11), except for the third dominant interaction for total river runoff, which exhibits bifactor enhancement. In high-elevation mountain areas, the influence of human activities is relatively small, and the interaction between different natural environmental elements is less affected by other unnatural factors.

Table 11. Interaction modes of the factors on runoff in the middle relief mountain region.

	Total River Runoff	Surface runoff	Groundwater
1st Dominant Interaction	nonlinear enhancement	nonlinear enhancement	nonlinear enhancement
2nd Dominant Interaction 3rd Dominant Interaction	nonlinear enhancement bifactor enhancement	nonlinear enhancement nonlinear enhancement	nonlinear enhancement nonlinear enhancement

4.2. Thoughts on the Rules of the Influencing Factors and Their Interactions for the Different Geomorphic Types

Considering the effects of the dominant factors and their interactions on the hydrological variables in the various geomorphic type regions, we found that the results of the factor detector provide an obvious rule and logical explanations, and there are three interesting interaction effects. First, for the top three dominant interactions, several factors have little effect on each other, but the effects of the interactions are significantly improved. For example, in the middle elevation plain region, the influence of each individual factor in the top two combinations (land use type and vegetation cover, land use type and slope) on the spatial distribution of the runoff is less than 10% (1–9.9%), but the interaction influences reach up to 25%, i.e., an increase of 90%. A similar situation occurs for the influence on surface runoff in the middle relief mountain region. This indicates that the interactions between two factors have a positive promoting effect on the spatial distribution of the runoff.

Second, the top three dominant interactions are not all ordered by the degree of influence of their individual factors. Several factors play a less important role alone, while in an interaction with other factors, their effect on the runoff was significantly increased. For instance, in the middle elevation hill region, landscape fragmentation and land use type are the greatly influencing factors on the spatial distribution of the groundwater. However, in the top dominant interactions, precipitation combined with the other factors have the highest influences and are much stronger than the combination of landscape fragmentation and land use type.

Third, based on the single-factor analysis, we found that although land use type and landscape fragmentation both have a significant influence on the runoff in the five geomorphic type regions, the interaction modes of these two factors are usually bifactor enhancement, rather than nonlinear enhancement. Because landscape fragmentation is calculated using the land use type data, there is a partial overlap of the influences of the two factors on the spatial distribution of the runoff. One thing needs to be explained is that landscape fragmentation represents the degree of fragmentation of landscape pattern, and analysis for land use types is to study the influence of different types on runoff. However, the reasons for these results are only preliminarily explained in a superficial way in this study, and an in-depth study on this issue was not conducted in this paper. This will be further explored in future research to fully understand the interaction mechanisms between the different factors and how they influence the various hydrological variables through such interaction mechanisms.

5. Conclusions

A typical karst basin in southwestern China was selected as the study area, and based on the simulation results of runoff generation in this area, the spatial variability of runoff was analyzed using a geographical detector, including the influences of the dominant factors and their interactions in the different geomorphic type regions.

First, factor detectors were conducted to determine that land use type, landscape fragmentation, precipitation, and vegetation cover are the dominant factors effecting the spatial distributions of the total river runoff, surface runoff, and groundwater, but there are differences in the leading factors among the different geomorphic type regions. In the relatively low elevation regions, such as the middle elevation plain, middle elevation terrace, and middle elevation hill regions, the influences of land use type and vegetation cover are stronger than in the other regions, with high *q* values and land use type *q* values of mostly greater than 20%. In the relatively high elevation regions, including the small relief mountain and middle relief mountain regions, the dominant factor is precipitation, and all of the *q* values of the different factors are low, around 10%. Compared with the above three geomorphic type regions, human activities are weaker in the mountain regions, and the effect of the external environment (e.g., precipitation) is more significant.

Second, the interaction detector results show that effect of the interactions are greater than the sum of the effects of the individual factors in the interaction on runoff generation in all of the geomorphic type regions, and the interaction modes of the same combination of factors changed with different geomorphologic types. The interaction modes include nonlinear enhancement and bifactor enhancement, and differences exist among the different geomorphic type regions. The effects of the interactions between the factors are stronger in the middle elevation plain, middle elevation terrace, and middle relief mountain regions than in the middle elevation hill and small relief mountain regions. In the middle elevation plain, middle elevation terrace, and middle elevation mountain regions, the main interaction mode is nonlinear enhancement. Furthermore, in the middle elevation plain region, the effects of the interactions between land use type and vegetation cover, land use type and slope, and landscape fragmentation and lithology increased by at least 89%, compared with the sum of the effects of their individual factors. In the middle elevation hill region, the interaction mode is mainly bifactor enhancement, and the third dominant mode of surface runoff and the first and second dominant modes of groundwater are nonlinear enhancement. In the small relief mountain region, the interactions between the factors in the middle elevation plain, middle elevation terrace, and middle relief mountain regions are stronger than those in the middle elevation hill and small relief mountain regions.

In this study, we explored the effects of factors and their interactions on the spatial distributions of runoff at the basin scale using a geographical detector. Compared with the methods used in previous studies, the degree of influence can be quantified using the *q* value, and the complex interactions between the factors can also be detected. It is important to determine how these factors interact with each other. Although geographical detectors are limited by the fact that they are statistical and do not have causality. These results can also provide a scientific basis for policymakers and provide a new perspective on the driving forces of land use change and on how the interactions between these factors. Understanding the influencing factors of runoff will further clarify the key factor affecting soil and water loss, and more targeted control measures should be determined in different geomorphologic types to improve the efficiency of rocky desertification control. Whatever, considering its advantages and disadvantages comprehensively, future studies should focus on the temporal dynamics of runoff and its driving factors on a larger scale.

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