Contribution analysis on spatial tradeoff/synergy of Karst soil conservation and water retention for various geomorphological types: Geographical detector application

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ARTICLE INFO

Keywords: Ecosystem services Synergistic relationship Quantitative attribution Geomorphological types Karst

ABSTRACT

Rocky desertification is the most typical ecological and environmental problem in Karst mountainous areas, which hinders sustainable development. Clarifying spatial relationship of ecosystem services including soil conservation and water retention and their dominant factors can provide scientific basis for containment of rocky desertification. The spatialization and quantification of dominant, interaction and sensitive factors affecting synergistic relationships between sediment yield and surface/slope runoff, water yield and slope runoff would be achieved in diverse geomorphological types. Geographically Weighted Regression (GWR) was used to quantitatively analyze spatial relationships between ecosystem services and variables using Soil and Water Assessment Tool (SWAT). Dominant, interaction and sensitive factors were quantitative identification based on Geographical Detector which can accurately reveal the driving factors and their explanatory power through stratification heterogeneity. Precipitation was dominant factor of synergistic relationship between sediment yield and surface/slope runoff, water yield and slope runoff, especially its explanatory power up to 55% in middle elevation plain, middle elevation hill, small relief mountain, and middle relief mountain. Precipitation is the driving force for the runoff and sediment yield occurrence, which was the important factor affecting the ecosystem service synergistic relationship variables. In middle elevation terrace, elevation dominated synergistic relationship between sediment yield and surface/slope runoff. Land use had different explanatory powers to the synergistic relationships of ecosystem service variables, due to diverse land coverages and impervious areas. As for synergistic relationship between sediment yield and slope runoff, the explanatory power of land use types declined with increase in relief degree of landform in mountainous areas. However, it was not related to relief degree of landform between sediment yield and surface runoff, water yield and slope runoff. Land use types, which are mostly determined by human activities, affect the soil erosion and water cycling processes. Besides, lithology types proved to be the sensitive factor because geological conditions are the background of soil erosion and also the important factor affecting runoff. Furthermore, multi-factor interaction significantly increased explanatory power of synergistic relationship. Moreover, their dominating power varied significantly with relief degree of landform, and these findings should be essential for rocky desertification containment.

1. Introduction

Ecosystem services refer to products and services through ecosystems that directly or indirectly benefit human survival (Costanza et al., 1997; Ma, 2005). Recently, due to the widespread effects of human activities on ecosystems, ecosystem services have been degraded or became unsustainable (Sun et al., 2017). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) report stated that the trend of global ability in nature to maintain contributions for a life of high quality has declined in 14 of 18 classes from 1970 to the present. Due to the ecosystem services, diversity and variability along with human preference, ecosystem services are not independent of each

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https://doi.org/10.1016/j.ecolind.2021.107470
Received 26 March 2020; Received in revised form 6 December 2020; Accepted 26 January 2021
Available online 17 February 2021
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other, but rather exhibit some trade-offs and synergies (Stosch et al., 2019). Evaluating trade-offs and synergies among ecosystem services have significance for formulating policies of regional development and ecological protection, maintaining regional ecological security, and promoting sustainable development. Thus, trade-offs and synergies have become the research hotspot with extensive research methods and broad application areas. Many scholars have studied trade-offs and synergies among ecosystem services which focus on types of trade-offs/synergies, analytical tools, scale effects, and uncertainty (Hou et al., 2017; Li and Wang, 2018; Santhi et al., 2001; Yang et al., 2018). For example, GIS analysis tools are often used to identify relationships of multiple ecosystem services and variables, which usually combine the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model, spatial autocorrelation and rose diagram to depict spatiotemporal patterns of ecosystem services (Lin et al., 2017; Tian et al., 2016; Xu et al., 2018). However, spatialization and quantitative identification of trade-offs and synergistic relationships remains insufficient.

Recent ecosystem services relationship research studied the relationships between macro-ecosystem services, such as water retention, carbon sequestration, soil conservation, food productivity, and habitat quality (Bottalico et al., 2016; Liu et al., 2019; Xu and Liu, 2019). For instance, Xu and Liu (2019) chose four ecosystem services to measure synergistic relationships using a local association model. Bottalico et al. (2016) evaluated trade-offs and synergies between wood production and carbon sequestration in central Italy by improving the InVEST model. Nevertheless, current trade-offs and synergies research ignores the concretized variables effects on ecosystem services, which hinders the expanding of ecosystem services mechanisms in ecosystem services research. For instance, surface runoff, slope runoff, and groundwater are important components of the hydrological cycle, which affect the hydrological process and nutrient loss, and also have significant effects on various ecosystem services such as soil conservation, water retention and carbon cycle (Dehotin et al., 2015). Owing to the geomorphological features, hydrometeorology and soil conditions in mountainous areas, spatial and quantitative study of sediment yield and hydrological variables relationships can assess the mountainous ecosystem services of trade-offs and synergies (Chen et al., 2018).

Karst mountainous region in southwest China is highly sensitive to climate change and human activities due to its special geomorphological features, intense population pressure, and scarce land resources (Fan et al., 2015). The ecological environment in this area, involves complex geomorphological types setting with vast spatial distribution patterns, which directly affect land cover conditions and land carrying capacity. It also controls the water and heat resources redistribution and takes a significant role in soil conservation, water retention and carbon fixation (Teixeira Guerra et al., 2017). Geomorphological forms research focuses mostly on dynamic geomorphology, tectonic geomorphology, climatic geomorphology, paleogeomorphology, rock geomorphology, and geomorphological zoning and mapping (Biermanns et al., 2019; Carbonel et al., 2019; Xin et al., 2013). Ecosystem services studies with different geomorphological types are however rare. Thus, ecosystem service synergistic relationships study for Karst areas can reveal dominant environmental factors rule change with different geomorphological types.

In view of this, Sancha River Basin (SRB) in Guizhou Province was used as the research area, where Soil and Water Assessment Tool (SWAT) and Geographically Weighted Regression (GWR) models were combined to quantitatively evaluate relationships between sediment yield and surface/slope runoff, water yield and slope runoff from 2010 to 2015. Based on the geographical detector, dominant factors affecting synergistic relationships between ecosystem service and variables, two pairs of ecosystem feature variables were quantitatively identified. The main purpose of this paper was to define dominant factors affecting relationships between ecosystem services and key variables in the Karst area of southwest China. The study included: (1) calculation of SRB annual average sediment yield, water yield, surface runoff, slope runoff, and evaluation of trade-off and synergistic relationships between sediment yield and surface/slope runoff, water yield and slope runoff in different geomorphological types; (2) quantitative attribution of single dominating factors and multi-interaction factors affecting synergistic relationships between sediment yield and surface/slope runoff, water yield and slope runoff in areas with different geomorphological types, and identification of sensitivity factors.

2. Data source and processing

2.1. Study area

Sancha River Basin (SRB) is located in southwestern Guizhou Province for the upstream of the Wujiang River (104°18'-106°18' E, 26°10'-27°00' N). The area of SRB is 7061 km² and the total length is 325.6 km (Fig. 1). The basin belongs to the typical peak-cluster depression area in the northwestern part of the Guizhou Province. Bedrock is dominated by carbonate sequence of limestone and dolomites (Han and Liu 2004). Karst formation forms a unique surface and subsurface binary hydrological structure. In karst areas, the bedrock is widely exposed and soil thickness, and also soil erosion is severe (Biermanns et al., 2019). High permeability of carbonate rocks and low level of soil formation create the vulnerable ecological karstic environment, and widespread disturbances resulting from human activities lead to rocky desertification (Jiang et al., 2014). SRB karst area is highly populated, creating conflicts between people and land, where unregulated land use has intensified rocky desertification and soil erosion. Similar scenarios were found to cause a severe reduction in groundwater recharge and runoff intensification (Anker et al., 2019).

2.2. Data

Building a SWAT model requires Digital Elevation Model (DEM), land use types, soil and meteorological data. DEM data (resolution: 30 m) were derived from Geospatial Data Cloud (http://www.gscloud.cn/). Land use types for 2010 were provided by Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn) with the resolution of 1 km. Soil data, which included soil spatial distribution (resolution: 1 km) and soil attribute data, were based on China Soil Map of Harmonized World Soil Database (HWSD). SRB has only one weather station within its large area, but one station cannot objectively and accurately reflect precipitation, temperature, humidity, and other meteorological conditions within the basin. Therefore, China Meteorological Assimilation Driving Datasets for the SWAT model (CMADS) was used for the SWAT model as meteorological data. CMADS incorporated technologies of LAPS (Local Analysis and Prediction System)/STMAS (Space-Time Multiscale Analysis System) and was constructed using multiple technology and scientific methods. Data sources for the CMADS include nearly 40,000 regional automatic stations under China’s 2,421 national automatic and business assessment centers. This ensures that the CMADS has wide applicability within the country, and that data accuracy was vastly improved. This dataset has been tested and verified in various basins of China with credible results (Meng et al., 2018, 2017; Shi et al., 2011). Soil data and CMADS were both derived from Cold and Arid Regions Sciences Data Center at Lanzhou, China (http://westdc.westgis.ac.cn/). In the paper, CMADS data for 2008–2015 were used to build the SWAT model.

In the SRB there are two hydrological stations, Yangchang hydrological station (105°11’ E, 26°39’ N) in the upper reaches and Longchangqiao hydrological station (105°28’ E, 26°20’ N) in the middle reaches. To verify the SWAT model, the total outlet of basin must be calibrated and verified. As there is no hydrological station in the total outlet of SRB. Therefore, Hongjiadu hydrological station at export for Liuchong Basin and Yachihle hydrological station at Wujiang River mainstream and the convergence of Liuchong and SRB were chosen. The average monthly flow at Hongjiadu hydrological station was subtracted
from flow at Yachihe hydrological station to verify the accuracy of outlet for SWAT model. Data for Yangchang, Longchangqiao, Hongjiadu, and Yachihe hydrological stations supply monthly average flow data for each station and monthly average sediment transport rate data for Yangchang hydrological station that were derived from the Wujiang River region of the Yangtze River Basin, People’s Republic Annual Hydrological Report from 2010 to 2015. NDVI data were obtained from MOD13A2 NDVI data (http://www.gscloud.cn/) and vegetation coverage was calculated using pixel dichotomy model based on vegetation index with the resolution of 1 km. According to Zhou et al. (2009), SRB contains five geomorphological types, including middle elevation plain, middle elevation terrace, middle elevation hill, small relief mountain and middle relief mountain. Data on geomorphological types (Table S1) and lithology types (Fig. S1) were obtained from Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn).

2.3. SWAT model

SWAT model is a comprehensive, semi-distributed and successive model which is exploited to assess effects about watersheds management and climate for water supply, sediment transport, agrochemical production (Abbaspour et al., 2015, 2007; Gassman et al., 2007). In the model, SRB was divided into unified Hydrological Response Units (HRUs) which can simulate higher levels of spatial detail. The model has been extensively applied since input datasets are easier to obtain and computational efficiency is higher which can simulate long-term management changes effects (Arnold and Allen, 1996; Arnold et al., 1998; Suttles et al., 2018).

The principle of the hydrological sub-model is water balance which can simulate process including precipitation, infiltration, surface runoff and evapotranspiration as follows (Fan and Shibata, 2014):

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

where \( SW_t \) and \( SW_0 \) are the final soil water content (mm) and initial soil water content (mm); \( t \) is the day for simulating (d); \( R_{day} \), \( Q_{surf} \), \( E_a \), \( W_{seep} \) and \( Q_{gw} \) represent precipitation (mm), surface runoff (mm), evapotranspiration (mm), the amount of percolation and bypass flow exiting the soil profile bottom (mm) and return flow (mm), respectively. In this paper, surface runoff is estimated daily using the modified Soil Conservation Service (SCS) curve number (CN) method. Slope runoff is the sum of surface runoff and subsurface flow.

The Modified Universal Soil Loss Equation (MUSLE) is used to calculate sediment yield which is caused by precipitation and runoff in each HRU in the SWAT model. In MUSLE, precipitation energy factor is replaced by runoff factor (Yesuf et al., 2015). The prediction accuracy of sediment yield is improved, and it allows calculation of estimated sediment yield for a single storm. Since runoff is the function for humidity and precipitation energy, the equation of sediment yield is represented as:

\[
sed = 11.8 \left( Q_{surf} \cdot q_{peak} \cdot area_{hru} \right)^{0.56} \cdot K_{sole} \cdot C_{sole} \cdot P_{sole} \cdot LS_{sole} \cdot CFRG
\]

where \( sed \) is sediment yield (t), \( Q_{surf} \), \( q_{peak} \) and \( area_{hru} \) are surface runoff volume (mm/ha), peak runoff rate (m³/s) and area (ha), respectively. \( K_{sole} \) represents erodibility factor, \( C_{sole} \) refers to vegetation cover and management factor, \( P_{sole} \) is conservation and supporting factor, \( LS_{sole} \) refers slope length and steepness factor, and CFRG represents surface roughness coefficient.

For the HRU division, the minimum threshold area of soil, land use and slope was set to 5%. If soil, land use, and slope area was lower than this threshold area, it was not considered in the model, and remaining soil, land use, and slope area was proportionally recalculated to ensure...
that simulated area of SRB sums to 100%. After several simulations, SRB was divided into 13 sub-basins. This model can be run on annual, monthly, and daily scales. In this study, the model was run on a monthly scale to simulate and calibrate runoff and sediment in SRB.

Before using the SWAT model to simulate SRB, parameters were calibrated and verified using accuracy fitting algorithm (SUFI-2) (Arnold et al., 2012). Through calibration of relevant parameters, the model results are applicable to SRB (Table 5). Nash-Sutcliffe Efficiency (NSE) and effectiveness of determination ($R^2$) were used as indices to evaluate applicability of SWAT model in SRB. When NSE $> 0.5$ and $R^2 > 0.5$, simulation results are considered to be approving (Moriasi et al., 2007). In this study, measured runoff and sediment data in SRB from 2010 to 2015 were selected for simulation and verification. The data for 2008–2009, 2010–2012, and 2013–2015 were taken as warm-up, calibration, and validation period, respectively.

2.4. GWR model

GWR model, which was proposed by Fotheringham et al. (1998), is for dealing with spatial non-stationary phenomena in regression analysis. By introducing the spatial location data into the regression coefficient, a local estimator of function is given for each geographical location using nonparametric estimation (Bramson et al., 1996). GWR model introduces the impact of geographic region to reflect spatial non-stationarity of parameters in different spaces which allows local parameter estimation rather than global parameter estimation. The regression parameters of a specific location are no longer all arbitrary parameters obtained from information, but the observations of adjacent data are used to estimate local regression. The variable changes with the change of spatial position. Thus, relationships between variables can change spatially, allowing results to better reflect objective reality. GWR model was introduced in this study to analyze relationships between sediment yield and surface/slope runoff, water yield and slope runoff under spatially nonstationary conditions. The model structure is as follows:

$$y_i(u,v) = \beta_i(u,v) + \sum \beta_j(u,v)X_j(u,v) + e_i(u,v)$$

(3)

where $(u,v)$ refers to the spatial location or geographic coordinates of observed point $i$ in space; $\beta_i(u,v)$ and $\beta_j(u,v)$ represent intercept parameter and local regression coefficient and $e_i$ is error. The estimation of the parameters $\hat{\beta}(u,v)$ is carried out as follows:

$$\hat{\beta}(u,v) = (X'W(u,v)X)^{-1}X'W(u,v)y$$

(4)

where $\hat{\beta}(u,v)$ is unbiased estimate of regression coefficient; $X$ and $Y$ are matrices of independent and dependent variables, respectively; and $w(u,v)$ is spatial weight matrix. In this study, $X$ was surface/slope runoff, and $Y$ was sediment yield and water yield which calculated.

2.5. Geographical detector

The geographical detector method is a statistical method for detecting spatial heterogeneity and its driving factors (Wang and Xu, 2017). The idea of geographical detector is that if independent variable has an important effect on dependent variable, and spatial distributions of variables have similarities to identify main influencing factors (Wang et al., 2010). The geographical detector can quantitatively characterize the explanatory power of each impact factor through $q$-statistics and detect the correlation and contribution degree between influencing factors. The method is divided into four modules: factor detector, interactive detector, risk detector, and ecological detector. This method has been applied in natural and socioeconomic research, including studies on environmental health (Adegboye et al., 2017), landslide hazards (Luo and Liu, 2018), natural ecology (Gao and Wang, 2019), and urbanization (Tian et al., 2017).

The $q$ statistic is a function of spatial heterogeneity (Wang et al., 2016), and measures the degree of spatial heterogeneity in variable $Y$ of factor $X$:

$$q = 1 - \sum_{h=1}^{L} N_h \sigma_h^2 / \sigma^2$$

(5)

where $h = 1, \ldots, L$ is stratification of $Y$ or $X$; $N_h$ and $N$ are numbers of units in layer $h$ and entire area, respectively; $\sigma_h^2$ and $\sigma^2$ are variances of layer $h$ and entire area, respectively; $q \in [0,1]$. In addition, dominant factors affecting relationships of ecosystem services and variables were determined by $q$ value.

The interaction detector can identify interactions between different factors and assess whether different factors interact with each other to enhance or reduce the explanatory power for variable $Y$. The type of interaction is categorized as nonlinear weakness, single factor nonlinear weakness, double factor enhancement, nonlinear enhancement, and independent (Ju et al., 2016). The risk detector counts the percentage of total number for stratified layers with significant differences on each environmental factor to the number of all stratified layer combinations, and then reflects the sensitivity of relationships on ecosystem service and variables to different environmental factors.

In this study, regression coefficients for synergistic relationships between sediment yield and surface/slope runoff, water yield and slope runoff were taken as variable $Y$, while vegetation coverage, land use types, precipitation, slope, elevation, and lithology types were taken as factor $X$. Geographical detector was applied to quantitatively identify dominant and interaction factors and identify sensitivity factors in synergistic relationships between sediment yield and surface/slope runoff, water yield and slope runoff on diverse geomorphological areas of SRB.

3. Results

3.1. Model validation and spatial distribution of ecosystem service and variables

3.1.1. Model calibration and validation

The simulation results of monthly runoff and sediment in SRB from 2010 to 2015 were verified. According to the sensitivity of relevant parameters, the ranges of parameter values were continuously adjusted to obtain a set of suitable parameters and validate the model (Fig. 2). $R^2$ and NSE for each station were higher than 0.7 during the calibration period (2010–2012) and higher than 0.5 during the verification period (2013–2015). Therefore, calibration and verification results were satisfactory (Table 1). The sediment yield of SRB simulated by the model was 2.93 t/km$^2$.a. Based on Guizhou Province Soil and Water Conservation Bulletin, sediment yield in the karst area from 2011 to 2015 was 2.79 t/km$^2$.a. Consistent results demonstrated that SWAT model was valid for simulating within SRB.

For the sake of accurately simulate hydrological processes of basin, the upper, middle and lower reaches of SRB were simulated and verified respectively. Because no hydrological station was set up in the lower reaches and total outlet of SRB, the total outflow of this study used results that flows of Yachihe hydrological station minus flows of Hongsitu hydrological station. Compared with previous studies that ignored the phenomenon of total outlet flow verification, this method had certain progress. However, this method had certain limitations. The total outlet of this study used the difference between Yachihe and Hongxiu hydrological stations, and ignored the flow of Zhijin hydrological station which located in Zhijin River, a tributary of Liuchong River. Runoff of Zhijin hydrological station was quite smaller than Hongxiu and Yachihe hydrological stations and had little effect on the difference between two stations. Therefore, Zhijin hydrological station was not considered in this study. In addition, many human disturbances affected the total outlet results, causing some errors. Nonetheless, the
validation results illustrated that SWAT model had good usability in SRB and produced credible simulation results.

3.1.2. Spatial distribution of hydrological variables and sediment in SRB

Based on the SWAT model, simulation results of water yield, surface runoff, slope runoff and sediment yield in SRB were obtained (Fig. 3). Surface runoff in SRB from 2010 to 2015 ranged from 12.64 to 685.66 mm, and surface runoff coefficient was 25.39%. Slope runoff ranged from 54.18 to 700.43 mm, and slope runoff coefficient was 29.25%. Water yield ranged from 226.64 to 686.46 mm and sediment yield ranged from 0.10 to 7.38 t/km$^2$·a. Sediment yield, water yield, surface/slope runoff all exhibited spatial heterogeneity, but some consistency in the spatial distribution of sediment yield, water yield, surface/slope runoff had existed. High-value areas of surface/slope runoff were mostly distributed in upstream and downstream of SRB, and values of surface/slope runoff were relatively small in midstream and southern areas. Surface runoff in SRB was generally low, with an average of 259.72 mm, which was consistent with the study of Tu et al. (2016). Only sub-basin 11, which was located in the west the basin had a surface runoff value higher than 240 mm. The high water yield area was located in the downstream of the basin, and the sub-basin 11 had the highest water yield, whose value was 686.46 mm. The average sediment yield value in the basin was 2.93 t/km$^2$·a. Sediment load in downstream of SRB was heavier and sediment yield was higher. In recent years, the ecological environment for soil conservation and water retention in SRB has been continuously improved, but local soil erosion is still severe.

3.2. Trade-off and synergistic relationships between sediment yield and surface/slope runoff, water yield and slope runoff

Fig. 4 demonstrated the relationships between different ecosystem service and variables in SRB. Relationships between sediment yield and surface/slope runoff, water yield and slope runoff showed strongly spatial heterogeneity. Given different magnitudes of ecosystem service and variables evaluated herein, values of sediment yield, water yield, surface/slope runoff were standardized to values in the range of 0–1 to make results comparable. Both trade-off and synergistic relationships were found between sediment yield and surface runoff in SRB between 2010 and 2015, which 98.54% of the SRB area was the synergistic relationship. In the hydraulic erosion aspect, surface runoff is one of the fundamental driving forces for erosion, and high surface runoff can easily cause soil erosion (Li et al., 2015). From 2010 to 2015, sediment yield and slope runoff had a synergetic relationship in 85.84% of SRB and trade-off relationship in 14.16% of the basin. The amount of soil erosion is determined by slope runoff capacity, and slope runoff has the ability to disperse soil and transport sediment. Thus, higher slope runoff corresponds to heavier soil erosion. Moreover, the spatial relationship of water yield and slope runoff was mainly synergetic, accounting for 99.73% of SRB.
Based on zonal statistics for three pairs of ecosystem service and variables in SRB, spatial relationships between sediment yield and surface/slope runoff, water yield and slope runoff in different geomorphological types were obtained. Sediment yield and surface runoff had a synergistic relationship in the middle elevation plain and middle elevation terrace. That was, higher surface runoff can cause more significant sediment yield. In middle elevation hill, small relief mountain and middle relief mountain, sediment yield and surface runoff exhibited both trade-off and synergistic relationships, but regression coefficients had no direct correlation with relief degree of landform. The area of trade-off relationship between sediment yield and surface runoff was not more than 5% in each geomorphological type. For all geomorphological types, sediment yield and slope runoff exhibited both trade-off and synergistic relationships in SRB. However, the trade-off relationship between various geomorphological types was weak. The weakest synergistic relationship was observed in the middle elevation hill (average regression coefficient of 0.10), whereas the strongest synergistic relationship was found in small relief mountain. In addition, the percentage of the area on trade-off and synergistic relationship between sediment yield and slope runoff was different in different geomorphological types. In all geomorphological types, the area occupied by synergistic relationship was greater than the trade-off relationship area. The synergistic relationship had the largest area in the middle elevation plain with an area of 92.70%. For middle elevation plain, middle elevation terrace and
middle elevation hill, water yield and slope runoff had synergetic relationship in SRB. However, water yield and slope runoff displayed both trade-off and synergetic relationship in small relief mountain and middle relief mountain that the areas of trade-off relationship both were less than 1%. Furthermore, the strongest synergetic relationship was in middle elevation hill (average regression coefficient of 1.07).

3.3. Quantitative identification for synergetic relationships between ecosystem service and variables on diverse geomorphological types

3.3.1. Attribution analysis of single dominant factors

The area proportion on synergetic relationship exceeded the trade-off relationship between sediment yield and surface/slope runoff, water yield and slope runoff (Fig. S2). In order to clarify the synergetic relationship mechanism, this study analyzed the synergetic relationship between sediment yield and surface runoff/slope runoff, water yield and slope runoff through geographical detector. Factor detector was used to quantitatively identify dominant factors affecting synergetic relationships between three pairs of key ecosystem service and variables for different geomorphological types (Fig. 5). The effects of dominant factors on spatial heterogeneity in synergetic relationships between three pairs of key ecosystem service and variables were also assessed. Synergetic relationships between different pairs of ecosystem service and variables were found to have different dominant factors with varying explanatory power in diverse geomorphological types.

The dominant factor about synergetic relationship between sediment yield and surface runoff was precipitation for middle elevation plain, middle elevation hill, small relief mountain, middle relief mountain and SRB (Fig. 5a). Elevation had a great impact on synergetic relationship between sediment yield and surface runoff/slope runoff in middle elevation terrace, where it was the dominant factor explaining 30.84% of spatial distribution. In mountainous areas, the explanatory power of elevation decreased with the increase relief degree of landform, and $q$ values were: middle elevation hill > small relief mountain > middle relief mountain. In relatively flat areas, the opposite elevation trend was observed, so the explanatory power of elevation in the middle elevation terrace was greater than the middle elevation plain. Lithology types dominated the second environmental factor in the middle elevation plain, middle elevation terrace and middle elevation hill. For relatively flat areas, the explanatory power of lithology types increased with the increase for relief degree of landform. In mountainous areas, the explanatory power of lithology types had not directly related to the relief degree of landform, which $q$ values were: middle elevation hill > middle relief mountain > small relief mountain. The slope had no significant explanatory power on spatial distribution about synergetic relationship between sediment yield and surface runoff on different geomorphological types.

As the synergetic relationship between sediment yield and surface runoff, precipitation was the dominant factor affecting synergetic relationship of spatial heterogeneity between sediment yield and slope runoff in middle elevation plain, middle elevation hill, small relief mountain, middle relief mountain and basin, that explanatory power in middle elevation hill was 53.56% (Fig. 5b). The dominant factor for middle elevation terrace was elevation, which explained over 55.56% of spatial distribution. The slope had a lower explanatory power in different geomorphological types, all of which did not exceed 15%. For relatively flat areas, the explanatory power of vegetation coverage decreased with an increase for relief degree of landform. In mountainous areas, the explanatory power of vegetation coverage had not directly related to the relief degree of landform, which $q$ values were: middle relief mountain > middle elevation hill > small relief mountain. Lithology types had different effects for different geomorphological types, explanatory power in the middle elevation terrace was 32.08%, while for small relief mountain only 3.66%. Geological condition is the background of soil erosion and also the important factor affecting runoff. The spatial relationship between sediment yield and slope runoff is interrelated with climate, topography and human elements. Thus, explanatory power of lithology types was also different in diverse geomorphological types.

For the synergetic relationship between water yield and slope runoff, precipitation was the dominant factor affecting synergetic relationship of spatial heterogeneity between water yield and slope runoff. Lithology types had different effects for different geomorphological types, explanatory power in the middle elevation terrace was 32.08%, while for small relief mountain only 3.66%. Geological condition is the background of soil erosion and also the important factor affecting runoff. The spatial relationship between sediment yield and slope runoff is interrelated with climate, topography and human elements. Thus, explanatory power of lithology types was also different in diverse geomorphological types.

Fig. 5. Statistics of $q$ value for single factors affecting synergetic relationship between sediment yield and surface runoff (a)/slope runoff (b), water yield and slope runoff (c).
runoff, precipitation was the dominant factor affecting synergistic relationship in middle elevation terrace, small relief mountain, middle relief mountain and SRB (Fig. 5c). Moreover, the explanatory power of precipitation for synergistic relationship in middle elevation terrace exceeded 80%. The dominant factor for synergistic relationship in middle elevation plain and middle elevation hill was lithology types, where the interpretation for the middle elevation plain was more than 30%. In mountainous areas, the explanatory power of precipitation increased with the increase relief degree of landform, and the \( q \) values were: middle relief mountain > small relief mountain > middle elevation hill. In relatively flat areas, the explanatory power of elevation for the synergistic relationship between water yield and slope runoff decreased with the decrease relief degree of landform, while the interpretation of lithology types decreased with the increase relief degree of landform. The interpretation of land use types was low among different geomorphological types, not exceeding 10%. In addition to the middle elevation terrace, precipitation and lithology types were the top two dominant factors for the other geomorphological types. Besides, the interpretation of elevation in the middle elevation terrace was the second, because the spatial heterogeneity of lithology types in the middle elevation terrace was low and the spatial heterogeneity of elevation was more significant, and the explanatory power of elevation was 47.28%.

3.3.2. Quantitative attribution of interaction factors

Interaction detector results showed that in five geomorphological types, the interaction of environmental factors enhanced explanatory power of the synergistic relationship between sediment yield and surface/slope runoff, water yield and slope runoff (Fig. 6). Except for the middle elevation plain and middle elevation hill, the combination of precipitation and elevation in three geomorphological types is one of the top three about explaining the synergistic relationship between sediment yield and surface runoff. The top three interactions in small relief mountain and middle relief mountain between sediment yield and surface runoff were a combination of precipitation and elevation, interaction of precipitation and land use types, superposition of precipitation and lithology types. In addition, the top three interaction factors in the middle elevation terrace between sediment yield and surface runoff were a combination of elevation and another environmental factor. Elevation, precipitation, lithology types, and land use types were the top four dominant factors, and a combination of elevation with the other three influencing factors greatly increased explanatory power for its synergistic relationship. In mountainous areas, the top three dominant interactions factors on the synergistic relationship between sediment yield and slope runoff were a combination of precipitation and another influencing factor, and interaction \( q \) values were more than 35%. Superposition of precipitation and other environmental factors had no direct relationship with relief degree of landform, and explanatory powers were expressed as: middle elevation hill > middle relief mountain > small relief mountain. A combination of elevation and other environmental factors in the middle elevation terrace significantly enhanced the explanatory power of the synergistic relationship between sediment yield and slope runoff, and explanatory power of combination elevation and slope explained the spatial distribution of 58.44%. In mountainous areas, the interaction between precipitation and lithology types was the dominant factor in the spatial synergy between water yield and slope runoff. For small relief mountain and middle relief mountain, the top three of explanation powers for interaction factors were: precipitation and lithology types > precipitation and elevation > precipitation and land use types. The superposition of precipitation and another environmental factor in the middle elevation terrace would greatly enhance the explanatory power of the spatial relationship between water yield and slope runoff, especially its explanatory power up to 85% in middle elevation terrace.

3.3.3. Quantitative identification sensitivity factors

Significant differences were observed in the synergistic relationship combinations percentage between sediment yield and surface runoff for different geomorphological types (Fig. 7a). For diverse geomorphological types were large differences in precipitation and land use types, exceeding 65% (Table S3). Middle elevation terrace was most sensitive to precipitation and land use types. Elevation was the most sensitive factor in middle elevation plain and small relief mountain, which corresponding significant differences percentages of 83.33% and 92.86%,
respectively. Among relatively flat and mountainous areas, middle elevation plain and small relief mountain had the lowest degree on relief of landform, respectively. Change in elevation made the spatial distribution of the synergistic relationship between sediment yield and surface runoff more sensitive. The synergistic relationship between sediment yield and surface runoff was much more sensitive to vegetation coverage than other environmental factors in the middle elevation hill (percentage of significant difference of 90%). In contrast, the synergistic relationship was most sensitive to land use types and vegetation coverage in middle relief mountain. In middle relief mountain, the difference of elevation was relatively large, that elevation range of middle relief mountain in SRB is 1050–2889 m, and it was more sensitive to land use changes than other geomorphological types.

For the synergistic relationship between sediment yield and slope runoff, a significant difference in percentages of combinations was found for environmental factors between different geomorphological types (Fig. 7b). Layers between environmental factors for different geomorphological types had large differences (Table S4). For example, precipitation and land use types were up to 100%, and the slope was lowest with a percentage of 0%. Among geomorphological types, middle elevation plain, middle elevation terrace, small relief mountain, and middle relief mountain were most sensitive to precipitation (significant difference of 100%). In addition, among environmental factors, the middle elevation hill was most sensitive to precipitation (significant difference of 93.33%).

Significant differences were existed between water yield and slope runoff in diverse geomorphological types, where the percentage of combinations ranges from 0 to 100% (Fig. 7c). The difference of precipitation between different geomorphological types was large, and the percentages with significant differences were all over 85% (Table S5). Additionally, middle elevation plain, middle elevation terrace and small relief mountain were most sensitive to precipitation, and the percentages with significant differences reached 100%. The difference of the vegetation coverage on the synergistic relationship between water yield and slope runoff in middle elevation hill was much greater than other environmental factors, with a significant difference of 100%. For the middle relief mountain, the synergistic relationship between water yield and slope runoff was the least sensitive to slope, with a sensitivity of 17.85%.

4. Discussion

Shallow soil layer, slow soil formation speed, special binary surface, and underground hydrological structure result in the fragile ecosystem of the karst area (Anker et al., 2019). Relationships between sediment yield and hydrological variables are complex and it is easy to cause soil erosion. In addition, dominant, interaction and sensitive factors were quantitatively analyzed affecting the synergistic relationship between sediment yield and surface/slope runoff, water yield and slope runoff with different geomorphological types.

4.1. Spatial relationships between ecosystem services and variables

At specific temporal and spatial scales, ecosystem service and variables are not independent. Instead, they exhibit complex interactions. Compared to other models that only can be used to estimate globally correlations between ecosystem service variables, GWR model can reflect the change in the relationship between ecosystem service and variables with spatial location, which is convenient for further exploring its spatial laws. In this study, both the trade-off and synergistic relationships were evaluated for sediment yield and surface/slope runoff, water yield and slope runoff. In addition, the spatial relationships between ecosystem service variables, ecosystem service and variables were affected by various factors, which relationships and the regression coefficients differed on different geomorphological types. Yuan et al. (2016) pointed out that surface sediment and surface runoff exhibited a very significant positive relationship. Surface runoff has a strong capacity to carry sediment in karst areas. Once surface runoff is generated, surface sediment yield will increase rapidly, which is consistent with the conclusion that sediment yield and surface runoff in this study mainly showed a synergistic relationship. Surface runoff is the driver of sediment loss, and surface runoff causes in the destruction, dispersion, and migration of soil particles, thereby resulting in stronger soil erosion (Zhao and Hou, 2018).
4.2. Dominant, interaction and sensitive factors

As an important system component on the earth’s surface, geomorphological type directly affects processes on the earth’s surface. Different geomorphological types have similarities and differences. A study on different geomorphological types helps to formulate ecological environmental protection policies based on local conditions. Many studies focus on the overall region, but research on different geomorphological types is still lack. Dominant factors between sediment yield and surface/slope runoff, water yield and slope runoff differed significantly on different geomorphological types. Karst areas of sediment areas and runoff result from combined effects of geomorphological factors, vegetation, climate, and lithology types. Precipitation is a driving force of soil erosion along with a source surface runoff (Wu et al., 2018). Precipitation was the dominant factor affecting the synergic relationship between sediment yield and surface/slope runoff in the middle elevation plain, middle elevation hill, small relief mountain and middle relief mountain. The dominating factor affecting the synergic relationship between two pairs of ecosystem service variables in the middle elevation terrace was elevation, which had an explanatory power exceeded 30%. Moreover, precipitation dominated the spatial distribution of the synergic relationship between water yield and slope runoff in the middle elevation terrace, small relief mountain and middle relief mountain. In middle elevation plain and middle elevation hill, lithology types dominated synergic relationship between water yield and slope runoff. The landform degree of relief is relatively low in the middle elevation terrace, and this area is sensitive to changes in elevation. Stratification of elevation in the middle elevation terrace embody synthesized differences of vegetation cover, land use and climate. Interaction for environmental factors increased the explanatory power of the synergic relationship between sediment yield and surface/slope runoff, water yield and slope runoff. A combination of elevation and other environmental factors in middle elevation terrace significantly enhanced the explanatory power of the synergic relationship between sediment yield and slope runoff.

In addition to environmental factors quantitative identification contribution to spatial heterogeneity, this study also analyzed sensitive factors using spatial statistics. Precipitation, lithology types, and elevation were also sensitive factors affecting the synergic relationship between sediment yield and surface runoff. Precipitation, lithology types and land use types were sensitive factors affecting the synergic relationship between sediment yield and slope runoff. For the synergic relationship between water yield and slope runoff, precipitation, elevation, lithology types were sensitive factors. Among them, precipitation is a driving force for the runoff and sediment yield occurrence, which was the most sensitive factor affecting the ecosystem service synergic relationship variables. Land use types, which are mostly determined by human activities, affect the soil erosion and water cycling processes (Zare et al., 2017). Different land use had different sensitivities to the ecosystem service variables synergic relationships, due to different land coverages and impervious areas (Zhou and Shangguan 2008).

4.3. Uncertainty analysis and future perspectives

No hydrological station was set in SRB lower reach or total outlet, so simulated runoff in lower reach could not be calibrated nor verified. To ensure the model accuracy and credibility, the total outlet runoff value was obtained by the runoff value of Yachihe hydrological station subtracting from the Hongjiadu hydrological station. Although this approach improved the results accuracy to some extent, uncertainty remained. $R^2$ and NSE during the verification period were lower than the calibration period, which may be related to errors in SWAT model. Potential errors in the SWAT model include spatial errors of precipitation, soil, and land use and also flow measurement. Mechanism of sediment yield in SRB is complex and has many influencing factors, including runoff generation mechanism and measurement to prevent soil erosion. The mechanism of sediment yield also affects the simulated results of sediment yield during the verification period. Therefore, future work will focus on reducing uncertainty in SWAT model simulation results and improving results during model calibration and verification.

5. Conclusion

This study took SRB as a representative research area, and quantitatively identified dominant, interaction and sensitive factors affecting the synergic relationship between sediment yield and surface/slope runoff, water yield and slope runoff from 2010 to 2015. The main conclusions are as follows:

(1) $R^2$ and NSE of runoff and sediment both exceeded 0.70 in the calibration period. Also, $R^2$ and NSE both exceeded 0.50 in the validation period, which suggested that the SWAT model simulation results were accurate and applicable to SRB. The average SRB surface runoff from 2010 to 2015 was 259.72 mm, and the surface runoff coefficient was 25.39%. The average slope runoff was 298.37 mm and the slope runoff coefficient was 29.25%. The average water yield was 419.71 mm and the average sediment yield was 2.93 t/km$^2$. High-value areas of surface runoff and slope runoff were mainly located in the basin’s upstream and downstream areas. In the SRB downstream, water yield and sediment yield were higher.

(2) From 2010 to 2015, the areas of synergic relationship between sediment yield and surface/slope runoff, water yield and slope runoff were 98.54%, 85.84% and 99.73% in SRB, respectively. Geomorphological type is one of the most basic geographical elements. These differences shape different natural landscapes and determine the redistribution of surface materials and energy. Different geomorphological types had different areas on trade-off and synergic relationships between sediment yield and surface/slope runoff, water yield and slope runoff. Areas of synergic relationship accounted for more than 90% in middle elevation plain between two pairs of ecosystem service key variables. The trade-off relationship took up the largest area in the middle elevation hill at 26.42% between sediment yield and slope runoff. In preventing soil and water loss, macro-controlling effects of geomorphological types and differences between geomorphological types should be considered to formulate corresponding measures.

(3) Precipitation was the dominant factor of synergic relationship between sediment yield and surface/slope runoff in SRB, especially its explanatory power up to 55% in middle elevation plain, middle elevation hill, small relief mountain, and middle relief mountain. While elevation was the dominant factor affecting the synergic relationship between sediment yield and surface/slope runoff in the middle elevation terrace. Precipitation dominated the synergic relationship between water yield and slope runoff in middle elevation terrace, small relief mountain, and middle relief mountain. Lithology types was the dominant factor for the synergic relationship between water yield and slope runoff in the middle elevation plain and middle elevation hill. In mountainous areas, with the increase in relief degree of landform, explanatory power of elevation and land use types decreased for synergic relationships between sediment yield and surface runoff, slope runoff respectively. However, it was not related to relief degree of landform between water yield and slope runoff.

A combination of different environmental factors can enhance the explanatory power of the synergic relationship between ecosystem services and variables. Interaction of precipitation and land use types has greatly enhanced explanatory power for the synergic relationships in small relief mountain and middle relief mountain between sediment yield and surface runoff. In mountainous areas, the explanatory power of combined land use types and elevation increased with the decrease in relief degree of landform for a synergic relationship between sediment yield and surface runoff. Superposition of precipitation and lithology types had improved the explanatory power of the synergic relationship between sediment yield and slope runoff in middle elevation hill.
and small relief mountain. The explanatory power of superposition about precipitation and vegetation coverage increased with the increase in relief degree of landform for the synergistic relationship between water yield and slope runoff.

CRediT authorship contribution statement

Jiangbo Gao: Conceptualization, Formal analysis, Methodology, Writing - original draft, Writing - review & editing, Funding acquisition, Project administration. Yuan Jiang: Data curation, Formal analysis, Methodology, Resources, Software, Investigation, Writing - original draft, Writing - review & editing, Visualization. Yaakov Anker: Writing - review & editing, Validation, Supervision.

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.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 41671098, No. 42071288), the National Key R&D Program of China (2018YFC1508900, 2018YFC1508801), the “Strategic Priority Research Program” of the Chinese Academy of Sciences (Grant Nos. XDA19040304 and XDA20020202).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107470.

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