

CHANGES IN FRESHWATER ECOSYSTEM SERVICES FROM 1960 TO 2017 UNDER CLIMATE CHANGE IN GUIZHOU, CHINA

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Abstract. The supply capacity of freshwater ecosystem services (FES) is affected by climate change as a result of global temperature rising. However, previous studies have rarely focused on the interannual, seasonal, and periodic change characteristics of FES. We analyzed the effects of climate change on FES from 1960 to 2017 in the Guizhou Province in China. The water yield and soil retention in Guizhou at an annual scale exhibited a decreasing trend between 1960 and 2017, whereas the annual nutrient retention exhibited an increasing trend. The change trends of the three FES in spring and autumn were significantly different from the change trends in summer and winter. The change rate of the nutrient retention in all four seasons from 1960 to 2017 was opposite of that of the water yield and soil retention. The peak period of the water yield, soil retention, and nutrient retention at the annual scale occurred at 28a (i.e. 28 year), whereas differences were observed for the peak period of the three FES at the seasonal scale. The results of this study benefit the scientific management of the FES and contribute to reducing the negative effects of global climate warming.

Keywords: *ecosystem service change, climate impact, spatial pattern, change period, InVEST model, Guizhou*

Introduction

Ecosystems are the basis for human survival and socioeconomic development and are critical support systems for all life on earth (Karp et al., 2015; Rau et al., 2018). Ecosystems provide humans with a variety of important services (e.g., biodiversity, carbon storage, soil retention, recreation, and grain production) that constitute the basis for the sustainable development of human society and economy (Costanza et al., 2014; Lee and Lautenbach, 2016). However, many ecosystem services have deteriorated in the past decades due to changes in the natural environment and increasing intensive human activities (Ma, 2005; Cerretelli et al., 2018). Therefore, research on ecosystem services is a topic of broad and current interest in many countries and regions (Dittrich et al., 2017; Dvarskas, 2018; Qiao et al., 2019).

Previous studies have indicated that natural environmental changes and human activities are important factors affecting ecosystem functions (Su and Fu, 2013; Wang et al., 2016; Mahmoud and Gan, 2018). As one of the key factors, climate change has affected ecosystem services by influencing the climate elements and climate-related factors (e.g., land use change) (Mooney et al., 2009; Gosling, 2013; Grimm et al., 2016). Research on the impacts of climate change on agriculture, freshwater, marine,

and forest ecosystem services has received considerable attention in many countries and regions (Costanza et al., 2011; Rocca et al., 2014; Maia et al., 2018; Huang et al., 2019). Lobell et al. (2011) found that the decline in food production in subtropical semi-arid regions was closely related to the reduction in precipitation. Future climate change will increase the occurrence and frequency of insect damage and thereby reduce the supply level of forest ecosystem services (Trumbore et al., 2015). Plant pollination will decline under the impacts of future climate change (Bartomeus et al., 2011). Furthermore, the loss of ecosystem service value is also a concern of many scholars. For example, Lam et al. (2016) observed that the global fishery income would decline by 35% by 2050 under a high CO₂ emission scenario. However, previous studies have focused more on the analysis of the impact of climate change on ecosystem services for two or more time periods (Lorencová et al., 2013; Fu et al., 2017) and less on the interannual, seasonal, and periodic characteristics of the changes in FES.

Guizhou Province in China is not only an ecologically fragile region but also an area sensitive to global climate change (Zhang et al., 2015). Key FES such as water yield, soil retention, and nutrient retention are provided by abundant natural vegetation in Guizhou (Han and Dong, 2017a; Han et al., 2016). FES are highly sensitive to climate change (Ma, 2005; Bangash et al., 2013; Hoyer and Chang, 2014). Climate change in Guizhou has strongly affected fragile ecosystems, thereby influencing the availability of FES (Han and Dong, 2017b). However, its complex influence on FES in this region remains unclear. Therefore, we analyzed the impacts of climate change on FES from 1960 to 2017 using Guizhou Province as an example. The results provide an understanding of the response mechanism of FES to climate change and scientific reference data for addressing the negative effects of climate change on ecosystem service management.

The following hypotheses are tested in this study: (1) there are differences in the impacts of climate change on different FES; (2) there are annual and seasonal characteristics of FES changes under the impact of climate change; (3) there is a periodicity in the changes in FES resulting from climate change.

Methodology

Study area

Guizhou Province is located in southwestern China (103°36'-109°35'E, 24°37'-29°13'N) and covers an area of 176 167 km² (Fig. 1). The climate is a subtropical humid monsoon climate. The annual average temperature in most parts of Guizhou is approximately 15 °C. The average temperature in January is 3-6 °C and the average temperature in July is 22-25 °C. The annual average precipitation is approximately 1100 mm (Han and Dong, 2017a). The temperature in Guizhou Province tends to show an increasing trend, while the amount of precipitation exhibits a decreasing trend over the past few decades (Ma et al., 2013). The topography is high in the west but low in the east. The main categories of landforms include plateau, mountain, hill and basin, with the mountainous areas accounting for 61.7% of the total across Guizhou Province (Han et al., 2020). The complex and diversified vegetation categories are attributed to the specific geographical conditions and the complications of topography (Han et al., 2019). An ecologically fragile Karst region consisting of carbonate rocks covers 13 × 10⁴ km² and has the characteristics of low environmental capacity, instability, and low resilience (Zhang et al., 2002).

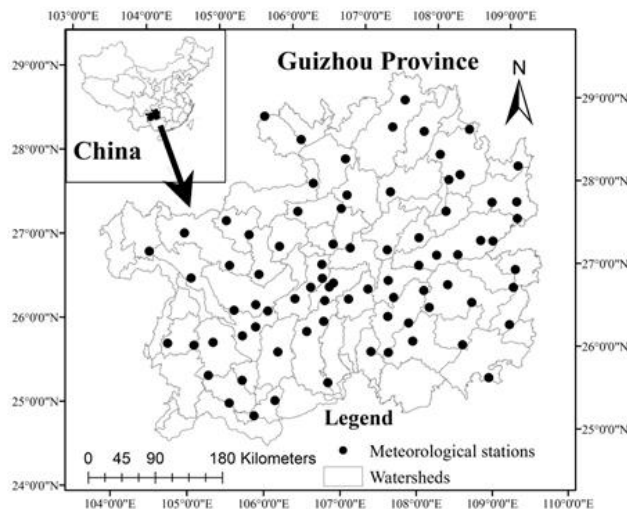


Figure 1. Location of study site

Data source

The daily observation data of 84 meteorological stations from 1960 to 2017 in Guizhou was provided by the climate center of Guizhou. The land use data were obtained by interpreting Landsat ETM⁺ remote sensing images from 2015. The soil data were provided by the soil database of China. The 30-m elevation data (ASTER GDEM) were downloaded from the Geospatial Data Cloud in China (<http://www.gscloud.cn>).

Methods

Assessment of FES

We assessed the FES in Guizhou by using the InVEST model, which was developed by Stanford University, the World Wide Fund for Nature, and the Nature Conservancy (Sharp et al., 2014). The parameters we used in the InVEST model were based on the research results of Han and Dong (2017a) and Han et al. (2016). We assume the climate change with no land use change from 1960 to 2017.

(1) Water yield

The water yield assessment was based on the Budyko curve (Budyko and Miller, 1974) and precipitation data:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \bullet P_x \quad (\text{Eq.1})$$

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \quad (\text{Eq.2})$$

$$\omega_x = Z \frac{AWC_x}{P_x} \quad (\text{Eq.3})$$

$$R_{xj} = \frac{k_{xj} \bullet ET_o}{P_x} \quad (\text{Eq.4})$$

where Y is the water yield, AET is the actual evapotranspiration, P is the precipitation, ω is a non-physical parameter of climate and soil, R is the Budyko aridity index, Z is the coefficient used by Zhang, AWC is the available soil moisture, K is the vegetation evapotranspiration coefficient; the evapotranspiration was calculated using the FAO56 Penman–Monteith equation (Allen et al., 1998).

(2) Soil retention

The soil retention was calculated using the Universal Soil Loss Equation (USLE):

$$W = RKLS \cdot USLE \quad (\text{Eq.5})$$

$$USLE = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (\text{Eq.6})$$

where W is the amount of soil retention, $RKLS$ is the maximum soil erosion (assuming there is no vegetation on the ground), R is the rainfall erosivity, which is calculated using the method of Zhang and Fu (2003), K is the soil erodibility, which is calculated using the method of Zhou et al. (2005), L is the slope length, S is the slope, C represents the vegetation cover and management factors, and P is the engineering factor.

(3) Nutrient retention

The retention of nitrogen and phosphorus represented the nutrient retention in this model (Redhead et al., 2018):

$$WP_i = 1 / ALV_i \quad (\text{Eq.7})$$

$$ALV_i = HSS_i \bullet pol_i \quad (\text{Eq.8})$$

$$HSS_i = \lambda_i / \lambda_w \quad (\text{Eq.9})$$

$$\lambda_i = \log(\sum_u Y_u) \quad (\text{Eq.10})$$

where WP is the nutrient retention value, ALV is the pollution load, pol is the output coefficient, HSS is the hydrological sensitivity, λ_i is the runoff coefficient, λ_w is the average runoff coefficient, and $\sum_u Y_u$ is the water yield.

Trend analysis

A linear regression analysis was used to determine the change trend of the FES; the slope of the equation represents the rate of change (Wei, 2007):

$$y = at + b \quad (\text{Eq.11})$$

where t is time, a is the slope of the regression equation, and b is the constant of the regression equation. A slope > 0 represents an increasing trend in FES and a slope < 0 represents a decreasing trend. The results are evaluated using the F-criterion.

Periodicity analysis

A wavelet analysis was used in this study to determine the periodic characteristics of the changes in FES (Torrence and Compo, 1998). This method is a time-scale analysis that detects changes in the signal frequency over time; it has been widely applied for periodicity analyses of hydrological and meteorological change (e.g., precipitation change over time) (Charlier et al., 2015; Yi and Shu, 2012).

$$\psi(t) = e^{ict} e^{-t^2/2} \quad (\text{Eq.12})$$

$$Wf(a,b) = |a|^{-1/2} \int_{-\infty}^{+\infty} f(t)\psi^* \frac{(t-b)}{a} dt \quad (\text{Eq.13})$$

where c is a constant, i is the imaginary part, $Wf(a,b)$ is the wavelet transform coefficient, $f(t)$ is the signal analysis function, a is the amplification factor, b is the shift factor, and ψ^* is the conjugate function of the wavelet function.

Results

Water yield

The slope of the regression equation for the change in annual water yield change across Guizhou was -0.6242, which indicates a downward trend for annual water yield ($P < 0.05$). The slope of the regression equation for the change to water yield in spring and autumn across the study area was -0.4406 and -0.7781, respectively, suggesting a declining trend of water yield in spring and autumn ($P < 0.05$). The slope of the regression equation for the change to water yield in the summer and winter was 0.4525 and 0.1369, suggesting an increasing trend of water yield in summer and winter ($P < 0.05$) (Fig. 2).

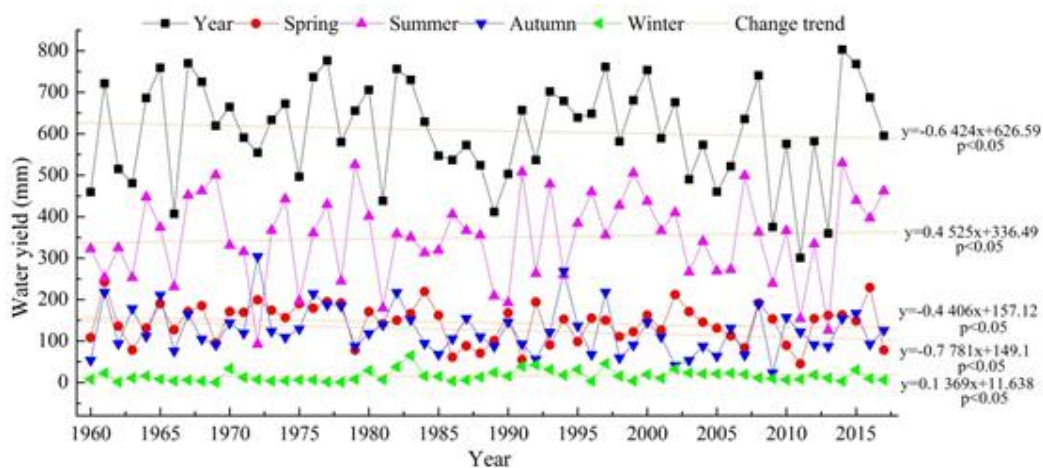


Figure 2. Inter-annual change in the water yield in Guizhou from 1960 to 2017

The amount of annual water yield during the periods of 1970-1979 and 1990-1999 was 636 mm and 639 mm, respectively, higher than in the periods 1980 and 1989, 2000 and 2009, as well as 2010 and 2017 (615 mm, 585 mm, 582 mm and 584 mm). The amount of water yield in spring and autumn (170 mm and 160 mm) during the period from 1970 to 1979 was higher than in other decades. While the amount of water yield in summer during the periods from 1960 to 1969 and from 1990 to 1999 (362 mm and 383 mm) was higher than in other decades. The amount of water yield in winter during such periods as 1980-1989, 1990-1999 and 2000-2009 was 22 mm, 25 mm and 19 mm, respectively, higher than in such periods between 1960 and 1969, 1970 and 1979, as well as 2010 and 2017 (Fig. 3).

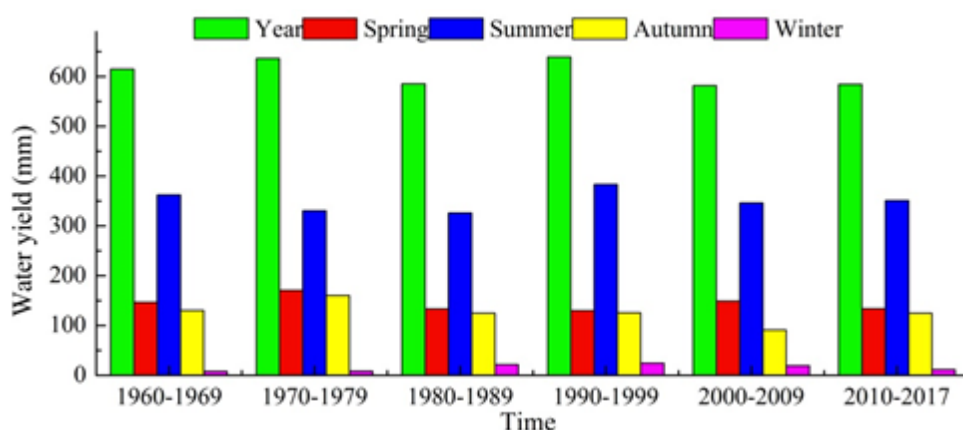


Figure 3. Changes in the water yield in Guizhou for six decades

The annual water yield decreased in the central, western, and northern parts of Guizhou whereas it increased in the eastern and southeastern parts (Fig. 4e). The water yield in spring and autumn exhibited a decreasing trend in most areas of Guizhou, except for the southeastern part (Fig. 4a, b). The summer and winter water yield exhibited an increasing trend in most areas of Guizhou, except for some regions in the western part (Fig. 4c, d).

Two periodic oscillations were observed in the annual change in water yield in Guizhou from 1960 to 2017; 6a and 28a were the peak years and the highest peak occurred in 28a (Fig. 5e). There were five periodic oscillations in the change in water yield in the spring and 5a, 9a, 13a, 18a, and 29a were the peak years and the latter had the highest peak (Fig. 5a). There were four periodic oscillations in the summer and 4a, 8a, 15a, and 28a (highest peak) were the peak years (Fig. 5b). There were four periodic oscillations in the autumn and 5a, 8a, 17a, and 28a (highest peak) were the peak years (Fig. 5c). There were three periodic oscillations in the winter and 4a, 7a, and 17a (highest peak) were the peak years (Fig. 5d).

Soil retention

The annual soil retention in Guizhou exhibited an increasing trend during 1960-2017 ($P < 0.05$). The amount of soil retention decreased in spring and autumn and increased in summer and winter ($P < 0.05$). The slope of the regression equation for the change to soil retention in summer (1.394) was higher than in spring, autumn and winter (-0.3683, -0.1828 and 0.1937) ($P < 0.05$) (Fig. 6).

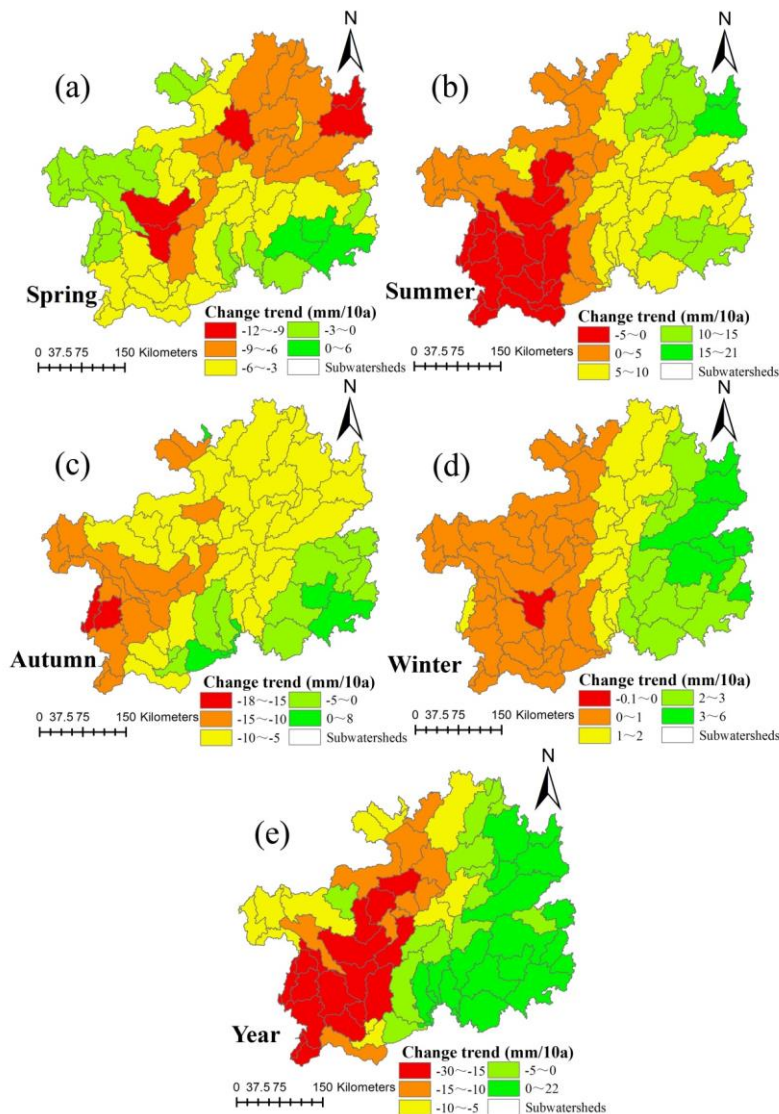


Figure 4. Spatial pattern of the changes in the water yield in Guizhou at annual and seasonal scales from 1960 to 2017

The decade of 1990-1999 showed the highest level of annual soil retention (1181 t/ha), while the low levels of soil retention observed during such periods as 1970-1979 and 1980-1989 (1041 t/ha and 1027 t/ha). The levels of soil retention in summer for six decades exceeded 550 t/ha, while those in spring, autumn, and winter for six decades fell below 300 t/ha (Fig. 7).

The annual soil retention exhibited an increasing trend from 1960 to 2017 in most parts of Guizhou, except for the northwestern and southwestern parts (Fig. 8e). Most areas in Guizhou showed decreases in the soil retention in spring and autumn. The areas of increasing soil retention in the spring were located in the northern part of Guizhou, whereas the areas of increasing soil retention in the autumn were located in the eastern and southern parts (Fig. 8a, c). The summer soil retention exhibited an increasing trend in most parts of Guizhou, except for some small regions of the southwestern and northwestern parts of Guizhou (Fig. 8b). The winter soil retention increased in all areas of Guizhou (Fig. 8d).

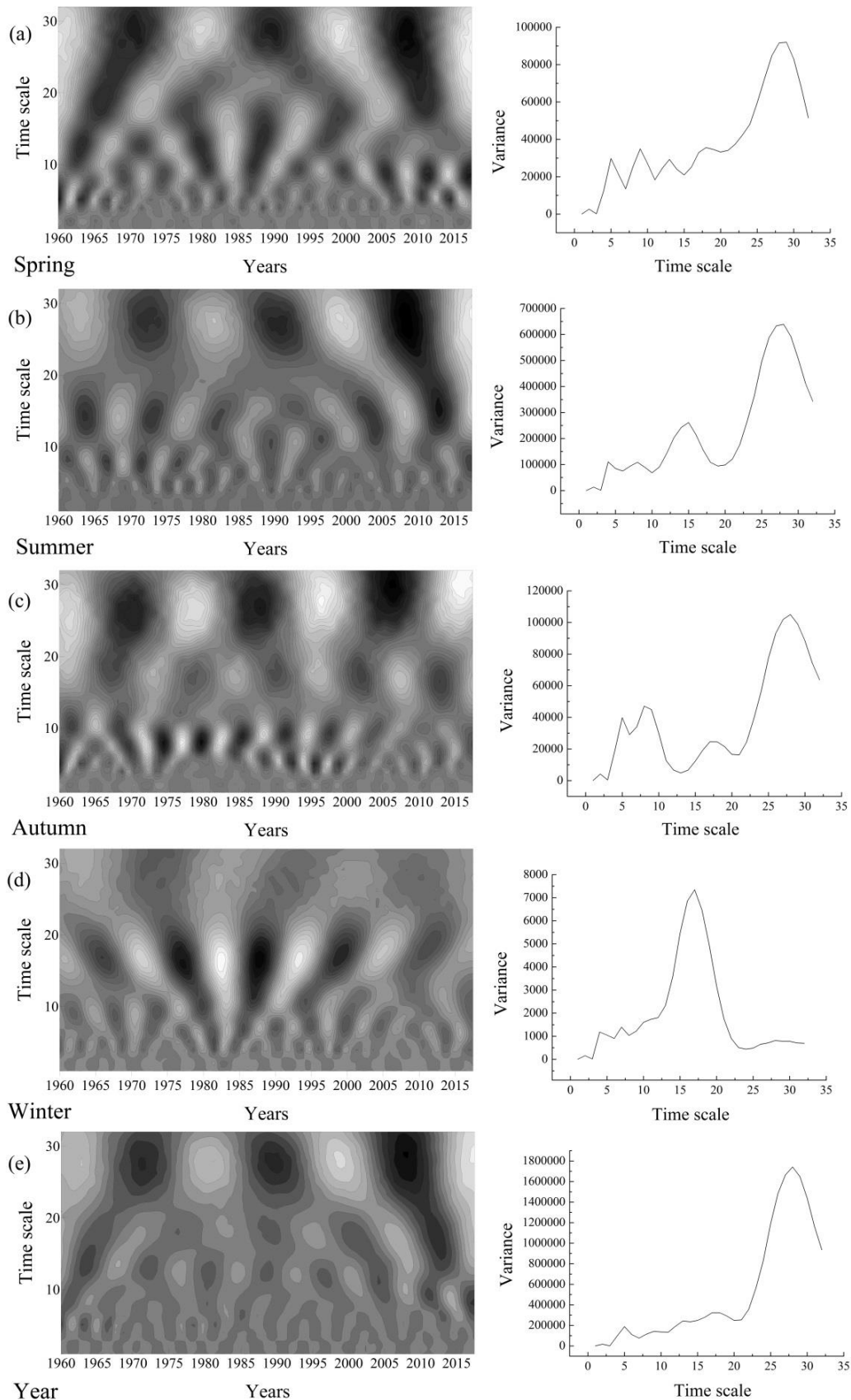


Figure 5. Periodicity of the water yield change in Guizhou at annual and seasonal scales from 1960 to 2017

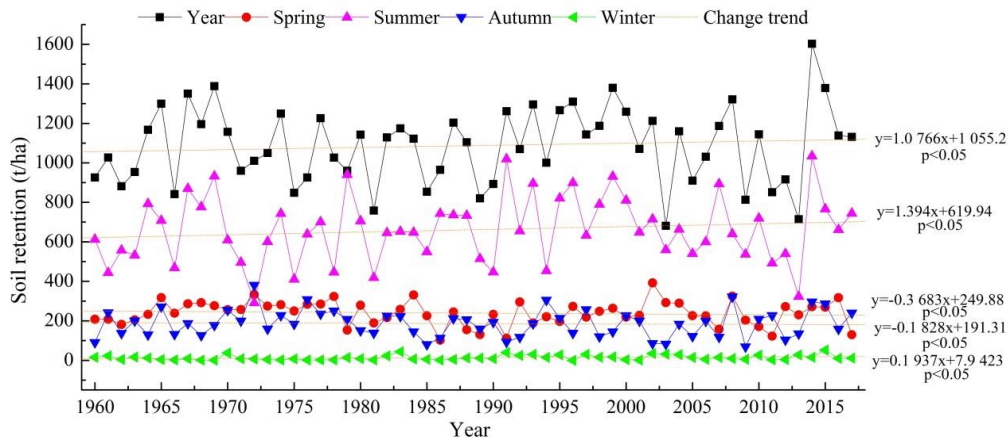


Figure 6. Inter-annual change in soil retention in Guizhou from 1960 to 2017

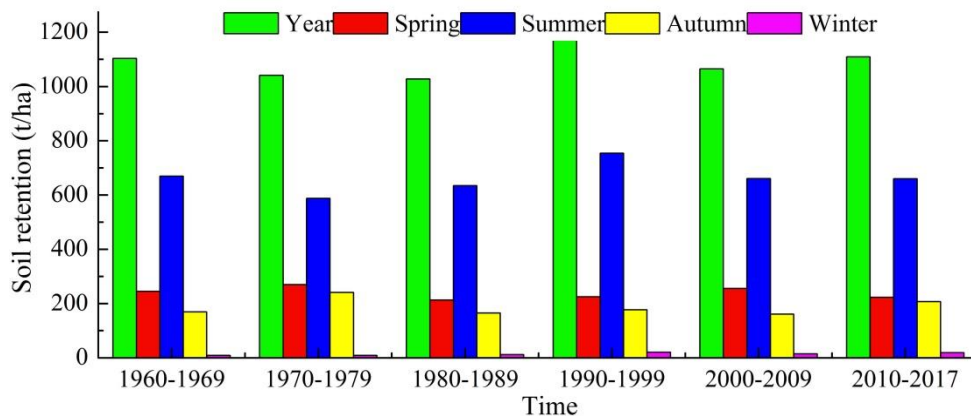


Figure 7. Changes in the soil retention in Guizhou for six decades

Three periodic oscillations were observed in the annual soil retention change in Guizhou between 1960 and 2017; the peak years included 7a, 15a, and 28a (highest peak) (Fig. 9e). Four periodic oscillations occurred for the spring soil retention change and the peak years included 4a, 9a, 13a, and 28a (highest peak) (Fig. 9a). Three periodic oscillations were observed for the summer soil retention change and the peak years included 7a, 15a, and 27a (highest peak) (Fig. 9b). There were four periodic oscillations in the autumn and the peak years included 5a, 9a, 17a, and 30a (highest peak) (Fig. 9c). Four periodic oscillations were observed for the winter and the peak years included 4a, 9a, 17a (highest peak), and 28a (Fig. 9d).

Nutrient retention

The annual nutrient retention in Guizhou exhibited an increasing trend between 1960 and 2017 ($P < 0.05$). The nutrient retention showed an increasing trend in spring and autumn, whereas a decreasing trend was observed for the summer and winter ($P < 0.05$). The slope of the regression equation for the change in nutrient retention was higher in spring (0.0213) than in autumn (0.0042). In contrast, the slope of the regression equation for the change to nutrient retention was greater in summer (-0.0034) than in winter (-0.0018) ($P < 0.05$) (Fig. 10).

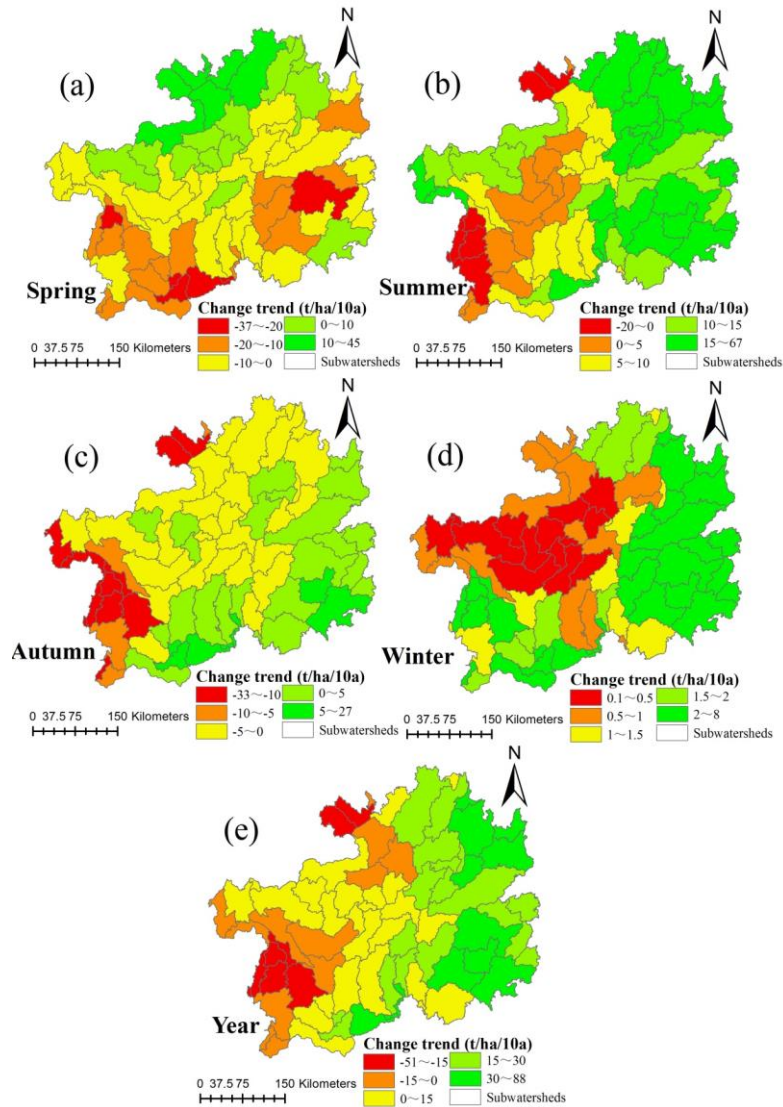


Figure 8. Spatial pattern of the changes in the soil retention in Guizhou at annual and seasonal scales from 1960 to 2017

The level of annual nutrient retention for six decades varied from 52.31 to 52.61 kg/km², which is close to that of nutrient retention in summer (52.07-52.33 kg/km²), but lower than in spring (53.08-54.38 kg/km²) and autumn (52.77-53.57 kg/km²). Compared with other seasons, the level of nutrient retention in winter for six decades (42.83-45.85 kg/km²) was the lowest (Fig. 11).

Except for the southeastern and northeastern parts of Guizhou, the annual nutrient retention increased in most areas during 1960-2017 (Fig. 12e). An increasing trend in the spring nutrient retention was observed in most areas of Guizhou (Fig. 12a). The summer nutrient retention declined in most areas and only small areas in the northwestern, western, and southeastern parts exhibited an increasing trend (Fig. 12b). The autumn nutrient retention decreased in the western and southern parts, whereas it increased in the central, northern and southwestern parts (Fig. 12c). Except for the southwestern, central, and southeastern parts, the winter nutrient retention increased in most parts of Guizhou (Fig. 12d).

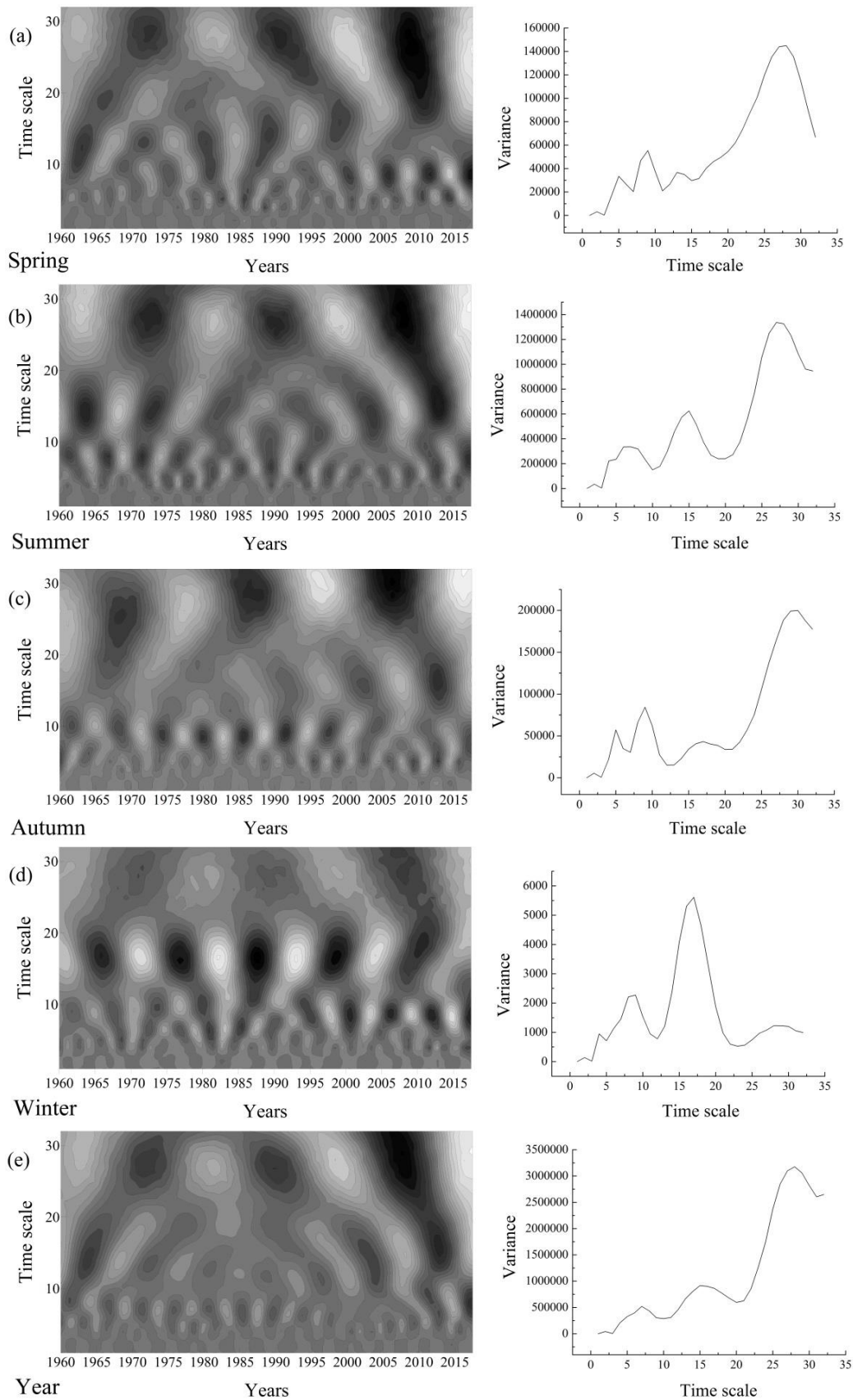


Figure 9. Periodicity of the soil retention change in Guizhou at annual and seasonal scales from 1960 to 2017

Only one periodic oscillation was observed in the spring, summer, autumn, and annual nutrient retention changes in Guizhou and the highest peak occurred in 28a (Fig. 13a, b, c, e). There were two periodic oscillations in the winter nutrient retention change in 10a and 28a (highest peak) (Fig. 13d).

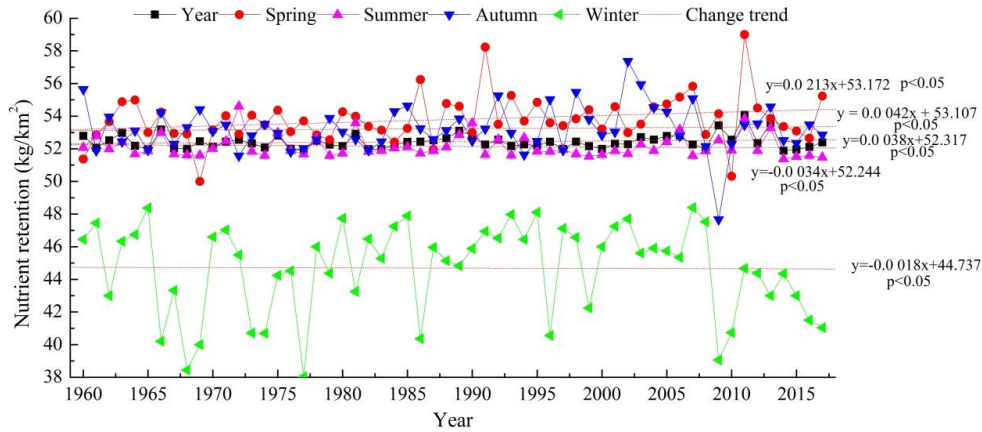


Figure 10. Inter-annual change in the nutrient retention in Guizhou from 1960 to 2017

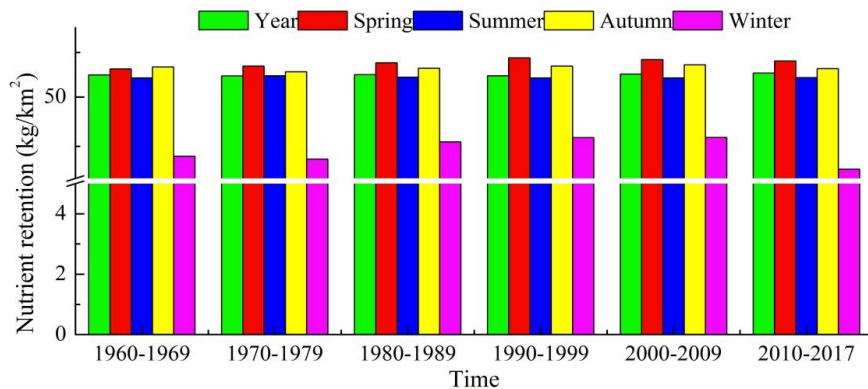


Figure 11. Changes in the nutrient retention in Guizhou for six decades

Discussion

Impacts of climate change on FES

The significant impact of climate change on FES in Guizhou is demonstrated in the study, as evidenced by the results of Bai et al. (2019) and Bucak et al. (2018). Nevertheless, there are some clear differences in the impact of climate change on different FES. Those similar results have been obtained in the research of Jorda-Capdevila et al. (2019) and Bai et al. (2019). Precipitation and evaporation are important climatic factors influencing changes in the water yield (Terrado et al., 2014; Fan et al., 2018). The decline in the annual, spring, and autumn precipitation in Guizhou was higher than the evaporation from 1960 to 2017, which led to a downward trend of the annual, spring, and autumn water yield. The increases in the winter and summer water yield were closely related to the increases in the winter and summer precipitation between 1960 and 2017 in this region (Table 1). The rainfall erosivity is an essential climatic factor affecting soil retention (Hoyer and Chang, 2014; Sánchez-Canales et al., 2015). The increases in the annual, summer, and winter rainfall erosivity

from 1960 to 2017 in Guizhou resulted in an increasing trend of the soil retention for the same periods. Similarly, the decline in the soil retention in spring and autumn were closely related to the decline in rainfall erosivity in spring and autumn (*Table 1*). In addition, precipitation and evaporation affected the amount of nutrient retention by influencing the surface runoff (Sharp et al., 2014). The increasing trend in the annual, spring, and autumn nutrient retention in Guizhou was related to the decrease in the water yield caused by the larger decrease in precipitation than evaporation from 1960 to 2017. Similarly, the declining trend in nutrient retention in summer and winter was closely related to the increase in the water yield resulting from an increase in precipitation (*Table 1*). In addition, the spatial pattern of FES change was closely associated with the distribution of changes in climatic factor. For example, the amount of precipitation showed decrease in the west but increase in the east over the last few decades in Guizhou (Zhao et al., 2018), which led to a declining trend in the west but an increasing trend in the east for the change to annual water yield. Similarly, the annual rainfall erosivity exhibited an upward trend in most parts of Guizhou except for west Guizhou (Liu et al., 2012), which contributed to spatial pattern of annual soil retention in this study.

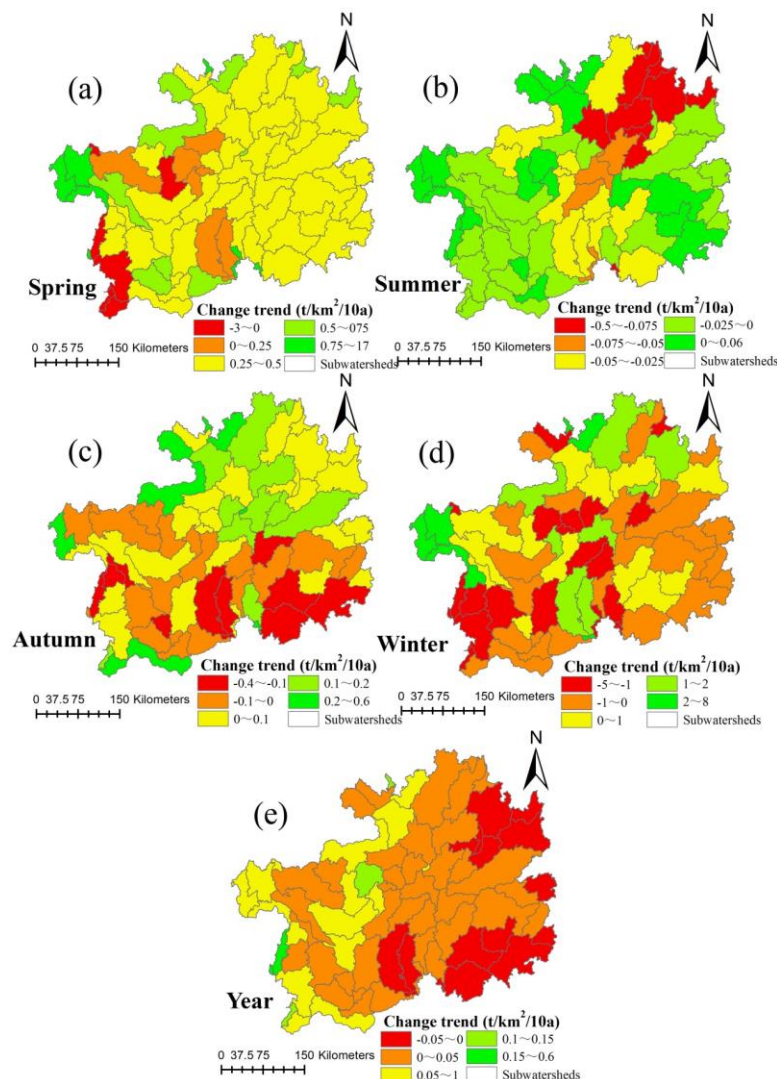


Figure 12. Spatial pattern of the changes in the nutrient retention in Guizhou at annual and seasonal scales from 1960 to 2017

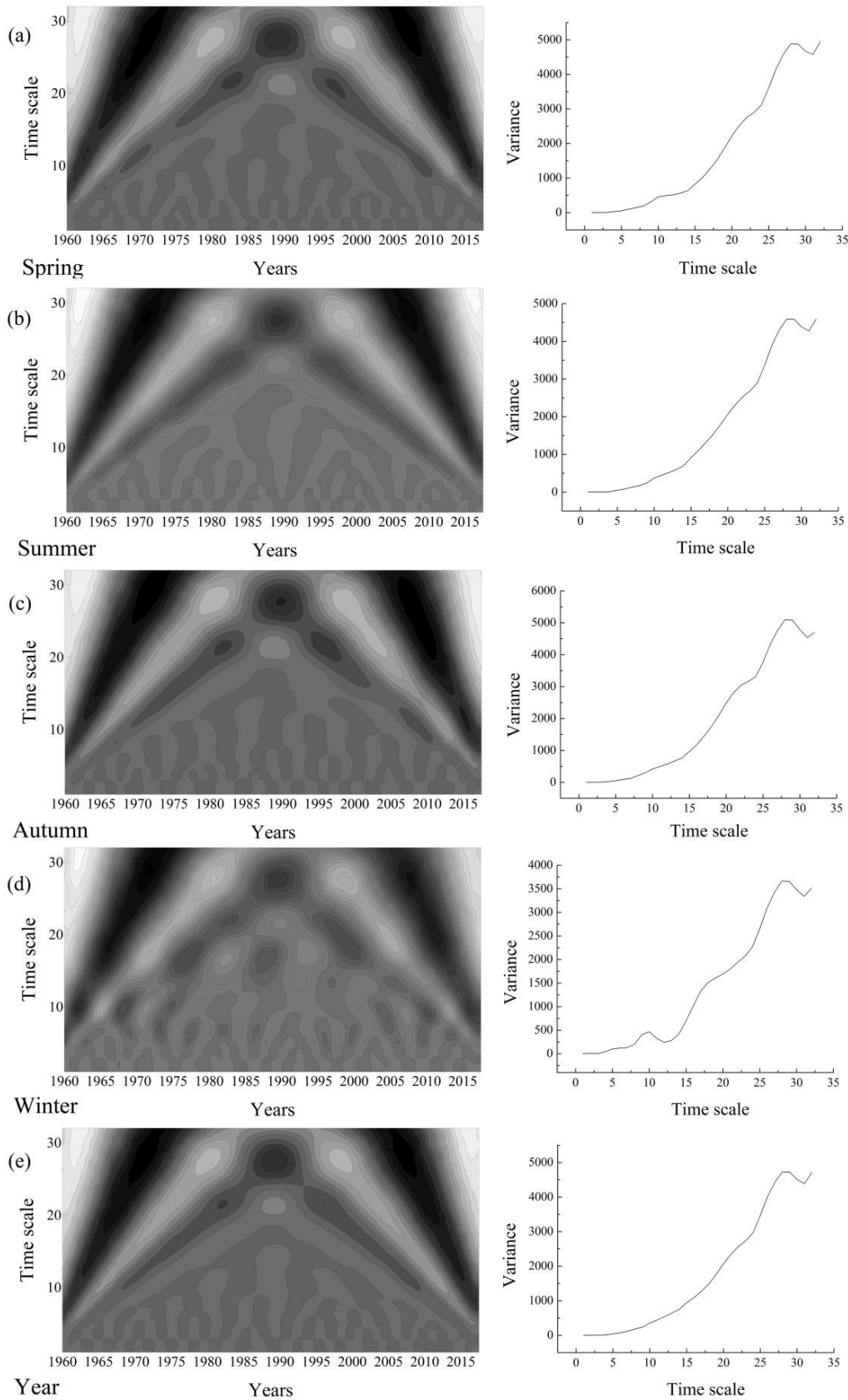


Figure 13. Periodicity of the nutrient retention change in Guizhou at annual and seasonal scales from 1960 to 2017

Table 1. Changes in climatic factors in Guizhou from 1960 to 2017

Climatic factors	Annual	Spring	Summer	Autumn	Winter
Precipitation (mm/10a)	-7.028	-4.899	2.125	-8.476	4.222
Evaporation (mm/10a)	-1.978	-0.211	-4.422	-0.427	3.102
Rainfall erosivity (MJ mm/ha/h/yr/10a)	61.827	-28.619	85.053	-5.115	11.187

Ecosystem management under the influence of climate change

The sustainable management of natural and human ecosystems is an important aspect when dealing with the negative impacts of climate change (Gutierrez et al., 2016; Anandhi, 2017). We should reduce the consumption of freshwater and improve the availability of freshwater for agricultural and industrial production, given the decreasing water yield in Guizhou. In addition, different types of water infrastructure should be established to minimize the negative influence of a decline in water yield. Although the annual precipitation in Guizhou exhibited a downward trend from 1960 to 2017, the annual rainfall erosivity exhibited an increasing trend. Thus, the natural vegetation cover (such as forest and grassland) should be improved in the study area to improve the soil retention capacity in the future. Furthermore, terraced fields are recommended for Guizhou because they are suitable for the mountainous area. Moreover, although the nutrient retention caused by the reduction in precipitation exhibited an increasing trend, it will result in decreasing water yield, which requires balancing the relationship between water yield and nutrient retention. The water yield should be increased to avoid a substantial decrease in nutrient retention in the future.

Conclusions

Decreasing trends in the annual, spring, and autumn water yield and soil retention were observed, whereas increasing trends occurred for the water yield and soil retention in summer and winter from 1960 to 2017 in Guizhou. The nutrient retention increased annually and in the spring and autumn, whereas it decreased in summer and winter. The peak period in terms of annual changes in the water yield, soil retention, and nutrient retention in Guizhou occurred in 28a. There were apparent differences in the peak periods of the water yield and soil retention change in spring, summer, and autumn. The peak period of the nutrient retention change in the four seasons was 28a. There was significant spatial heterogeneity in terms of the changes in the water yield, soil retention, and nutrient retention at annual and seasonal scales in Guizhou. The changes to FES in different Karst landforms are supposed to be highlighted in the future research. In this sense, it is necessary for scholars to focus attention on the combined effects of land use and climate changes on the temporal FES changes in the future.

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Conflict of interests. The authors declare no conflict of interests.

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APPENDIX

Meteorological stations in Guizhou

Meteorological stations	Meteorological stations	Meteorological stations	Meteorological stations	Meteorological stations	Meteorological stations
Hezhang	Yinjiang	Sansui	Tongzi	Zhenyuan	Tianzhu
Weining	Shiqian	Taijiang	Chishui	Yuping	Jinping
Shuicheng	Cenggong	Jianhe	Xishui	Tongren	Qinglong
Puan	Jiangkou	Leishan	Daozhen	Wanshan	Xingren
Panxian	Shibing	Liping	Zhengan	Nayong	Guanling
Wuchuan	Qianxi	Zhenfeng	Dafang	Zhenning	Ziyun
Yanhe	Zhijin	Wangmo	Renhuai	Xiuwen	Baiyun
Dejiang	Anshun	Xingyi	Zunyi	Qingzhen	Huishui
Songtao	Liuzhi	Anlong	Jinsha	Pingba	Longli
Bijie	Puding	Ceheng	Zunyixian	Guiyang	Huaxi
Xifeng	Changshun	Wudang	Meitan	Guiding	Dushan
Kaiyang	Fuquan	Luodian	Fenggang	Kaili	Sandu
Suiyang	Huangping	Pingtang	Wengan	Duyun	Libo
Yuqing	Majiang	Rongjiang	Sinan	Danzhai	Congjiang