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The spatiotemporal patterns of rainfall erosivity in Yunnan Province, southwest China: An analysis of empirical orthogonal functions

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ABSTRACT

Rainfall erosivity (R) influences the formation mechanisms and succession processes of soil erosion. Knowing of the R factor facilitates the prediction of soil erosion and of the impact of climate change on erosion. However, defining of the R factor is challenging because its spatiotemporal variation can be complex. We combined the Empirical Orthogonal Function (EOF), North criteria, and Mann-Kendall test (M-K) to investigate the spatiotemporal patterns of the R factor for a study area in a typical mountain plateau region of Yunnan Province (YP), China. Daily rainfall records from 1960 to 2012 were collected from 115 national meteorological observation stations in YP. Based on the daily rainfall erosivity estimating model, we determined that the average annual R factor was 4383.85 $\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}}$, the seasonal R factor exhibited an order of summer > autumn > spring > winter, and the summer R was significantly higher than winter R. The spatiotemporal variation of the R factor was complex and did not reveal a uniform pattern. The spatial distribution revealed that the annual and seasonal R factors in the west were higher than those in the east, and R in the south were higher than those in the north. The temporal trends of annual, summer, and autumn R factors had decreasing trends from 1960 to 2012. On the contrary, the spring and winter R factors showed an increasing trend. The EOF analysis identified two typical spatiotemporal patterns of the annual R factor in YP, and three for spring, summer, autumn, and winter R factors. These patterns represented the influence of the monsoon, circulation systems, and complex terrain conditions on the rainfall in the YP.

1. Introduction

Soil erosion is a major environmental and agricultural problem worldwide (Vanmaercke et al., 2015), because it can reduce soil infiltration rates, change soil water-holding capacity, decrease soil nutrient content, and affect soil quality (Lal, 1990; Pimentel et al., 1995; Gobin et al., 2004). Parts of China experience severe soil erosion, and the country has been one of the most threatened by soil erosion globally (Hao et al., 2003; Ma et al., 2012). According to the First National Water Conservancy Survey in China (Liu et al., 2013a), the total soil erosion area was 129.32×10^4 $\mathrm{km^2}$ in 2012, accounting for 13.47% of China's territory. The erosion processes are affected by rainfall, terrain, soil composition, crop type, and management and supporting conservation practices (Wischmeier and Smith, 1958).

Rainfall is the main external factor contributing to soil erosion caused by water. The impact of raindrops detaches soil particles and subsequent runoff causes soil erosion. The potential of rain to generate soil erosion is known as rainfall erosivity (R factor for short); R is an important factor in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) for erosion prediction. Wischmeier and Smith (1978) defined R as the average of the annual summations of storm 'EI_{30}' values. 'E' represents rainfall energy, and 'I_{30}' represents the maximum 30-min rainfall intensity during a storm. This factor has been widely tested, adopted, and used worldwide (Panagos et al., 2015; Wang et al., 1995).

As an important and fundamental input parameter for soil erosion modeling, the R factor has become a focus of many studies (Diodato and Bellocchi, 2012; Hou et al., 2014; Vrieling et al., 2014; Diodato et al., 2013). However, the Wischmeier and Smith (1978) EI_{30} index requires breakpoint rainfall data, which are rainfall data with high temporal resolution over long periods of time, that are not always easily available. Instead, many simple methods for estimating EI_{30} have been developed that use readily-available hourly, daily, monthly, and annual rainfall data (Richardson et al., 1983; Huang et al., 1992; Mikhailova et al., 1997; Yu and Rosewell, 1998; Mannaerts and Gabriels, 2000; Zhang et al., 2003; Silva, 2004; Shamshad et al., 2008; Alipour et al., 2012). However, annual and monthly rainfall data are relatively coarse and cannot meet the needs of the precise R-value calculations (Zhang and Fu, 2003). Hourly rainfall data are difficult to obtain, and their application to R-value calculations is limited. By contrast, daily rainfall data can

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provide detailed information on the variation characteristics of precipitation, and thus contribute to the accuracy and reliability of the R-factor estimation (Richardson et al., 1983). Following these findings, Zhang et al. (2002) established a rainfall erosivity estimation model based on daily rainfall data in China. Combined with easy availability of data, this model has been widely used in various regions of China (Huang et al., 2013; Yang and Lu, 2015).

The spatial and temporal distribution of the R factor can alter characteristics of soil erosion at different times and regions (Huang et al., 2013) because it can directly influence the formation mechanisms and succession processes of erosion (Hamlaoui-Moulai et al., 2013). The temporal variation and spatial characteristics of the R factor have discussed worldwide (Zhang et al., 2002; Silva, 2004; Angulo-Martínez and Beguería, 2009; Bonilla and Vidal, 2011; Liu et al., 2013b; Panagos et al., 2015; Vallebona et al., 2015). Nearly all of those studies reported that the R factors were characterized by a distinct inter-annual variability, unevenness in the annual distribution, and spatial heterogeneity. Variation of the R factor can change with environmental conditions (Ramos and Durán, 2014). Furthermore, geostatistical methods, which have been widely used to map the spatial variation of the R factor (Bonilla and Vidal, 2011; Ramos and Durán, 2014; Panagos et al., 2015; Silva, 2004; Vallebona et al., 2015), cannot completely account for the complicated spatiotemporal patterns under different environmental conditions (Liu et al., 2013b). Recently, empirical orthogonal function (EOF) analysis, which can characterize the dominant patterns of complex space–time processes, has been widely applied in identification of temporal and spatial patterns of climate change (Obled and Creutin, 1987; Sauquet et al., 2000), hydrological processes (Gottschalk et al., 2015; Krasovskaia and Gottschalk, 1995; Yu and Lin, 2015) and other earth surface processes (Braud and Obled, 1991; Kitterrød and Gottschalk, 1997; Sauquet et al., 2000; Yu and Chu, 2010). EOF analysis relies on the decomposition of a dataset in terms of orthogonal basis functions, which are determined from the data (Shi et al., 2015). The EOF method guarantees that the first principal component (PC) explains more of the total variance in the data than any other single representation, and that each subsequent PC explains the optimal amount of the remaining variance (Yu and Lin, 2015).The advantage of this process is obtaining snapshots of essentially pure spatial and temporal patterns of the space-time datasets. EOF analysis has been most extensively used in atmospheric sciences (Hannachi et al., 2007). However, few studies have applied EOF to the analysis of the spatial structure and the temporal variation of the R factor.

The Yunnan Province (YP) is a typical mountain plateau region in southwestern China, where approximately 84% of the land surface is mountainous and >88% of the slopes are >6° (Development and Planning Committee of Yunnan Province, Land Resource Bureau of Yunnan Province, 2004; Cui et al., 2008). Under the strong influence of the Indian and East Asian monsoons, the climate in the YP is characterized by abundant precipitation, uneven distribution, rainy summers, and dry winters (Zhang, 1988).Steep slopes coupled with abundant precipitation create a severe risk of soil erosion. According to the first National Water Conservancy Survey in China, the area affected by soil erosion was estimated to be almost 1.1×10^5 km^2, accounting for 27.6% of the land area in the province (Liu et al., 2013a). Meanwhile, YP, which is upstream, is the birthplace of many major, internationally-important rivers, such as the Mekong, Salween, and Red. Soil and water conservation projects and river sediment control in YP has attracted much attention of the downstream settlements (Chaplot et al., 2005; Le et al., 2010).

In this study, the daily precipitation data from 115 meteorological stations in YP from1960 to 2012 were collected, and the annual and seasonal R factors were calculated. The purpose was to a) map the mean annual and seasonal R factor of YP and b) identify the spatio-temporal patterns of R in YP using EOF.

2. Materials and methods

2.1. Study area

The study area is located in southwestern China in the Yunnan Province, bordering the Himalayan Range and the Xizang Plateau to the west and Vietnam and Laos to the south at 97°31′39″ to 106°11′47″E, 21°08′32″ to 29°15′08″N. The study area covers 3.83×10^5 km^2, and the cultivated land area is approximately 6.39×10^4 km^2 (Development and Planning Committee of YP, Land Resource Bureau of YP, 2004). The topography is characterized by high mountains and deep valleys in the west, and a karst plateau in the east, resulting in a landscape tilting from the northwest to the southeast. The elevation varies from 76 m to 6740 m, with a mean elevation of 2000 m (Jin, 2004). Red soils are the most widely-distributed zonal soils (Development and Planning Committee of Yunnan Province, 1990). The weather is influenced by monsoons and characterized by abundant precipitation (Barton et al., 2004). The mean annual precipitation is approximately 1100 mm. Under the combined effect of complex terrain and strong monsoons, the precipitation in Yunnan exhibited a significant temporal and spatial variation (Liu et al., 2010).

2.2. Rainfall data

Rainfall data were collected by the National Meteorological Observatory (NMO) stations and provided by the Yunnan Climate Center. There are a total of 133 meteorological stations in YP, most of them with observation data starting in year 1960. Several of the weather stations ceased operation during the 1980s and 1990s; Three of them have been replaced the location. To make the best use of the available data and obtain the best spatial coverage, 115 stations with observations from 1960 to 2012 were selected for analysis. These stations were at altitudes from 136 to 3319 m, with 85% of them were above 1500 m (Fig. 1).

RClimDex software developed by Xuebin Zhang at the Climate Research Branch of the Meteorological Service of Canada was used to assess the quality of rainfall data (http://etccdi.pacificclimate.org/index.shtml). The main purpose of the analysis was to identify errors in data processing. Precipitation values less than zero were flagged as erroneous. The identified potential outliers were manually checked, validated, corrected or removed. Furthermore, the RHtestV3 software package was used to assess data homogeneity (also available from http://etccdi.pacificclimate.org/index.shtml); for this purpose, a two-phase regression model was used to check for multiple-step change points in a time series (Wang, 2003). The penalized maximal F (PMF) test showed that all 115 stations passed the test under the significant statistic level of 0.05.

2.3. Calculation of rainfall erosivity

The R factors were calculated by the rainfall-erosivity estimating model based on daily rainfall data in China and developed by Zhang et al. (2002). The model was verified by EI_{30} and the results showed that the average model simulation accuracy was 0.718, and the average relative error was 4.2%. The model worked very well for regions where rainfall was abundant (Zhang et al., 2002). Therefore, it was widely verified and applied in China, including in the First National Water Conservancy Survey (Huang et al., 2013; Liu et al., 2013a; Yang and Lu, 2015). The formulas follow:

$$M_i = \alpha \sum_{j=1}^{k} (P_j)^{\beta} \tag{1}$$

$$\beta = 0.8363 + \frac{18.177}{P_{d12}} + \frac{24.455}{P_{y12}} \tag{2}$$

$$\alpha = 21.586\beta^{-7.1891} \tag{3}$$