Nat Hazards (2014) 74:585–602
DOI 10.1007/s11069-014-1199-z

ORIGINAL PAPER

Evaluation of rainfall erosivity and its temporal variation in the Yanhe River catchment of the Chinese Loess Plateau

B. J. Yue · Z. H. Shi · N. F. Fang

Received: 31 December 2013 / Accepted: 18 April 2014 / Published online: 4 May 2014

Abstract The potential of rain to generate soil erosion is known as the rainfall erosivity (*R*), and its estimation is fundamental for a better understanding of the erosive ability of certain rainfall events. In this paper, we investigated the temporal variations of rainfall erosivity using common daily rainfall data from four meteorological stations during 1956 to 1989 and 2008 to 2010 periods in the Yanhe River catchment of the Chinese Loess Plateau. The adaptability of several simplified calculation models for *R* was evaluated and compared with the results of previous studies. An exponential model based on the modified Fournier index (MFI) was considered as the optimum for our study area. By considering the monthly distribution and coefficient of variation of annual precipitation, equations based on two indices, the MFI and its modification F_F, produced a higher calculation accuracy than mean annual precipitation. The rainfall erosivity in the Yanhe River catchment has a remarkable interannual difference, with a seasonality index ranging from 0.69 to 1.05 and a precipitation concentration index from 14.51 to 27.46. In addition to the annual rainfall amounts, the extreme wave of monthly rainfall distribution also has an effect on the magnitude and temporal variation of rainfall erosivity, especially interannual variation. For long time series of rainfall erosivity, a trend coefficient *r* of −0.07 indicated a slight decline in erosivity in the Yanhe River catchment from 1956 to 2010.

Keywords Rainfall erosivity · Model evaluation · Temporal variation · The Loess Plateau

B. J. Yue · Z. H. Shi · N. F. Fang
State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling 712100, Shaanxi Province, People's Republic of China

B. J. Yue
University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

Z. H. Shi (✉)
College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, People's Republic of China
e-mail: pengshi@mail.hzau.edu.cn

1 Introduction

Soil erosion is considered as one of the most important environmental problems worldwide. The potential for rain to cause soil erosion is typically referred to as "rainfall erosivity" (the *R* factor), and it has been used to describe the property of precipitation (Wischmeier and Smith 1978). In the research of Renard and Freimund (1994), rainfall erosivity was considered as one of the best indicators of the erosive potential of the impact of raindrops. Rainfall erosivity is a basic parameter of the Universal Soil Loss Equation (USLE) and its revised form (RUSLE), and thus, accurate estimations are fundamental for a better understanding of the erosion ability of certain rainfall events. Moreover, rainfall erosivity has become increasingly important because of its application as an input parameter for modeling soil erosion and water quality, forecasting soil loss, and optimizing soil and water conservation (Renard et al. 1997; Lee and Heo 2011).

Rainfall erosivity (*R* factor or EI_{30}) has been widely investigated in previous studies for different purposes (Wischmeier and Smith 1978; Arnoldus 1980; Renard et al. 1997; Ferro et al. 1999; Shi et al. 2012; Fiener et al. 2013). Continuous rainfall intensity data must be available to compute EI_{30}; however, such data are limited for many locations in the world. Even when sufficient pluviograph data are available, it is difficult to calculate rainfall erosivity because of the complicated and tedious computational procedure (Lee and Heo 2011). Various simplified models and methods based on more readily available precipitation data have been proposed to overcome this problem. Annual precipitation has been widely used as a simple parameter for estimating rainfall erosivity in many countries, and a strong correlation exists between annual precipitation and annual rainfall erosivity (Renard and Freimund 1994; Xu 2005; Zhang et al. 2005). Several previous studies have predicted rainfall erosivity using daily rainfall amounts (Zhang et al. 2002; Pan and Wen 2013) and monthly rainfall data (Ferro et al. 1999; Diodato and Bellocchi 2007). Oduro-Afriyie (1996) and da Silva (2004) employed monthly rainfall data and the Fournier index (F) to compute erosivity indices for stations. The modified Fournier index (MFI), which considers mean monthly and annual rainfall, is another commonly applied parameter for estimating annual rainfall erosivity and developing soil loss maps (Beskow et al. 2009). In addition to the simplified models, other potential methods to assess the *R* factor were also developed, such as the theory of artificial neural networks (ANNs) applied by Bhatt et al. (2007) to estimate annual rainfall erosivity. The evaluation efficiency was found to be higher with the ANN model than with simple regression models.

Although the general relationship between daily rainfall amounts and EI_{30} is widely applicable, the relationship is site-specific (Yu 1998). The Chinese Loess Plateau suffers from a high erosion rate, with an average annual soil loss of 5,000–10,000 t km^{-2} and rates exceeding 20,000 t km^{-2} in certain locations (Chen et al. 2007). Shi and Shao (2000) reported that the serious soil erosion on the Loess Plateau is predominately caused by storm events in the summer that are short and intense, with high rainfall erosivity. Therefore, understanding the peculiarity of the *R* factor in this region is an important task. Many studies have analyzed the spatiotemporal distribution characteristics and the relationships between rainfall and rainfall erosivity on the Chinese Loess Plateau (Yin and Xie 2005; Xin et al. 2011). Xu (2005) discussed the relationships between precipitation, vegetation, and erosion and identified two precipitation thresholds to calculate the *R* factor. Xin et al. (2011) collected daily rainfall data from 60 meteorological stations and investigated the spatiotemporal variations of annual rainfall erosivity during the 1956–2008 period.

According to Nearing et al. (2005), the main intrinsic factors controlling rainfall erosivity include the amount, duration, kinetic energy, and intensity of the rainfall as well as its spatial and temporal variability within one rainfall event. The spatiotemporal heterogeneity and uneven characteristics of rainfall will directly influence the magnitude and distribution of soil erosion (Wei et al. 2007; Lu et al. 2012a, b). In the context of global climate change, changes in climate extremes and patterns of precipitation will be increasingly manifested in important and tangible ways (Karl and Trenberth 2003; Wei et al. 2009; Lu et al. 2012a, b). Therefore, studies of the changing tendencies and temporal variations of long-term series of rainfall events and rainfall erosivity are critical for determining the formation mechanism and succession process of water erosion and even for the evolution of the global environment (Hamlaoui-Moulai et al. 2013). Previous studies have greatly enhanced the understanding of spatiotemporal variations in annual rainfall and erosivity in the Yanhe River catchment; however, there is still insufficient detailed information about which model should be used to calculate R factors for specific regions and how rainfall erosivity couples temporally and spatially with its influencing rainfall factors.

The objectives of this study were (1) to evaluate the adaptability of several rainfall erosivity models which are based on daily, monthly, annual rainfall amount and erosivity indices and recommend the method that should be adopted for the Yanhe River catchment and (2) to investigate the temporal variations of rainfall erosivity and identify its governing factors in the Yanhe River catchment in recent decades.

2 Materials and methodology

2.1 Study area

The Yanhe River catchment (longitude 36°21′–37°19′N; latitude 108°38′–110°29′E) is located in the centrally hilly region of the Loess Plateau of China and covers a total area of 7,725 km^2 (Fig. 1). The catchment is characterized by a typical warm and temperate continental monsoonal climate with a mean annual temperature ranging from 8.8 to 10.2 °C and an annual mean precipitation of approximately 520 mm. Over 70 % of the total annual precipitation occurs from June to September (Fig. 2). The Yanhe River catchment belongs to a typical loess hilly–gully region and is covered by thick mantle of loess, which is an erosion-prone fine silt soil (Fu and Gulinck 1994). The concentrated rainfall distribution and underlying surface can result in serious erosion caused by the strong energy of runoff. The mean annual runoff in the area is 289.0×10^6 m^3, with a runoff modulus of 36.4×10^3 m^3 km^2 a^{-1} (Su et al. 2012). More than 90 % of this watershed is covered with ridges and crisscrossed with gullies because of the long-term incision by soil erosion. The elevation in the study area ranges from 495 to 1,795 m (average of 1,218 m), and the slope varies from 0° to 54.6°, with an average of 23.5°. The major types of land use are slope farmland, terrace farmland, orchard, forestland, grassland, construction land, water bodies, and wasteland with low vegetation coverage.

2.2 Data sources

In analyzing the distribution of rainfall and rainfall erosivity, we employed daily precipitation data from four meteorological stations in the Yanhe River catchment released from the Loess Plateau Data Sharing Service Center (http://loess.geodata.cn/Portal/?isCookieChecked=true). Datasets for Yan'an are from 1965 to 1989 and from 2008 to 2010 (1970 and 1974 are not included), data from Ansai are from 1980 to 1989 and from

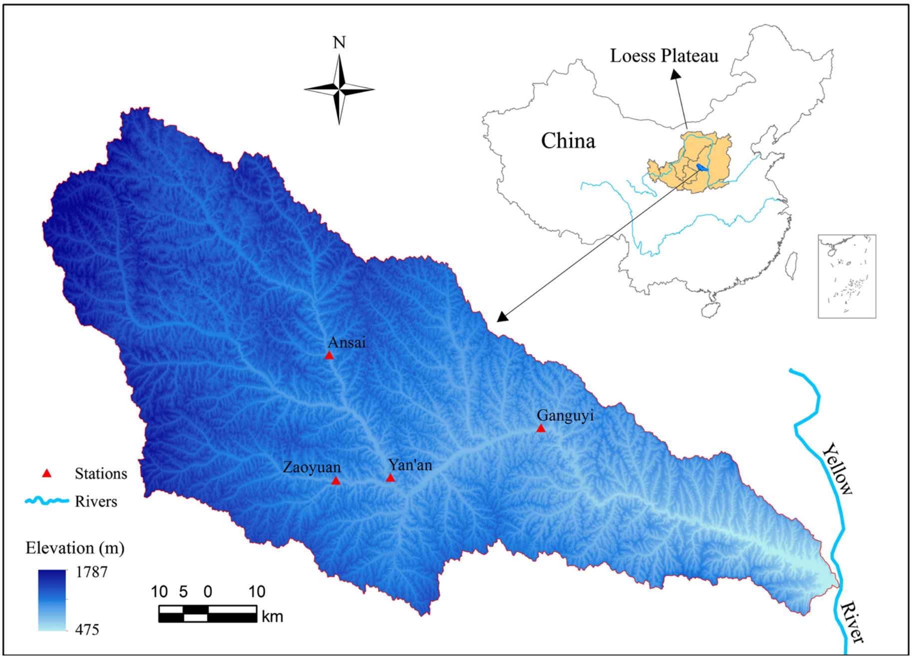

Fig. 1 Location of the study area and its digital elevation model (DEM)

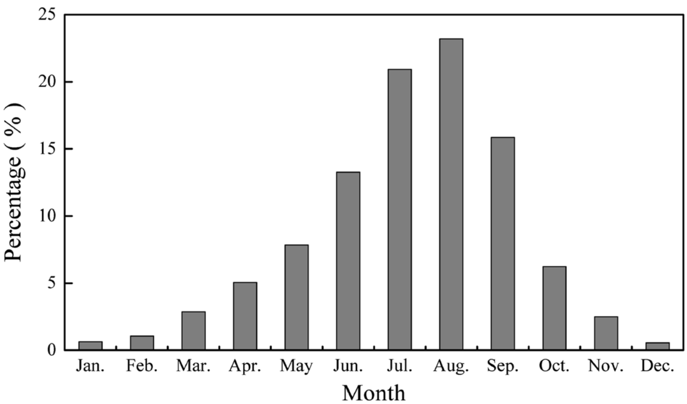

Fig. 2 Monthly distribution of rainfall in the Yanhe River catchment over the 1956–1989 and 2008–2010 periods

2008 to 2010, data from Zaoyuan are from 1971 to 1989, and data from Ganguyi are from 1956 to 1989 and from 2008 to 2010 (1970 is not included). Table 1 summarizes the information for each station. Monthly and annual precipitations were then established from the collected data to calculate the *R* factors. The topographical information was obtained from a digital elevation model (DEM) with a resolution of 30 m × 30 m downloaded from the International Scientific Data Service Platform (http://www.gscloud.cn/).

2.3 Evaluated models

Rainfall erosivity is typically calculated using either EI_{30} (the classical method) or conventional meteorological data. During actual implementation, the classical method is rather unsuitable because detailed rainfall information is difficult to collect. Consequently, various types of simplified models based on daily, monthly, and annual precipitation and other rainfall indices were proposed to estimate the rainfall erosivity, which have achieved excellent results in practice. Table 2 summarizes commonly used models used to calculate rainfall erosivity.

2.4 Rainfall indices

We chose three rainfall erosivity indices (all measured in mm): F, developed by Fournier (1960), MFI, developed by Arnoldus (1977), and F_F, developed by Ferro et al. (1999). All three indices combine the precipitation totals of all months and the mean annual precipitation (MAP) and present high correlations with the R factor (Arnoldus 1980; Oduro-Afriyie 1996; Ferro et al. 1999). The indices can be calculated using the following formulas:

$$F = \frac{p^2}{P} \quad (1)$$

where F means the Fournier index (mm), p is the highest monthly rainfall (mm), and P means annual rainfall amount (mm).

$$\mathrm{MFI} = \sum_{i=1}^{12} \frac{p_i^2}{P} \quad (2)$$

where MFI is the modified Fournier index (mm), p_i is the rainfall amount (mm) for month i, and P is the annual rainfall amount(mm).

$$F_F = \frac{P}{12}\left[\frac{\sum_{j=1}^{N} P_j\left[1 + \mathrm{CV}^2(P_j)\right]}{\sum_{j=1}^{N} P_j}\right] \quad (3)$$

where F_F represents the modification of the MFI (the modified Fournier index) in mm, P_j means precipitation (mm) of the year j, coefficient of variation (CV) is the variation coefficient of monthly precipitation in the year j, and P is the mean annual rainfall (mm) of the study period.

2.5 Data analysis

Rainfall erosivity was calculated for the Ansai, Yan'an, Zaoyuan, and Ganguyi stations for a 37-year climate normal period from 1956 to 1989 and from 2008 to 2010, except for Ansai station, for which only 13 years of data were available. The missing values for certain years were interpolated using the multiyear average for the station. We considered the average results of previous studies in Table 4 as the evaluated value and carried out the calculated values on the basis of daily rainfall records and simplified models listed in Table 2. The differences between the evaluated and calculated values were compared by mean absolute percentage error (MAPE, in %) analyses according to Lee and Heo (2011) to determine the adaptation of models as follows:

Table 1 Geographical position (UTM WGS 1984, zone 49N; X = Northing, Y = Easting, e.g., 36.52 = 36°52′), elevation, and length of daily rainfall records of the four meteorological stations in the Yanhe River catchment

Station No.	Station	X	Y	Altitude (m a.s.l.)	Length of record (years)	MAP (mm)	Prec. during 6–9 (mm)
1	Yan'an	36.38	109.27	940	26	544.59	398.74
2	Ansai	36.52	109.19	1,050	13	497.27	368.44
3	Zaoyuan	36.38	109.20	960	19	538.38	395.62
4	Ganguyi	36.42	109.48	880	36	522.86	380.40

MAP = mean annual precipitation, *Prec.* = precipitation

$$\mathrm{MAPE}(\%) = \left|\frac{(\mathrm{EV} - \mathrm{CV})}{\mathrm{EV}}\right| \times 100\,\% \tag{4}$$

where EV refers to the estimated rainfall erosivity, and CV means the actual calculated rainfall erosivity.

3 Results

3.1 Rainfall erosivity calculation

The mean annual erosivity R factor was calculated using models in Table 2, and the results were listed in Table 3. The missing values for certain years were interpolated using the multiyear average and substitutions of other stations in the catchment. For the long-term mean R factor of a single station, the R factors were averaged for approximately 36 years of a climate normal period from 1956 to 1989 and from 2008 to 2010.

The resulting R factors of the tested regression equations vary considerably. They range from the lowest average of nearly 906.51 MJ mm ha^{-1} h^{-1} a^{-1} (Table 2, Eq. 11) to the highest of 5,840.72 MJ mm ha^{-1} h^{-1} a^{-1} (Table 2, Eq. 14). A weakly spatial variation is indicated with the CV of different models and ranges from 2.18 to 10.44 %. Amount-based models (Table 2, Eqs. 8–12) reveal generally low rainfall erosivity compared with index-based models (Table 2, Eqs. 13–18), with R factors ranging from 906.51 (Table 2, Eq. 11) to 2,225.21 MJ mm ha^{-1} h^{-1} a^{-1} (Table 2, Eq. 9) for the amount-based models and from 1,205.76 (Table 2, Eq. 16) to 5,840.72 MJ mm ha^{-1} h^{-1} a^{-1} (Table 2, Eq. 14) for the index-based models.

3.2 Assessment of the models

Because of a lack of sufficient continuous and high-resolution rainfall intensity data in the Yanhe River catchment, we compared our calculation results with previous studies (Table 4) to evaluate the efficiency of the applied regressions in this study. Based on high-resolution rainfall measurements, the R factors in previous studies were calculated by the method proposed by Wischmeier and Smith (1978) or by revised empirical equations after statistical review. Previous study sites included portions or the entirety of our study area (e.g., the Yangou River catchment, which is adjacent to the Yan'an station). Therefore, we

Table 2 Regression functions to approximate the erosivity of rainfall

Type of regression	Code	Equations	References
Eq. based on the MAP	8	$R = 0.0483\text{MAP}^{1.61}$ ($P < 850$) $R = 587.8 - 1.219\text{MAP} + 0.004105\text{MA}P^2$ ($\text{MAP} \geq 850$)	Renard and Freimund (1994)
	9	$\text{Ra} = 0.35\text{MAP} + 3.85$	Renard and Freimund (1994)
Eq. Based on prec. per month (Pm)	10	$R_{\text{month}} = 7.05\text{rain}_{10} - 88.92\ \text{days}_{10}$	de Santos Loureiro and de Azevedo (2001)
Eq. based on prec. per day (Pd)	11	$Ri = \alpha[1 + \eta\cos(2\pi fi - \omega)]\sum_{K=1}^{n} P_{d\geq 12.7}^{\beta}$ with: $\alpha = 0.369(1 + 0.098)\frac{0.36\varphi}{\text{MAP}}$ $f = \frac{1}{12};\quad \omega = \frac{\pi}{6};\quad \beta = 1.49;\quad \mu = 0.29$	Yu and Rosewell (1996)
	12	$Rj = \alpha\sum_{k=1}^{n} P_{d\geq 12}^{\beta}$ with: $\alpha = 21.586\beta^{-7.1891}$ $\beta = 0.8363 + \frac{18.144}{P_{d12}} + \frac{24.455}{P_{y12}}$	Zhang et al. (2002)
Eq. based on F	13	$\text{Rm} = 42.307F + 69.763$	da Silva (2004)
	14	$\text{Rm} = 227F^{0.548}$	Shamshad et al. (2008)
Eq. based on the MFI	15	$R = 0.7397\text{MFI}^{1.847}$ ($\text{MFI} < 55$ mm) $R = 95.77 - 6.081\text{MFI} + 0.4770\text{MFI}^2$ ($\text{MFI} \geq 55$ mm)	Renard and Freimund (1994)
	16	$R = \alpha\text{MFI}^{\beta}$ with: $\alpha = 10^{2.124 - 1.495\beta + 0.00214P_{d\max}}$ $\beta = 0.8363 + \frac{18.144}{P_{d12}} + \frac{24.455}{P_{y12}}$	Men et al. (2008)
	17	$R = 21.56\text{MFI}^{0.927}$	Angulo-Martínez and Beguería (2009)
Eq. based on F_F	18	$R = 2.7015F_F^{1.41}$	Ferro et al. (1999)

Rainfall parameter explanations: *Eq.* denotes equation and *prec.* denotes precipitation, R mean annual R factor, Ri and Rj are the rainfall erosivity (MJ mm ha^{-1} h^{-1} a^{-1}) in month ***i*** and half-month ***j***, respectively, and Ra in Eq. 2 is a unit of 10 MJ mm ha^{-1} h^{-1} a^{-1}, $rain_{10}$ monthly prec. from days with $\geq$10 mm (mm), $days_{10}$ number of days in one month with prec. $\geq$10 mm, $P_{d>12.7\ (12)}$ mean daily prec. of days with $\geq$12.7 (12) mm (mm), n number of days with prec. $\geq$12.7 (12) mm, P_{dmax} maximum daily prec. in an average year, k index of the number of days with prec. $\geq$12.7 (12) mm. α, β, μ regional constants, φ mean prec. during the summer season (May–October) (mm), *MAP* is the mean annual precipitation in mm. F, *MFI*, and F_F represent the Fournier index, modified Fournier index, and modification of the MFI in mm, respectively

Table 3 Mean annual rainfall erosivity R factor (MJ mm ha^{-1} h^{-1} a^{-1}) and the coefficient of variation (CV%) among stations for the Yanhe River catchment calculated from 1956 to 1989 and from 2008 to 2010 based on the erosivity indices and regression equations

Type of approximation/author(s)	Code	Climate station				Average	CV (%)
		Yan'an	Ansai	Zaoyuan	Ganguyi		
R factors based on the mean annual prec. (MAP)							
Renard and Freimund (1994)	8	1,247.38	1,077.39	1,226.02	1,182.55	1,183.33	6.39
Renard and Freimund (1994)	9	2,291.05	2,125.43	2,269.34	2,215.01	2,225.21	3.32
R factors based on prec. per month (Pm)							
de Santos Loureiro and de Azevedo (2001)	10	1,101.19	964.65	1,101.79	1,081.46	1,062.27	6.19
R factors based on prec. per day (Pd)							
Yu and Rosewell (1996)	11	955.16	808.84	943.98	918.08	906.51	7.38
Zhang et al. (2002)	12	1,862.41	1,479.02	1,858.91	1,797.22	1,749.39	10.44
R factors based on the Fournier index (F)							
da Silva (2004)	13	5,110.43	4,857.44	5,066.66	5,080.30	5,028.71	2.30
Shamshad et al. (2008)	14	5,957.63	5,670.77	5,915.36	5,819.14	5,840.72	2.18
R factors based on the modified Fournier index (MFI)							
Renard and Freimund (1994)	15	4,688.72	4,042.30	4,635.60	4,759.80	4,531.60	7.28
Men et al. (2008)	16	1,265.46	1,108.20	1,220.40	1,229.00	1,205.76	5.63
Angulo-Martínez and Beguería (2009)	17	1,551.23	1,466.71	1,535.94	1,539.59	1,523.37	2.52
R factors based on F_F							
Ferro et al. (1999)	18	2,033.74	1,831.66	1,911.50	1,923.66	1,925.11	4.32

prec. precipitation, *MAP* mean annual precipitation, F_F the modification of MFI

consider the average results to be adequate evaluation data and representative of the preconditions of physio-geographic comparability and consistency.

Table 5 presents the results of the MAPE (%) analyses for the Yanhe River catchment and Yan'an station for the evaluation data and calculations. Based on the MFI, Eq. 17 produces the lowest MAPE, with values of 1.32 % for the Yanhe River catchment and 3.62 % for the Yan'an station, respectively. Three regression equations based on F produce values that are 206.26–289.15 % of the MAPE % value and are almost threefold higher than the corresponding evaluation data. For the Yanhe River catchment, the average MAPE reaches 30.41, 13.67, and 21.80 % for Eqs. 8–12, Eqs. 16–17, and Eq. 18, respectively. Models that use the MFI and F_F as parameters are more efficient than the other equations, except Eq. 15. The MFI and F_F employed in our research more accurately predict the rainfall erosivity in the Yanhe River catchment, suggesting that the MFI and F_F are better proxies of rainfall amounts when estimating the R factor.

3.3 Temporal distribution of rainfall erosivity

The average annual rainfall erosivity (R, MJ mm ha^{-1} h^{-1} a^{-1}) of the Yan'an, Ansai, Zaoyuan, and Ganguyi stations for the 1965–1989 and 2008–2010 periods was calculated using meteorological station data based on Eq. 17, which was proposed by Angulo-Martínez and Beguería (2009). Figure 3 presents the temporal distribution of the R factor.

Table 4 Mean annual R factors for adjacent study areas in previous studies

Authors	Study site	MAP (mm)	R factor (MJ mm ha^{-1} h^{-1} a^{-1})	Method	Study period (years)
Wang et al. 1996	Yan'an	–	1,476.5	Wischmeier and Smith (1978)	1956–1984
Yin and Xie (2005)	The Loess Plateau	140–1,000	327–4,416, Yan'an 1,350.6	Xie et al. (2001) (revised from Wischmeier and Smith 1978)	1965–1979
Liao et al. (2009)	Yangou catchment	509.91	492.73–4,716.41, average 1,765.73	Zhang et al. (2002)	1951–2005
Liu et al. 2010	Yanhe River catchment	356.24–591.42	585.29–2,417.70, average 1,580.58	Zhang et al. (2002)	1980–2003

Figure 3a–d presents the rainfall erosivity of the Yan'an, Ansai, Zaoyuan, and Ganguyi stations, respectively. The missing records for the four stations have different lengths of time series in the rainfall erosivity calculations. The missing values of the Yan'an and Ganguyi stations for 1970 were interpolated from the results of Liao et al. (2009), with the average of the calculated R factors in the Zaoyuan and Ganguyi stations replacing the missing value of the Yan'an station in 1974. Values of rainfall erosivity have a significant temporal variation, ranging from 834.48 to 2,371.95, 906.13 to 1,899.35, 920.57 to 2,247.03, and 748.38 to 2,546.62 MJ mm ha^{-1} h^{-1} a^{-1} for the Yan'an, Ansai, Zaoyuan, and Ganguyi stations, respectively. For Zaoyuan and Ganguyi station, the lowest R factor occurred in 1974, whereas the highest occurred in 1985 and 1981, respectively.

4 Discussion

4.1 Selection of the optimal evaluation model for R

Based on regression models, the results from Renard and Freimund (1994), de Santos Loureiro and de Azevedo (2001), Zhang et al. (2002), Men et al. (2008), Angulo-Martínez and Beguería (2009), and Ferro et al. (1999) correspond positively with evaluation data according to the MAPE analyses in Table 5. Most of the models in the above studies included exponential regressions, except for Eqs. 9 and 10. These models revealed that linear and exponential relationships based on the annual or daily precipitation, the MFI, and F_F can be used to estimate the rainfall erosivity in the study area.

Figure 4 presents the relationship between the long-term mean annual rainfall R factors derived from Equation 17 and long-term MAP data. The relationship has a different correlation coefficient when simple linear regressions ($R^2 = 0.73$) and exponential fittings ($R^2 = 0.75$) are employed separately. Exponential fitting is more appropriate for describing the mathematic relationship between the R factor and MAP. Our result corresponds with the result from Xin et al. (2011), who concluded that event rainfall erosivity (EI) was well fitted to the event precipitation amount (P) by an exponential relationship. Mannaerts and Gabriels (2000) also observed a significant relationship using the

Table 5 The MAPE (%) analyses of evaluation data compared to the calculations of regression equations for the Yanhe River catchment and Yan'an station

Code of equations	MAPE (%)		Code of equations	MAPE (%)	
	Yanhe River catchment	Yan'an station		Yanhe River catchment	Yan'an station
8	40.78	49.65	14	269.53	289.15
9	25.13	18.52	15	186.70	206.26
10	32.79	28.07	16	23.71	17.34
11	42.64	37.61	17	3.62	1.32
12	10.68	21.65	18	21.80	25.64
13	218.15	233.80	–	–	–

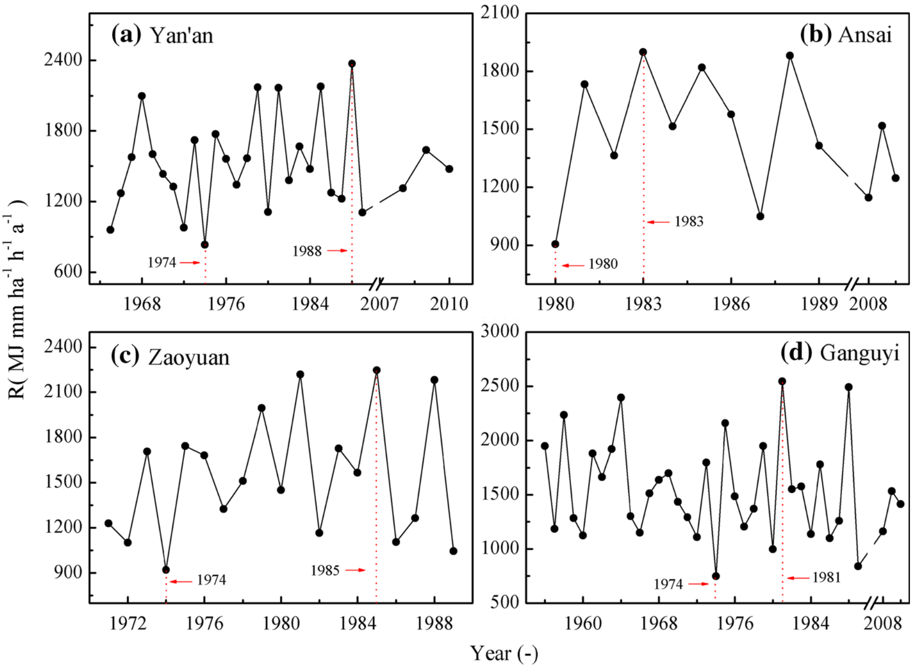

Fig. 3 Temporal distribution of *R* factors derived by Eq. 17 for the Yanhe River catchment

exponential equation for the Cape Verde Islands by considering erosive storms with a threshold of 9 mm.

Compared with the annual and/or monthly rainfall data, the use of daily rainfall records can provide a better understanding of rainfall erosivity (Xin et al. 2011). Moreover, regression equations that using the MFI or the MFI and the MAP can accurately estimate the *R* factor (Eqs. 16 and 17). Men et al. (2008) conducted a regression analysis on data from the Hebei Province in the North China Plain, which is characterized by semiarid conditions (MAP of 350–818 mm). The regression integrates the MFI and the maximum daily precipitation data for days using a 12 mm threshold. This threshold was similar to the threshold of 12.7 mm suggested by Wischmeier and Smith (1978) and was reported as a practical threshold for separating erosive and non-erosive storms for the Yellow River Basin in China (Zhang et al. 2002). Similarly, Zhang et al. (2002) used 12.7 mm as a threshold to derive a model based on the daily rainfall amount. We obtained a reasonable evaluation in the Yanhe River catchment using this method. de Santos Loureiro and de Azevedo (2001) used $rain_{10}$ (monthly precipitation from days which rainfall amount exceeded 10 mm) instead of $rain_{month}$ (monthly precipitation amount) to eliminate some of the non-erosive precipitation in their study, which was thought to be the best available indicator of monthly rainfall temporal concentrations and to improve the proportion of variance explained by R^2 (Schönbrodt-Stitt et al. 2013). The exponential equations used in our study based on threshold parameters, such as $P = 12.7$ and $rain_{10}$, are suitable for our study area and are sufficient to describe the relationship between the *R* factor and erosive rainfall.

The *R* factors calculated according to da Silva (2004) and Shamshad et al. (2008) for the Yanhe River catchment are distinctly higher (5,028.71 and 5,840.72 MJ mm ha^{-1} h^{-1} a^{-1}) than the evaluation data, although they have linear or exponential regression styles that are similar to methods based on the MAP or MFI. This result reflects the different climatic conditions in the study regions considered by da Silva and Shamshad (Brazil and Peninsular Malaysia, respectively), which are located in the tropics and experienced more rainfall throughout the year for which the regression function was developed. Moreover, models based on the monthly F included all of the rainfall amounts in every month, which would inevitably include non-erosive events in the calculation and overestimate the *R* factor for the Yanhe River catchment because it has summer-dominated rainfall patterns and erosivity thresholds. Contrary to the simple linear and exponential function regressions, Eq. 15, which is a complex quadratic function and was applied by Renard and Freimund (1994) to assess rainfall erosivity in the USA, yielded a higher evaluation (4,531.60 MJ mm ha^{-1} h^{-1} a^{-1}) for our study area. This regression form was not suitable for the Yanhe River catchment even though it was used in a similar manner as the MFI in Eqs. 16 and 17.

The calculated *R* factor of 904.51 MJ mm ha^{-1} h^{-1} a^{-1} based on the method of Yu and Rosewell (1996) was distinctly lower than the evaluated value. This model was developed in New South Wales in South Australia, which has an arid to humid subtropical and oceanic climate. Because of the lower MAP and high climate variation in the moderate climate zone, this regression considerably underestimates the rainfall erosivity in arid and semiarid regions, such as the Yanhe River catchment.

Equation 12, which was proposed by Zhang et al. (2002), produced a low MAPE for the Yanhe River catchment; however, our evaluation data were based on the results of two previous studies. Therefore, the practicality of applying this method to our study area has been tested, and there is no further discussion of this method in our study.

4.2 Development of estimating the *R* factor by erosivity indices

Rainfall indices are important for describing the potential of rainfall to generate erosion and correspond to the rainfall aggressiveness in a specific region (Mello et al. 2013). These indices are calculated based on the distribution and CV of monthly rainfall in a year, which can accurately reflect the classic monthly properties (Angulo-Martínez and Beguería 2009; Schönbrodt-Stitt et al. 2013). The MFI and F_F imported in our research more accurately predict the rainfall erosivity in the Yanhe River catchment, particularly when an exponential relationship is applied (Tables 2, 5).

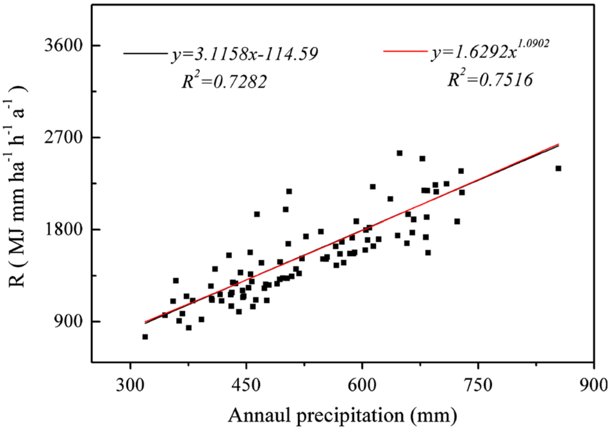

Fig. 4 Relation between the long-term annual precipitation and long-term mean annual rainfall *R* factors derived by Eq. 17 for the Yanhe River catchment

The F index was selected because the Chinese Loess Plateau has similar climatic conditions to West Africa, where this index was originally developed and for which meteorological data were readily available. Because F is a function of MAP, it can better relate erosion to other rainfall-caused phenomena. The MFI is another simplified regional index that combines the precipitation totals of all months with the MAP and is strongly correlated with the erosivity factor of Wischmeier and Smith (Arnoldus 1980). F_F considers the link between the monthly rainfall depths and corresponding annual rainfall, including the annual coefficient of rainfall variation. F_F is considered a better estimator of the *R* factor because it considers the seasonal distribution of rainfall (Ferro et al. 1999). The Loess Plateau has inhomogeneous distributions of annual rainfall that are typically concentrated in a single month or over several months. The indices included in this study that summarize the rainfall erosivity should be verified against the monthly properties of this region.

Figure 5 presents a consistent distribution of all erosivity indices in four stations, except F at the Yan'an station. Similar to the MAP, the Ansai station has the three lowest erosivity indices, whereas the Yan'an station has the highest MAP and MFI and F_F indices among all stations. The MFI and F_F for all stations have higher values than F, ranging from 95.03 (Ansai station) to 101.01 mm (Yan'an station) and 101.85 (Ansai station) to 109.70 mm (Yan'an station), respectively. The value of F for the wettest month for all stations lies within Class 2 (40–60 mm) of the F index classification according to Oduro-Afriyie (1996) and indicates a "moderate" erosivity risk. All three indices consider the annual variation of the MAP, but the Ganguyi station has a higher index value than the Zaoyuan station even though it received less average rainfall in the past. This result was mainly caused by the monthly distribution of annual precipitation in these two stations. The MFI typically exhibits a stronger correlation with the MAP than F (Renard et al. 1997), and this result was also observed for the Yanhe River catchment in our study. The MFI displays a stronger correlation with the MAP compared to F and F_F, with R^2 values of 0.85, 0.77, and 0.23, respectively.

Therefore, substituting the erosivity indices for annual precipitation to estimate the rainfall erosivity is an important step. The strong correlation between the annual mean F and the R factor encouraged the use of the MFI in applications. By summing all of the monthly F values, the MFI was able to express the interannual characteristics of the monthly index, which has applications worldwide (Mello et al. 2013). The MFI more accurately summarizes the annual erosivity than the monthly F, especially in areas in which meteorological conditions have strong seasonal variations. In these regions, the MFI is a better indicator of annual rainfall erosivity than F and the MAP (Le Roux et al. 2005). When calculating the rainfall erosivity for a period of N years, F_F correlates positively with the R factor (Ferro et al. 1991). In the Yanhe River catchment, the CV of monthly rainfall averages 1.16 and varies significantly each month. The MAPE analyses in Table 5 verify that when the CV of monthly rainfall is considered, F_F can enhance the accuracy of parameter models. For regions like the Yanhe River catchment which has great saltation of rainfall distributions, erosivity indices MFI and F_F can deservedly enhance the accuracy of the rainfall erosivity predictions.

4.3 Governing factors of temporal variations in the R factor

Rainfall is the most complex climatic element in terms of its temporal and spatial variations. According to Eltaif et al. (2010), the differences in R factors between proximal locations were caused by both differences in the amount of precipitation and the intensity and monthly distribution of rainfall, which is similar to the interannual R factor. Moreover, the distribution of rainfall throughout the year can display marked changes that may have important impacts on the timing and magnitude of erosive rainfalls, even in the absence of changes in the overall rainfall amounts (Sumner et al. 2001).

As shown in Fig. 6, the total rainfall amount of the Zaoyuan and Ganguyi stations in 1974 was 391.9 and 319 mm, with a minimum MFI of 57.38 and 45.90 mm, respectively. The lack of erosive rainfall was the immediate cause of the lowest R factor between the stations, as shown in Fig. 5. However, the annual precipitation at the Ganguyi station was 648.40 mm in 1981 (Fig. 6b). Approximately 43.04 % of the annual rainfall occurred in August (279.1 mm), and the MFI reached its highest value of 171.99 mm in 1981, revealing an extremely inhomogeneous rainfall concentration throughout the year that led to high rainfall erosivity. To assess the seasonal rainfall regime in our study area, we evaluated the seasonality index (SI) proposed by Walsh and Lawler (1981) and the precipitation concentration index (PCI) proposed by Oliver (1980) as follows:

$$\mathrm{SI} = \frac{1}{P}\sum_{n=1}^{12}\left|X_n - \frac{P}{12}\right| \tag{5}$$

$$\mathrm{PCI} = \sum_{n=1}^{12}\left(\frac{X_n^2}{P^2}\right) \times 100 \tag{6}$$

where X_n is the rainfall in month n and P is the annual precipitation. The interannual variation of the R factor in the Yanhe River catchment was weighted by the trend coefficient r, defined as

$$r = \frac{\sum_{i=1}^{n}(R_i - R_{\mathrm{ave}})(i-t)}{\sqrt{\sum_{i=1}^{n}(R_i - R_{\mathrm{ave}})^2 \sum_{i=1}^{n}(i-t)^2}} \tag{7}$$

where i presents the number of years, R_i is the R factor for the ith year, R_{ave} is the yearly average of the R factor, and t is a sequence parameter associated with the year number n,

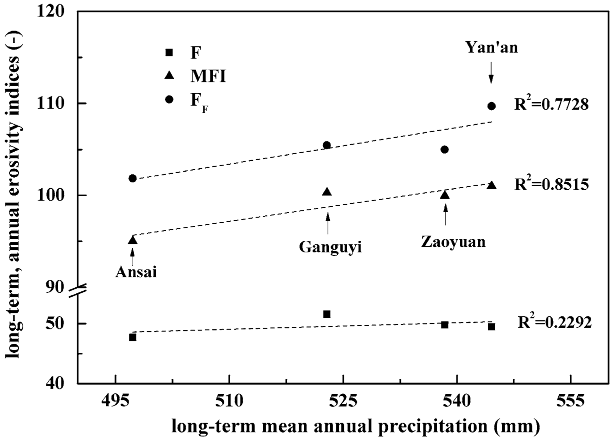

Fig. 5 Relation between the long-term mean annual precipitation (MAP) and the Fournier index (F) in wettest month of a year, modified Fournier index (MFI), and modification of the MFI (F_F) in the wettest month of a year

$t = (n + 1)/2$. The r value could reflect the direction and extent of a given secular variation and suggest an increasing trend when positive and a decreasing trend when negative. The absolute value of r indicates the degree of variation.

All subjects in discussion have a large interannual variability in the Yanhe River catchment during the study period (Fig. 7). With the lowest SI values in 1974 (0.69) and 1979 (1.05) (Fig. 7a), the Yanhe River catchment suffered a markedly long dry season rainfall style that is classified according to Walsh and Lawler (1981). The PCI in the Yanhe River catchment also had a clear interannual variation similar to the SI, which varies from

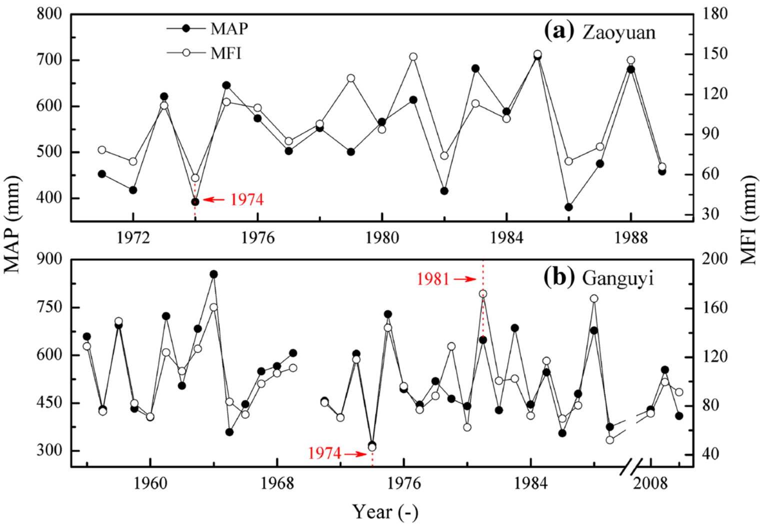

Fig. 6 Interannual variation of the mean annual precipitation (MAP) and modified Fournier index (MFI) at the **a** Zaoyuan and **b** Ganguyi stations

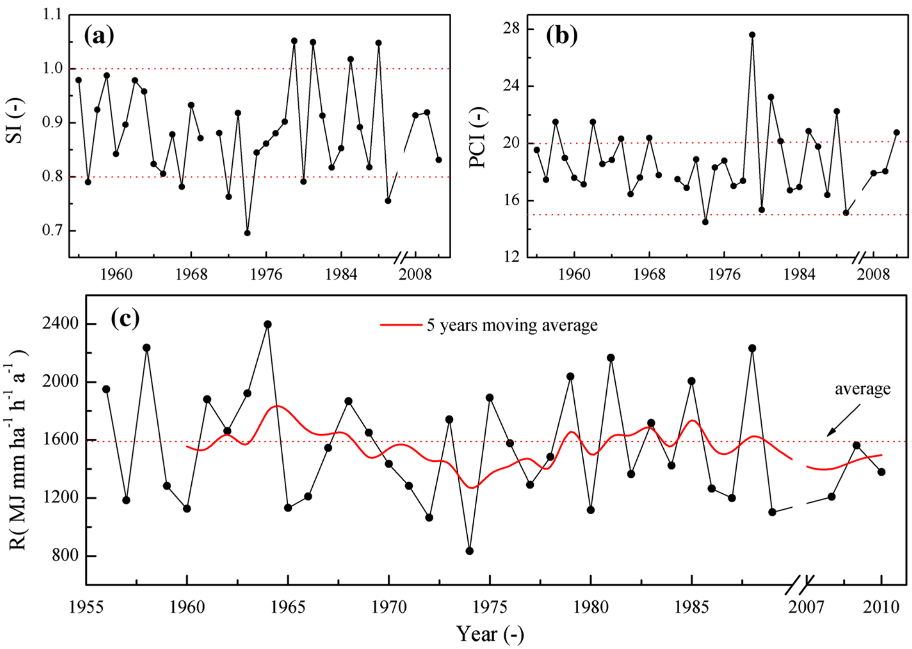

Fig. 7 Interannual variation of the **a** seasonality index (SI), **b** precipitation concentration index (PCI), and **c** rainfall erosivity *R* factor and its 5-year moving average in the Yanhe River catchment during the 1956–1989 and 2008–2010 periods, excluding the years with missing data; all indexes were calculated from the averages of data from the Yan'an, Ansai, Zaoyuan, and Ganguyi stations

14.51 in 1974 to 27.61 in 1979 (Fig. 7b). A highly seasonal distribution of rainfall throughout the catchment was observed in both years. The average MAP in 1974 was 355.45 mm, with 89.55 occurring in September, and the relatively limited and fragmented rainfall was the major cause of the low SI and PCI. The average rainfall amount in 1979 was 489.98 mm, which was approximately the average for several years (530.94 mm); however, nearly 45 % of the rainfall occurred in July (218.91 mm), which led to a sharp increase in rainfall seasonality. The *R* factor (Fig. 7c) has a similar variation pattern for the SI and PCI and ranges from 834.78 (1974, $P = 355.45$, SI = 0.69, and PCI = 14.51) to 2,396.06 MJ mm ha^{-1} h^{-1} a^{-1} (1964, $P = 853.7$, SI = 0.82, and PCI = 18.64). Rainfall with either high volumes or high seasonal variation can lead to a high *R* factor. In addition to MAP, the extreme wave of monthly rainfall distributions weighted by the SI and PCI can affect the temporal variability, particularly the annual variability of rainfall erosivity. Years with high *R* factors always have either large rainfall amounts or a distinct seasonality (high SI and PCI).

For long-term series of rainfall erosivity, the trend coefficient *r* over the 1956–1989 period was −0.01 but reached −0.07 when 2008–2010 was included, which indicated a slight decrease in the Yanhe River catchment during the 1956–2010 period when the missing data were excluded. The weak variation of rainfall erosivity allowed us to ignore the influence of rainfall when explaining changes in the soil erosion for such situations as the discharge of sediment in the Yanhe River catchment in recent decades.

5 Conclusions

The evaluation of the rainfall erosivity *R* factor is fundamental for a better understanding of the erosion potential of certain rainfall events. High-resolution rainfall data (pluviograph data) are required to compute rainfall erosivity directly; however, such data are not available for many locations, and calculations of such data (when available) are intricate and time-consuming. In this study, a series of simplified methods based on readily available data and rainfall indices were assessed for their ability to predict rainfall erosivity in the Yanhe River catchment on the Chinese Loess Plateau. An exponential relationship is more suitable to describe the mathematic relationships in the *R* factor and MAP, with an R^2 value of 0.75, compared with 0.73 for a linear fitting. The resulting *R* factors of the tested regression equations vary widely, ranging from the lowest at nearly 906.51 MJ mm ha^{-1} h^{-1} a^{-1} (Eq. 11) to the highest at 5,840.72 MJ mm ha^{-1} h^{-1} a^{-1} (Eq. 14). When comparing our results to the evaluations from previous studies, the exponential regression equation based on the MFI proposed by Angulo-Martínez and Beguería (2009) was shown to be the most accurate (MAPE = 3.62 %) estimation of the *R* factor in our study area. As indices, the MFI and F_F are better proxies of the MAP than F when approximating the *R* factor because their regression coefficients with the MAP are 0.85 and 0.77, respectively. The results of the SI (0.69–1.05) and PCI (14.51–27.46) analyses indicated a highly seasonal distribution of rainfall throughout the Yanhe River catchment. In addition to MAP, the extreme wave of monthly rainfall distributions weighted by the SI and PCI can also affect the temporal variability, particularly the annual variability of rainfall erosivity. The trend coefficient *r* was −0.07 for the long-term series of rainfall erosivity, which indicated a slight decrease in the Yanhe River catchment during the 1956–2010 period when the missing data were excluded. The multiyear variation of rainfall erosivity in Yanhe was weak; therefore, the influence of rainfall played less of a role in the changes of sediment in the Yanhe River catchment in recent decades.

Acknowledgments Financial support for this research was provided by the National Natural Science Foundation of China (Nos. 41271296 and 41301294), the “Hundred-talent Project” of the Chinese Academy of Sciences, and the Major Programs of the Chinese Academy of Sciences (KZZDEW-04-03).

References

Angulo-Martínez M, Beguería S (2009) Estimating rainfall erosivity from daily precipitation records: a comparison among methods using data from the Ebro Basin (NE Spain). J Hydrol 379:111–121

Arnoldus HMJ (1977) Methodology used to determine the maximum potential average annual soil loss due to sheet and rill erosion in Morocco. In: assessing soil degradation. FAO Soils Bull 34:39–51, Rome

Arnoldus HMJ (1980) An approximation of the rainfall factor in the universal soil loss equation. In: De Boodt M, Gabriels D (eds) Assessment of erosion. Wiley, New York, pp 127–132

Beskow S, Mello CR, Norton DL, Curi N, Viola MR, Avanzi JC (2009) Soil erosion prediction in the Grande River Basin, Brazil using distributed modeling. Catena 79:49–59

Bhatt VK, Bhattacharya P, Tiwari AK (2007) Application of artificial neural network in estimation of rainfall erosivity. Hydrol J 30(1&2):29–39

Chen LD, Wei W, Fu BJ, Lü YH (2007) Soil and water conservation on the Loess Plateau in China: review and perspective. Prog Phys Geog 31:389–403

da Silva AM (2004) Rainfall erosivity map for Brazil. Catena 57:251–259

de Santos Loureiro N, de Azevedo Coutinho M (2001) A new procedure to estimate the RUSLE EI30 index, based on monthly rainfall data and applied to the Algarve region, Portugal. J Hydrol 250:12–18

Diodato N, Bellocchi G (2007) Estimating monthly (R)USLE climate input in a Mediterranean region using limited data. J Hydrol 345:224–236

Eltaif N, Gharaibeh M, Al-Zaitawi F, Alhamad M (2010) Approximation of rainfall erosivity factors in North Jordan. Pedosphere 20:711–717

Ferro V, Giordano G, Iovino M (1991) Isoerosivity and erosion risk map for Sicily. Hydrol Sci J 36:549–564

Ferro V, Porto P, Yu BF (1999) A comparative study of rainfall erosivity estimation for southern Italy and southeastern Australia. Hydrol Sci J 44:3–24

Fiener P, Neuhaus P, Botschek J (2013) Long-term trends in rainfall erosivity–analysis of high resolution precipitation time series (1937–2007) from Western Germany. Agric For Meteorol 171:115–123

Fournier F (1960) Climatet erosion; la relation entre l'erosion du solpar l'eau et les precipitations atmosperiques. Presses universi-taires de Frances, Paris, p 201

Fu BJ, Gulinck H (1994) Land evaluation in an area of severe erosion: the Loess Plateau of China. Land Degrad Rehabil 5:33–40

Hamlaoui-Moulai L, Mesbah M, Souag-Gamane D, Medjerab A (2013) Detecting hydro-climatic change using spatiotemporal analysis of rainfall time series in Western Algeria. Nat Hazards 65:1293–1311

Karl TR, Trenberth KE (2003) Modern global climate change. Science 302:1719–1723

Le Roux JJ, Sumner PD, Rughooputh SDDV (2005) Erosion modelling and soil loss prediction under changing land use for a catchment on Mauritius. S Afr Geogr J 87:127–140

Lee J-H, Heo J-H (2011) Evaluation of estimation methods for rainfall erosivity based on annual precipitation in Korea. J Hydrol 409:30–48

Liao X, Xu XX, Liu PL (2009) The Dynamic Feature Analysis of Rainfall Erosivity in Yan'an Area Based on Daily Rainfall Amounts. Res Soil Water Conserv 16(2):34–37 41 (in Chinese)

Liu CL, Yang QK, Xie HX (2010) Spatial and temporal distribution of rainfall erosivity in the Yanhe River basin. Environ Sci 31(4):850–857 (in Chinese)

Lu YH, Fu BJ, Feng XM, Zeng Y et al (2012a) A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. PLoS ONE 7(2):e31782

Lu YH, Liu SG, Fu BJ (2012b) Ecosystem service: from virtual reality to ground truth. Environ Sci Technol 46:2492–2493

Mannaerts CM, Gabriels D (2000) Rainfall erosivity in Cape Verde. Soil Till Res 55:207–212

Mello C, Viola M, Beskow S, Norton L (2013) Multivariate models for annual rainfall erosivity in Brazil. Geoderma 202:88–102

Men MX, Yu ZR, Xu H (2008) Study on the spatial pattern of rainfall erosivity based on geostatistics in Hebei Province. Front Agric China 2:281–289

Nearing MA, Jetten V, Baffaut C et al (2005) Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61:131–154

Oduro-Afriyie K (1996) Rainfall erosivity map for Ghana. Geoderma 74:161–166

Oliver JE (1980) Monthly precipitation distribution: a comparative index. Prof Geogr 32:300–309. doi:10.1111/j.0033-0124.1980.00300.x

Pan JH, Wen Y (2013) Estimation of soil erosion using RUSLE in Caijiamiao watershed, China. Nat Hazards. doi: 10.1007/s11069-013-1006-2

Renard KG, Freimund JR (1994) Using monthly precipitation data to estimate the R-factor in the revised USLE. J Hydrol 157:287–306

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water:a guide to conservation planning with the revised universal soil loss equation (RUSLE). The USDA Agricultural Handbook (AH). No. 703, pp 384

Schönbrodt-Stitt S, Bosch A, Behrens T, Hartmann H, Shi XZ, Scholten T (2013) Approximation and spatial regionalization of rainfall erosivity based on sparse data in a mountainous catchment of the Yangtze River in Central China. Environ Sci Pollut Res 20:6917–6933

Shamshad A, Azhari M, Isa M, Hussin W, Parida B (2008) Development of an appropriate procedure for estimation of RUSLE EI30 index and preparation of erosivity maps for Pulau Penang in Peninsular Malaysia. Catena 72:423–432

Shi H, Shao MA (2000) Soil and water loss from the Loess Plateau in China. J Arid Environ 45(1):9–20

Shi ZH, Ai L, Fang NF, Zhu HD (2012) Modeling the impacts of integrated small watershed management on soil erosion and sediment delivery: a case study in the Three Gorges Area, China. J Hydrol 438–439:156–167

Su CH, Fu BJ, Wei YP et al (2012) Ecosystem management based on ecosystem services and human activities: a case study in the Yanhe watershed. Sustain Sci 7:17–32

Sumner G, Homar V, Ramis C (2001) Precipitation seasonality in eastern and southern coastal Spain. Int J Climatol 21:219–247

Walsh RPD, Lawler DM (1981) Rainfall seasonality: description, spatial patterns and change through time. Weather 36:201–208

Wang WZ, Jiao JY, Hao XP (1996) Distribution of rainfall erosivity R value in China. J Soil Eros Soil Conserv 2(1):29–39 (in Chinese)

Wei W, Chen LD, Fu BJ et al (2007) The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China. J Hydrol 335:247–258

Wei W, Chen LD, Fu BJ (2009) Effects of rainfall change on water erosion processes in terrestrial ecosystems: a review. Prog Phys Geog 33(3):307–318

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. Agriculture Handbook No. 537, USDA, Washington, p 58. http://naldc.nal.usda.gov/download/CAT79706928/PDF

Xie Y, Zhang WB, Liu BY (2001) Rainfall erosivity estimation using daily rainfall amount and intensity. Bull Soil Water Conserv 21(6):53–56 (in Chinese)

Xin ZB, Yu XX, Li QY, Lu XX (2011) Spatiotemporal variation in rainfall erosivity on the Chinese Loess Plateau during the period 1956–2008. Reg Environ Chang 11:149–159

Xu JX (2005) Precipitation–vegetation coupling and its influence on erosion on the Loess Plateau, China. Catena 64:103–116

Yin SQ, Xie Y (2005) Spatial variations and seasonal distributions of rainfall erosivity on Loess Plateau. Bull Soil Water Conserv 25(4):29–33 (in Chinese)

Yu BF (1998) Rainfall erosivity and its estimation for Australia's tropics. Aust J Soil Res 36:143–165

Yu BF, Rosewell C (1996) An assessment of a daily rainfall erosivity model for New South Wales. Soil Res 34:139–152

Zhang WB, Xie Y, Liu BY (2002) Rainfall erosivity estimation using daily rainfall amounts. Sci Geogr Sin 22:705–711 (in Chinese)

Zhang GH, Nearing M, Liu B (2005) Potential effects of climate change on rainfall erosivity in the Yellow River basin of China. Trans ASAE 48:511–517