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Spatial and temporal variation in rainfall erosivity in a Himalayan watershed

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ABSTRACT

Global climate change can modify rainfall patterns, leading to more extremes with associated erosion events. Rainfall erosivity, or the R-factor based on the Revised Universal Soil Loss Equation (RUSLE), indicates the potential water erosion risk and it plays an important role in water and soil conservation assessments. However, calculation of the R-factor requires high resolution data series, and thus we present an alternative model that can be used to accurately calculate the R-factor. Our erosivity model uses daily rainfall with advised regression parameters to estimate the R-factor in the watershed, which was selected by comparing the actual R-factor with 10 min high resolution rainfall data and the estimated R-factor with daily rainfall data from 1998 to 2002. The mean annual R-factor map was derived in the study using cokriging. The annual R-factor in the Kejie watershed was classified as medium and medium-strong erosivity, with a mean value of 3264 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$ which represented a range from 2505 to 5538 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$. A simple power relation between annual R-factor and annual rainfall was derived. The long-term change trend analysis showed no significant increasing or decreasing trend observed for the region; however, there was a significant increasing trend observed in two stations in September, one station in March. The annual R-factor with a coefficient of variation of 0.30 indicated inter-annual variation of the R-factor in the watershed was not so apparent. The intra-annual R-factor analysis illustrated the apparent seasonal and monthly distribution, about 65% from the summer season, and the maximum monthly R-factor occurring in July, followed by August and June. Consequently, the adjusted daily model can be applied in this Himalayan mountain area when high-resolution rainfall data is unavailable. The R-factor map and the simple power relation provided a useful tool for land-use planner and agriculture management in the Kejie watershed.

1. Introduction

Soil erosion induced by water is a major environmental threat with concerns that changing patterns of rainfall related to global climate change will increase erosion risks, in interaction with land cover and land use (Ma et al., 2010). Assessment of this concern requires a detailed analysis of the existing data sets, as a basis for interpreting future climate change scenarios. Rainfall erosivity, as presented by Hudson (1971), and Wischmeier and Smith (1978), describes an interaction between the kinetic energy of raindrops and the soil surface indicating the potential ability for rainfall to cause soil loss.

Vegetation cover, soil infiltration, erodibility and rainfall erosivity are the major factors impacting soil erosion. Among of them, rainfall erosivity is particularly difficult to predict and control. Numerous studies have assessed the relationship between conventional rainfall characteristics and soil detachment (Arnoldus, 1977; Hudson, 1971; Wischmeier and Smith, 1978). The (Revised) Universal Soil Loss Equation (USLE/RUSLE) R-factor is the most frequently used as a measure of soil erosivity (Brown and Foster, 1987; Renard et al., 1997; Wischmeier and Smith, 1978).

The RUSLE R-factor was first calculated by Wischmeier and Smith (1978), in which the R-factor was determined by calculating the average annual sum of the product of a storm's kinetic energy E and its maximum 30-min intensity I_{30}, known as the EI_{30}. Wang et al. (1995) recommended EI_{30} to calculate the rainfall erosivity (R-factor) in China by analyzing the correlation coefficients between different combined factors (i.e. EI_5, EI_{10}, EI_{15}, EI_{30}, EI_{60},PI_{30}), and the soil erosion

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data from 10 representative erosive plots located in Northern China, Southern China, and Western China. The original method requires high resolution rainfall data with continuous pluviographic records; however, these are rarely available in many parts of the world (Aronica and Ferro, 1997; Diodato, 2005; Silva, 2004). These factors have become a constraint for applying RUSLE in soil and water conservation programs. Thus several models, based on correlations between the measured R-factor and the available rainfall, have been developed to estimate the rainfall R-factor from daily, monthly, or yearly rainfall (Arnoldus, 1977; Ferro et al., 1999; Renard and Freimund, 1994; Wang et al., 1995; Yu and Rosewell, 1996a; Zhang et al., 2002). The results from these different time resolution data sets indicate that the daily model provides a more-accurate performance than the monthly and yearly models (Angulo-Martinez and Begueria, 2009; Zhang and Fu, 2003). Angulo-Martinez and Begueria (2009) found daily models based on the Yu and Rosewell (1996a) equations were most satisfactory, and the model was also recommended by Ning and Shi (2003) to calculate R-factor in Southwestern China. Additionally, the model proposed by Zhang et al. (2002), in which the R-factor in half-month was estimated based on daily rainfall data, has been widely used in China (Zhang and Fu, 2003). Schonbrodt-Stitt et al. (2013) compared 15 models and recommended the model based on the modified Fournier index regression to calculate the annual R-factor in the Yangtze River in China. The coefficients were estimated based on the daily and annual rainfall (Men et al., 2008).

Over the past four decades, profound land use changes occurred in the Kejie watershed in the Salween River basin, and the annual runoff and annual rainfall have remained unchanged (Ma et al., 2009). However, a decreasing trend in the amount of suspended sediment has been observed in the outlet of the Kejie watershed. Consequently, R-factor analysis will help to understand the process of soil erosion within the watershed. Rainfall erosivity mapping and spatial and temporal variations are the key issues for soil erosion and landslide risk assessment, agricultural management, and soil conservation practices (Meusburger et al., 2012). However, no specific relationship has been established between the calculated R-factor and the available type of rainfall data in the Kejie watershed. Therefore, the objectives of this study were to (1) calculate the actual R-factors in the Xizhuang sub-watershed based on the 10-minute rainfall data over 5 years; (2) select a suitable daily model for R-factor estimation in the Kejie watershed; (3) estimate the monthly and annual R-factors at the sites during the period 1965–2010; (4) analyze the temporal variations of the R-factor in the study site; and (5) map the mean annual R-factor and analyze its spatial distribution.

2. Materials and methods

2.1. Description of the watershed

The Kejie watershed, located in western Yunnan, China, forming part of the eastern Himalayan range, lies within 24 º 46′06″N-25 º 22′39″N and 98 º 55′47″E-99 º 40′28″E, and is the upstream watershed in the Salween Basin with a total area of 1755km^2(Fig. 1). The Donghe River, the main water course, is one of the tributaries of the Salween River Basin.

The Kejie watershed is a middle-mountain area with 1924 m.a.s.l of mean elevation which ranges between 963 m.a.s.l (the Kejie hydrological station) and 3076 m.a.s.l (the Lashitou mountain peak). In total area, around 7% lies below 1,500 m.a.s.l, 37% above 2,000 m.a.s.l, and 56% between 1,500 and 2,000 m.a.s.l. The average slope of the watershed is about 16.4°.

The mean annual precipitation is 1117 mm with a maximum of 2267 mm recorded in 2001 at the Yiwangshui site and a minimum of 653 mm recorded in 1965 at the Shidian site. As one might expect, the spatial distribution of rainfall is influenced by the topography of the watershed. Additionally, more than 80% of the precipitation occurs in the monsoon season from May to October. The variation coefficient of annual rainfall is 0.14. The annual rainfall change trend was weak with a significant increasing trend over September at the Baoshan site (Ma et al., 2009). The mean monthly temperature varies between 15.4 °C and 22.6 °C in the summer and from 7.2 °C to 19.8 °C during the winter months. The major types of land cover include forest, grassland, cropland, and barren land. During the past two decades, the Kejie watershed has been reforested extensively at the expense of grassland, cropland and barren land (Ma et al., 2009).

The Xizhuang sub-watershed lies in the northwest part of the Kejie watershed covering 34.56 km^2. It forms the upper-stream of Donghe River with elevations ranging from 1695 to 3060 m.a.s.l. A monitoring hydro-meteorological network was put in place there from 1997 to 2003 by the People and Resource Dynamics in Mountain Watersheds of the Hindu Kush-Himalaya Project (PARDYP) (Ma et al., 2008). The higher temporal resolution rainfall data (10 minute interval) was collected from the Xizhuang sub-watershed.

2.2. Available rainfall data

Five rainfall sites with long-term daily rainfall data are located in or adjacent to the Kejie watershed (three of them taking measurements from 1965–2010, and two from 1965–2005), and seven short-term rainfall sites were situated in the Xizhuang sub-watershed (of which six sites with the 10 min rainfall data took measurements from 1998 to 2002, and one measured daily data from 2000–2002) (Fig. 1). Characteristics of all the sites have been listed in Table 1. Long-term daily rainfall data at the Baoshan site was provided by the National Meteorological Information Centre of China (http://cdc.cma.gov.cn), at the Shidian and Changning sites by the Baoshan Meteorological Bureau, and the final two sites Kejie and Beimiao by the Baoshan Hydrological Bureau. The 10 minute rainfall data was collected by PARDYP project (Ma et al., 2008). Six siphon rain-gauges with continuous graphical record took measurements from 1998 to 2002. Gangwangken data covered a period from January 1998 to December 2002; the data for the other five sites (Damaidi, Sangoushui, Lijiasi, Qingshui and Xizhuang) were available only from wet season (June to November) measurements taken from 1998 to 2000, and during the whole calendar year from 2001 to 2002. Daily data from the highest altitude at Yiwanshui covers 3 years (2000–2002), which was used as reference site to interpolate mean annual R-factor. The 10 minutes rainfall data was used to calculate R-factor, and to evaluate the experimental models. The long-term and short-term daily rainfall data was used to estimate annual and monthly R-factor, then to map the mean annual R-factor.

2.3. Computation of rainfall erosivity

The RUSLE (EI_{30}) was calculated using the rainfall intensity data recorded every 10 min at the six sites with short-term datasets in the Xizhuang sub-watershed. Following this, three empirical models (Men et al., 2008; Yu and Rosewell., 1996a; Zhang et al., 2002) were based on daily rainfall regressions, and were selected to estimate the monthly and yearly R-factors at the same six sites. The original equation of empirical parameters in model 1 (Zhang et al., 2002) and model 3 (Men et al., 2008) were used in our study, and model 2 (Yu and Rosewell., 1996a) was modified to be suitable in China. By comparing the estimated annual R-factor with the actual annual R-factor, a suitable daily model was selected to estimate monthly and annual R-factor at the five sites with long-term daily rainfall and at 1 site with 3-year daily rainfall (the Yiwanshui site).

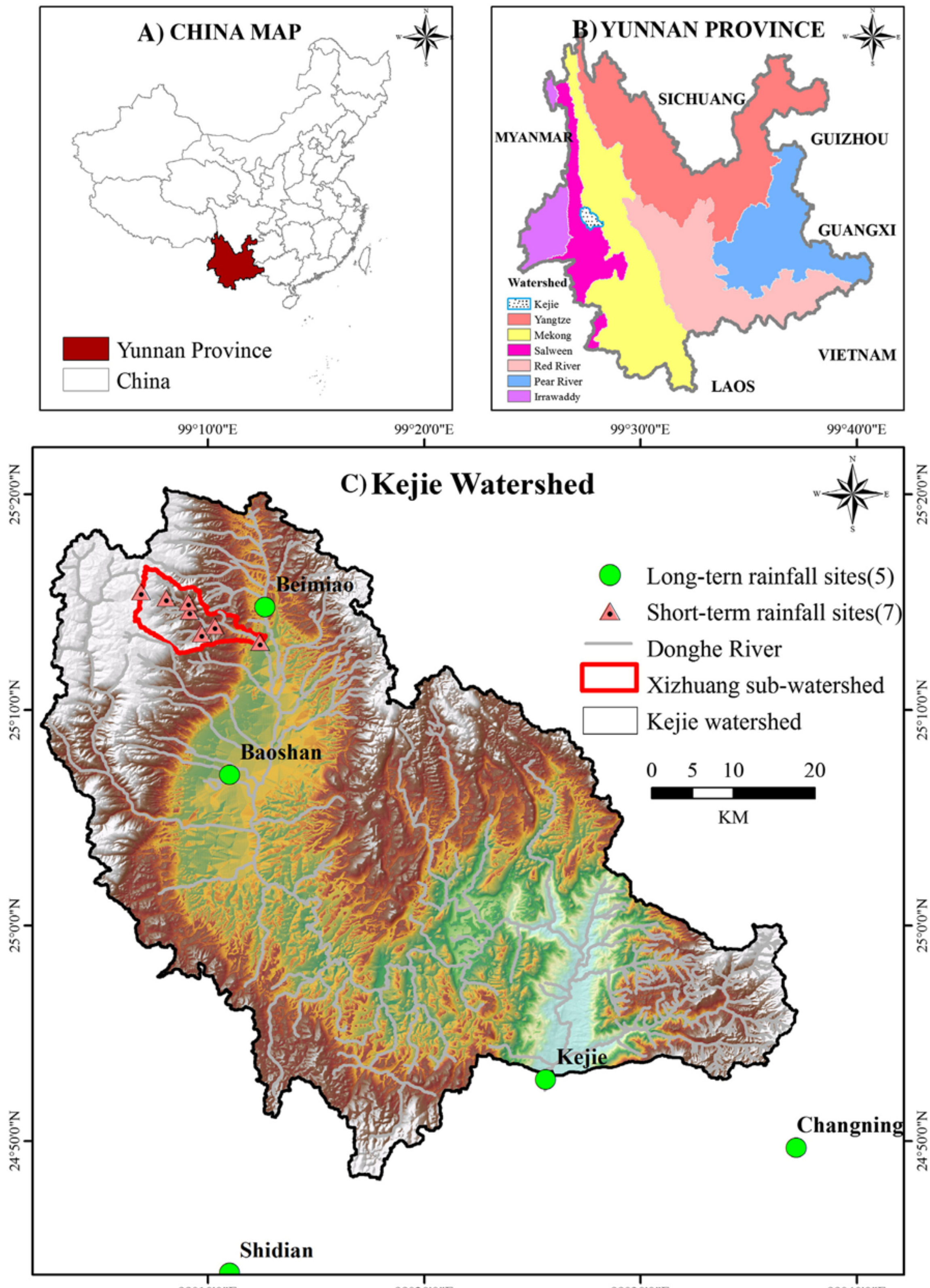

Fig. 1. Location of the Kejie watershed, southwestern China, eastern Himalayan region (Xizhuang sub-watershed is located in the northwestern watershed where seven sites with short-term rainfall are available).

2.3.1. Calculation of R-factor of RUSLE in sub-watershed

Daily EI_{30} in the Xizhuang sub-watershed for the period 1998–2002 was calculated using the rainfall intensity data recorded every 10 minutes. The RUSLE model, using the Brown and Foster (1987) approach, was used to calculate annual rainfall erosivity. The rainfall erosivity is the product of kinetic energy of a rainfall event and its maximum 30-minute intensity:

$$R = \sum_{k=1}^{n} (EI_{30})_k \quad (1)$$

Table 1
Characteristics of the rainfall stations in the Kejie watershed.

Site Name	Latitude	Longitude	Elevation (m)	Resolution	Period
Yiwanshui	25°15′30″	99°06′52″	3060	daily	2000–2002
Damaidi	25°15′11″	99°08′02″	2225	10 min	1998–2002
Sangoushui	25°15′00″	99°09′04″	2090	10 min	1998–2002
Lijiasi	25°14′35″	99°09′07″	1970	10 min	1998–2002
Gangwangkeng	25°13′32	99°09′41″	1955	10 min	1998–2002
Qingshui	25°13′54″	99°10′17″	1852	10 min	1998–2002
Xizhuang	25°13′08″	99°12′22″	1705	10 min	1998–2002
Beimiaoshuiku	25°14′47″	99°12′38″	1729.8	daily	1965–2005
Baoshan	25°07′	99°11″	1652	daily	1965–2010
Kejie	24°52′50″	99°25′36″	968.5	daily	1965–2005
Changning	24°49′41″	99°37′12″	1658	daily	1965–2010
Shidian	24°43′51″	99°11′00″	1489	daily	1965–2010

Note: the sites were divided into two groups, and the name of the sites with short-term data in the Xizhuang sub-watershed was ordered from west to east, which can easily be identified from Fig. 1. Additionally, the name of the sites with long-term data was marked in the Fig. 1.

where R is the annual rainfall erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}), n is the number of erosive events in one year, and EI_{30} is the rainfall erosivity index of a single event. k The event erosivity is defined as:

$$EI_{30} = \left(\sum_{r=1}^{0} e_r v_r\right) I_{30} \quad (2)$$

where e_r is the unit rainfall energy (MJ ha^{-1} mm^{-1}), and the v_r is the rainfall volume (mm) during a time period r. I_{30} is the maximum rainfall intensity during a period of 30 minutes in the event (mmh^{-1}). The unit rainfall energy is calculated for each time interval as follows:

$$e_r = 0.29[1-0.72\exp(-0.05 i_r)] \quad (3)$$

where i_r is the rainfall intensity during the time interval (mmh^{-1}).

An erosive event was identified using the modified criteria proposed by Meusburger et al. (2012) which was basing on the criteria given by Renard et al. (1997): (i) the cumulative rainfall of an event should be greater than 12.7 mm; or (ii) the event has at least one peak that is greater than 8.47 mm in 20 minutes and (iii) a rainfall-period of less than 1.27 mm in 6 h is used to divide a longer storm period into two separate storm events.

2.3.2. Estimation of MUSLE R-factor in sub-watershed

Model 1. Zhang et al. (2002) developed a daily model to estimate the R-factor in China. The annual R-factor was derived from aggregation of the half-month R-factor as follows:

$$M_i = \alpha \sum_{j=1}^{k} \left(D_j\right)^{\beta} \quad (4)$$

where M_i is the half-month R-factor (MJ mm ha^{-1} h^{-1}), and D_j is the erosive rainfall for day j in one half-month. D_j is equal to the actual rainfall, if the actual rainfall is greater than 12.7 mm. Otherwise D_j is equal to zero. k is the number of days in the half-month. α and β are empirical parameters which are determined by the following regression equation:

$$\beta = 0.8363 + \frac{18.144}{\overline{P}_{d12}} + \frac{24.455}{\overline{P}_{y12}} \quad (5)$$

$$\alpha = 21.586\beta^{-7.1891} \quad (6)$$

where $\overline{P}_{d12}$ is the average daily rainfall that is larger than 12.7 mm and $\overline{P}_{y12}$ is the yearly average rainfall for days with rainfall greater than 12.7 mm.

Model 2. Yu and Rosewell (1996a) proposed a model to estimate the R-factor for the month j using daily rainfall in which the seasonal variation of parameter α was modeled parametrically using a periodic function:

$$EI_j = \alpha[1+\eta\cos(2\pi fi+\omega)]\sum_{k=1}^{N} R_k^{\beta}, \text{when} R_k > R_0 \quad (7)$$

where EI_j is the j month R-factor (MJ mm ha^{-1} h^{-1}), R_k is the daily rainfall amount, R_0 is the threshold rainfall amount (=12.7 mm), N is the number of rain days with rainfall amount in excess of R_0 in the month. The sinusoidal function with a fundamental frequency $f = \frac{1}{12}$ is used to describe the possible seasonal variation of the coefficient. α, β, and η are empirical parameters.ω is adjusted to $\frac{5}{6}\pi$ by Ning and Shi (2003) to be suitable to southwestern China. And β is determined by using the regression equation derived from China (Eq. (5)) in this study. α and η are estimated using the formula suggested by Yu and Rosewell (1996a) as follows:

$$\log\alpha = 2.11-1.57\beta \quad (8)$$

$$\eta = 0.58 + \frac{0.25P}{1000} \quad (9)$$

where P is the mean annual rainfall (mm).

Model 3. Men et al. (2008) proposed an exponential equation to estimate annual R-factor by calculating the modified Fournier index which was applied in East China:

$$R_a = \alpha F_{\text{mod}}^{\beta} \quad (10)$$

where R_a is the annual R-factor (MJ mm ha^{-1} h^{-1}), F_{mod} is the modified Fournier index which was determined by the monthly and annual rainfall as in the following formula:

$$F_{\text{mod}} = \sum_{i=1}^{12} \left(\frac{P_m^2}{P_a}\right) \quad (11)$$

α and β are empirical parameters, β was determined by using the same equation as the Eq. (5) in model 1, α was determined by the regression equation:

$$\alpha = 10^{2.124-1.495\beta+0.00214 P_{d\max}} \quad (12)$$

where $P_{d\max}$ is the maximum daily rainfall in an average year.

2.3.3. Estimation of rainfall erosivity

The monthly R-factor of the five sites with long time series, along with the Yiwanshui site with 3-year data, was estimated using the

Table 2
Evaluation of performance for three models interpreting the annual R-factor in the Xizhuang sub-watershed.

	MSDE	RMSE	R^2
Model 1 (Zhang et al., 2002)	−0.73	1456	0.90
Model 2 (Yu and Rosewell, 1996a)	−0.14	**276**	**0.97**
Model 3 (Men et al., 2008)	**−0.09**	386	0.91

Note: MSDE stands for the mean standardized errors; RMSE stand for the root-mean-squared errors; R2 stands for the coefficient of determination.

Table 3
Descriptive statistics of annual R-factor at the sites in the Kejie watershed.

Station Name	Length of time series (years)	Annual R ($MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$)			CV	Max/Min	Max/Mean
		Max	Min	Mean			
Damaidi	5	7014	3576	5118	0.33	2.0	1.4
Sangoushui	5	6961	2921	4901	0.39	2.4	1.4
Lijiasi	5	5835	2854	4533	0.28	2.0	1.3
Ganwangkeng	5	6125	2750	4566	0.33	2.2	1.3
Qingshui	5	6447	2448	4344	0.36	2.6	1.5
Xizhuang	5	4982	2474	3919	0.26	2.0	1.3
Beimiaoshuiku	41	6080	1718.9	3206.8	0.28	3.5	1.9
Baoshan	46	5127.3	1161.9	2747.7	0.31	4.4	1.9
Kejie	41	4407.5	1151.6	2488.1	0.32	3.8	1.8
Changning	46	7201.5	1556.8	3968.3	0.29	4.6	1.8
Shidian	46	4552.4	925.5	2456.7	0.30	4.9	1.9

advised daily model 2 (Yu and Rosewell, 1996a). The annual R factor was aggregated from the monthly R-factor for the 12 rainfall sites. The relationship between annual rainfall and annual R-factor at the 12 rainfall sites with 253-year datasets (3 sites with 46 y, 2sites with 41 y, 6 sites with 5 y, and 1 site with 3 y) was analyzed with the R statistical analysis package -Nonlinear Least Squares (R Core Team, 2012). The annual R-factor of Kejie and Beimiaoshuiku from 2006 to 2010 was extrapolated by using the derived relationship.

The average monthly and annual R-factor at the five sites with long-term datasets was computed by averaging the monthly or annual value from 1965 to 2010, respectively. A period of 20–25 years has been recommended as the minimum time frame for computing the average R-factor (Wischmeier and Smith, 1978). Thus the five sites with a 46 year record period (1965–2010) are sufficient to compute mean monthly and annual R-factor.

2.4. Temporal variability of R-factor analysis

A Mann-Kendall trend test (Kendall, 1975; Mann, 1945) was able to identify monotonic change trends of a time-series, and has been extensively used with environmental time series (Burn et al., 2004; Hipel and McLeod, 2005; Ma et al., 2009). For our purposes, we used it to identify the trend of annual and monthly R-factor at five sites with long-term data in our study. Calculation was carried out using the Kendall package in R statistical analysis package (R Core Team, 2012).

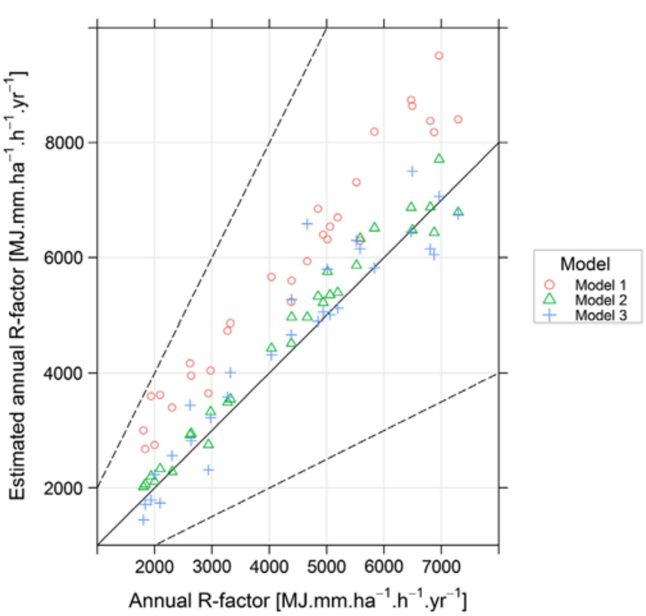

Fig. 2. Scatter plot of estimated annual R-factor from three daily models and annual R-factor (EI_{30}) at six sites in Xizhuang sub-watershed (Solid line stands for 1:1 line, and dash line stands for 1:0.5 and 1:2 lines, respectively).

2.5. Spatial rainfall erosivity mapping

The spatial distribution of R-factor was interpolated from the point R-factor. There were several techniques existing for mapping R-factor, but the accuracy of mapping depends on the interpolation method and the quality of the data. In our case, there were only 12 points available in the study area, and seven of them were mainly located in sub-watershed with area of 34.56km^2 (Fig. 1). The number of the sites and the spatial distribution were not sufficient to do simple spatial interpolation in the Kejie watershed with area of 1755 km^2. R-factor is highly correlated with the rainfall amount in the mountain area (Schonbrodt-Stitt et al., 2013). A hypothesis was assumed that there was a high correlative relationship between the annual R-factor and the elevation which was tested using the mean annual R-factor and the digital elevation model in the Kejie watershed. The spatial distribution of R-factor could be interpolated by aiding the digital elevation model of the Kejie watershed.

The cokriging method, a geo-statistical interpolation technique, was selected to interpolate the spatial map of the mean annual R-factor for it incorporates the effect of the neighboring primary data (R-factor) and the secondary data (elevation), and it makes best prediction compared to other models (Goovaerts, 1999; Hu et al., 2012). The method of cokriging was described by Goovaerts (1999) and can be found in ArcGIS Desktop Help website (http://resources.arcgis.com/en/help/main/10.1/index.html#/Understanding_cokriging). Cokriging was implemented in Geostatistical Analyst in the ESRI ArcGIS9.3 software.

Cross-validation was used to evaluate the predication of the model for there were only 12 points available in the study area (which uses all of the data) to estimate the trend and autocorrelation models, removing each data location, one at a time, and predicted the associated data value. Five summary statistics, namely the mean errors (ME), the root-mean-squared errors (RMSE), the average standard errors

Table 4
Mann-Kendall trend test of R-factor in Kejie watershed ($\alpha = 0.05$).

Site name	Recorded year	tau	2-sided *p*-value
Beimiaoshuiku	1965–2005	−0.015	0.902
Baoshan	1965–2010	0.098	0.270
Changning	1965–2010	0.092	0.373
Kejie	1965–2005	0.107	0.328
Shidian	1965–2010	0.221	0.031

Note: *tau* is the Mann-Kendall rank correlation coefficient.

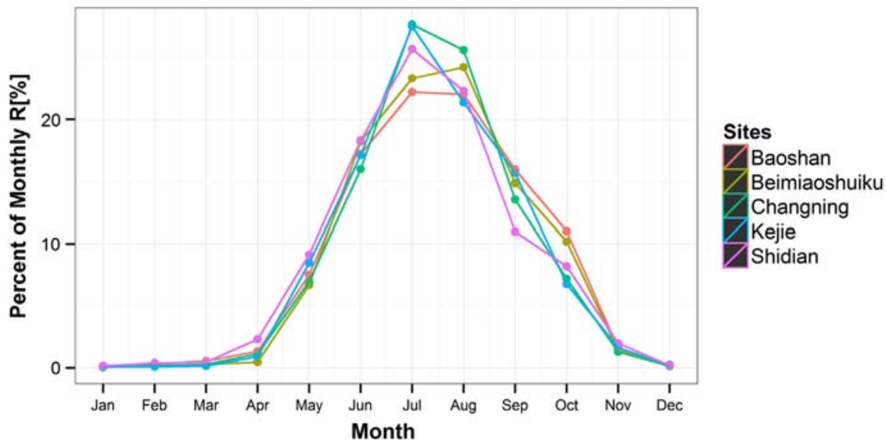

Fig. 3. Monthly contributions to the mean annual R-factor at the five sites with long-term rainfall data in the Kejie watershed (1965–2010).

(ASDE), the mean standardized errors (MSDE), and the root-mean-square standardized errors (RMSDE) described the errors of the prediction. The goal is to have the MSDE value near zero, a small RMSDE value, the ASDE value near RMSE, and the RMSDE value close to 1. The value of RMSE and ASDE show the variability of the predictions from the true values, if MSDE are close to RMSE, the variability in prediction is correctly assessed; if MSDE are greater than RMSE, the variability in prediction is overestimated; If MSDE is less than RMSE, the variability in prediction is underestimated. If RMSDE are greater than 1, the variability in prediction is underestimated; on the contrary, the variability in prediction is overestimated.

3. Results

3.1. The actual R-factor in the Xizhuang sub-watershed

According to the criteria of erosive rainfall events, a total of 1274 events were identified for the six sites. From these events, a monthly R-factor (EI_{30}) was calculated by using Eq. (1) - Eq. (3) at the six sites with 5-year rainfall data in the Xizhuang sub-watershed. Table 3 listed the statistics of annual R-factor for the six sites. The mean annual R-factors varied between 3919 and 5118 MJ.mm.ha^{-1}.h^{-1}.yr^{-1} from site to site during 1998-2002. The maximum value of 7014

Table 5
Mann-Kendall trend test of monthly rainfall erosivity in the Kejie watershed (1965–2005) ($\alpha = 0.05$).

Month	Site name	tau	2-sided *p*-value	Month	Site name	tau	2-sided *p*-value
Jan	Beimiaoshuiku	−0.094	0.463	Jul	Beimiaoshuiku	−0.068	0.537
	Kejie	−0.020	0.883		Kejie	−0.066	0.552
	Changning	0.060	0.633		Changning	−0.068	0.537
	Shidian	0.069	0.584		Shidian	0.044	0.694
	Baoshan	−0.075	0.553		Baoshan	−0.149	0.174
Feb	Beimiaoshuiku	0.059	0.644	Aug	Beimiaoshuiku	−0.110	0.317
	Kejie	0.021	0.883		Kejie	−0.004	0.982
	Changning	0.105	0.389		Changning	−0.020	0.866
	Shidian	−0.061	0.611		Shidian	0.076	0.493
	Baoshan	0.064	0.594		Baoshan	0.027	0.814
Mar	Beimiaoshuiku	0.222	0.073	Sep	Beimiaoshuiku	0.163	0.135
	Kejie	**0.268**	**0.040**		Kejie	0.133	0.225
	Changning	0.098	0.424		Changning	0.054	0.629
	Shidian	0.128	0.309		**Shidian**	**0.296**	**0.007**
	Baoshan	0.031	0.804		**Baoshan**	**0.287**	**0.009**
Apr	Beimiaoshuiku	0.053	0.684	Oct	Beimiaoshuiku	−0.066	0.551
	Kejie	0.069	0.576		Kejie	0.114	0.301
	Changning	−0.098	0.413		Changning	−0.001	1.000
	Shidian	−0.061	0.605		Shidian	0.119	0.280
	Baoshan	0.050	0.677		Baoshan	0.016	0.893
May	Beimiaoshuiku	0.185	0.102	Nov	Beimiaoshuiku	0.010	0.941
	Kejie	0.137	0.230		Kejie	−0.001	1.000
	Changning	0.139	0.211		Changning	−0.068	0.556
	Shidian	0.152	0.174		Shidian	−0.026	0.831
	Baoshan	0.120	0.290		Baoshan	−0.062	0.607
Jun	Beimiaoshuiku	−0.066	0.551	Dec	Beimiaoshuiku	−0.242	0.062
	Kejie	−0.035	0.753		**Kejie**	**−0.304**	**0.018**
	Changning	−0.085	0.438		Changning	−0.010	0.946
	Shidian	−0.012	0.919		Shidian	−0.045	0.732
	Baoshan	−0.028	0.805		Baoshan	−0.188	0.138

Note: *tau* is the Mann-Kendall rank correlation coefficient.

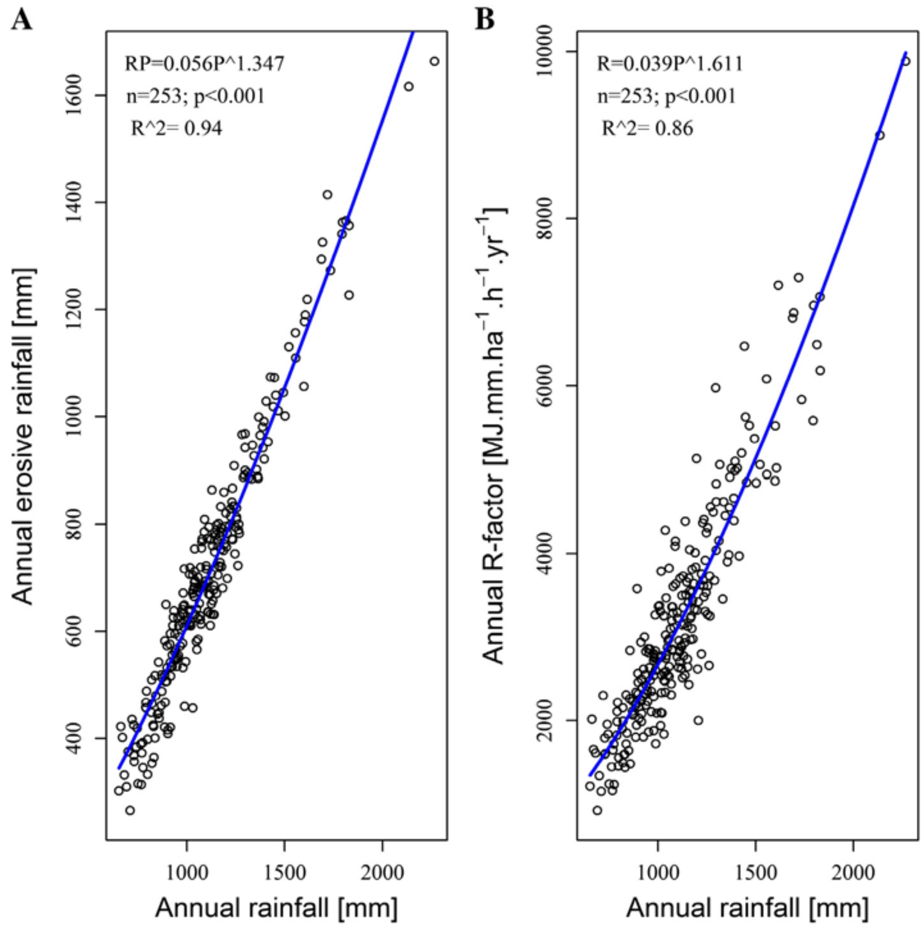

Fig. 4. The relationship between annual rainfall, annual erosive rainfall, and annual R-factor at 12 sites, utilizing a 253-year dataset (3 sites with 46 y, 2 sites with 41 y, 6 sites with 6 y, 1 sites with 3 y) in the Kejie watershed.

$MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$ was observed at the Damaidi site in 2001, and the minimum value of 2448 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$ observed at the Qingshui site in 1998. The coefficient of variation ranged between 0.26 and 0.39 during 1998–2002, the ratio of max and mean values ranged around 1.3–1.5, and the ratio of maximum and minimum values were between 2.0–2.6.

3.2. The estimated R-factor in the Kejie watershed

3.2.1. Performance of the daily models

The relationship between the annual R-factor (EI_{30}) and the annual estimated R-factor from three models at the six sites with 5-year rainfall data was shown in Fig. 2. The estimated annual values of the R-factor by 3 models were aligned with the annual EI_{30} index at the six sites. Specific to models 2 and 3, the scatter plot of the estimated annual values and annual EI_{30} at the six sites was plotted between the 1:0.5 and 1:2 lines, mostly concentrated on the 1:1 line (Fig. 2); Regarding model 1, the corresponding part was dispersed between the 1:1 and 1:2 lines, which indicated the model overestimated the annual values on the whole. The annual estimated values by daily model 2 was closer to the 1:1 line than the values estimated by daily model 3, which indicated performance of daily model 2 was better than daily model 1 and model 3.

Table 2 lists the statistical indexes for the three models in annual modeling. Both models overestimated annual rainfall erosivity (MSDE < 0.0), especially model 1(Zhang et al., 2002), and have a good explanation ($R^2 \geq 0.90$). Model 2 (Yu and Rosewell, 1996a) with advised parameters, along with model 3 (Men et al., 2008), are better than model 1 with MSDE near zero and a lower RMSE. Model 2 has the best performance with lowest value of RMSE and the highest value of R^2.

Accordingly, daily model 2 was selected to estimate both the monthly and annual R-factor in the Kejie watershed for further analyses.

3.2.2. Temporal variability of the annual R-factor

The annual mean, maximum, and minimum R-factor at the five sites with long-term rainfall data is listed in Table 3. A maximum value of 7202 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$ was observed at the Changning site in 1966, and a minimum value of 926 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$ observed at the Shidian station in 1988. The variation coefficient of annual R-factor was about 0.30 with a maximum value (0.32) at the Kejie site and minimum value (0.28) at the Beimiaoshuiku site. These were within the lower range of values in southern China (0.3–0.5) (Wang et al., 1996). The maximum value was about 4.2 times that of the minimum value, ranging from 4.9 times (Shidian) to 3.5 times (Beimiaoshuiku). The maximum value is about 1.9 times of the mean value and displayed less variation (1.8–1.9 times). All three indexes indicated low inter-annual variability of the annual R-factor.

The changing trend of the annual R-factor at the same five sites was quantified using the Mann-Kendall correlation test (Table 4). Although a slightly increasing trend was observed at the Shidian, Kejie, Baoshan and Changning sites and a slightly decreasing trend was observed at the Beimiaoshuiku site, these trends weren't significant ($\alpha = 0.05$) across the five sites, and thus we accept the null-hypothesis that there is no trend in these data over the observation period.

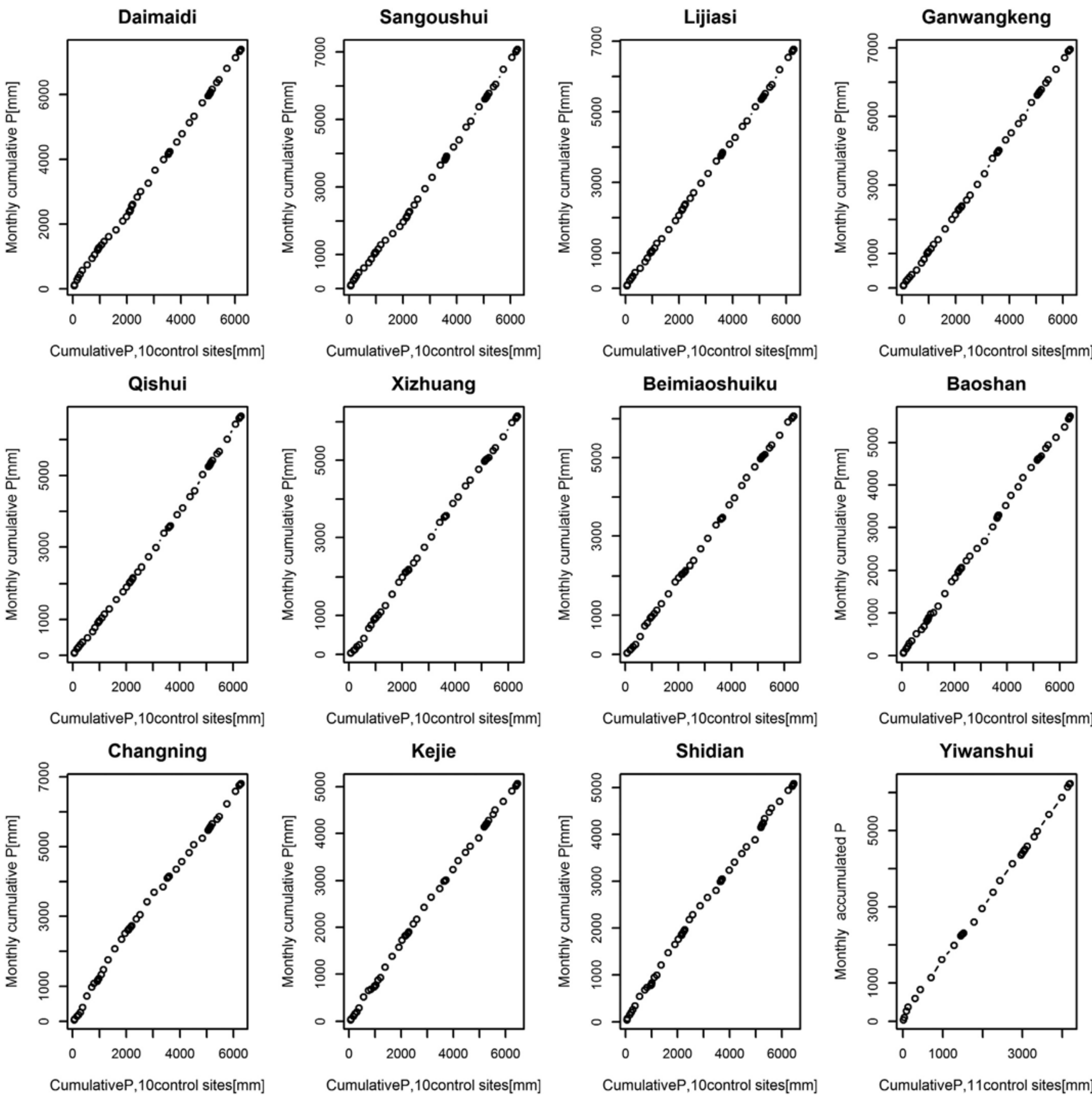

Fig. 5. The monthly rainfall cumulative mass curves between the test sites (excluding the Yiwanshui site) and the control sites over a period from January, 1998, to December, 2002. The Yiwanshui site was compared to the control sites (the other 11 sites) from January, 2000, to December, 2002, in the Kejie watershed.

3.2.3. Temporal variability of monthly R-factor

The monthly variability at the five sites with long-term rainfall data was similar(Fig. 3), with the maximum contribution in July ranging 22% to 28%, followed by August (21–26%), June (16–18%), September (11–16%), October (7–11%), May (7–9%), November (1–2%), April (1–2%), March (0.2–0.5%), February (0.1–0.4%), January and December (0.1–0.2%). About 65% of the annual R-factor was from the summer season (June–August), 26% from the autumn season (September–November), 9% from the spring season (March–May), and less than 0.5% from the winter season (December–February).

A statistically-significant increasing trend was detected in September at the Shidian and Baoshan sites, in March at the Kejie site ($\alpha = 0.05$), and a significant decreasing trend in December at the Kejie site ($\alpha = 0.05$). For other sites, the null hypothesis of no change was accepted from January to December (Table 5). The significant monotonic increasing trend of monthly rainfall R-factor in September at the Baoshan site was coincided with the changing trend of monthly rainfall in September at the Baoshan site (Ma et al., 2009).

3.3. Spatial distribution of the average annual R-factor

Daily erosive rainfall was identified according to the criteria for erosive events (Meusburger et al., 2012). A power-function relationship was tested between annual rainfall, annual erosive rainfall, and the

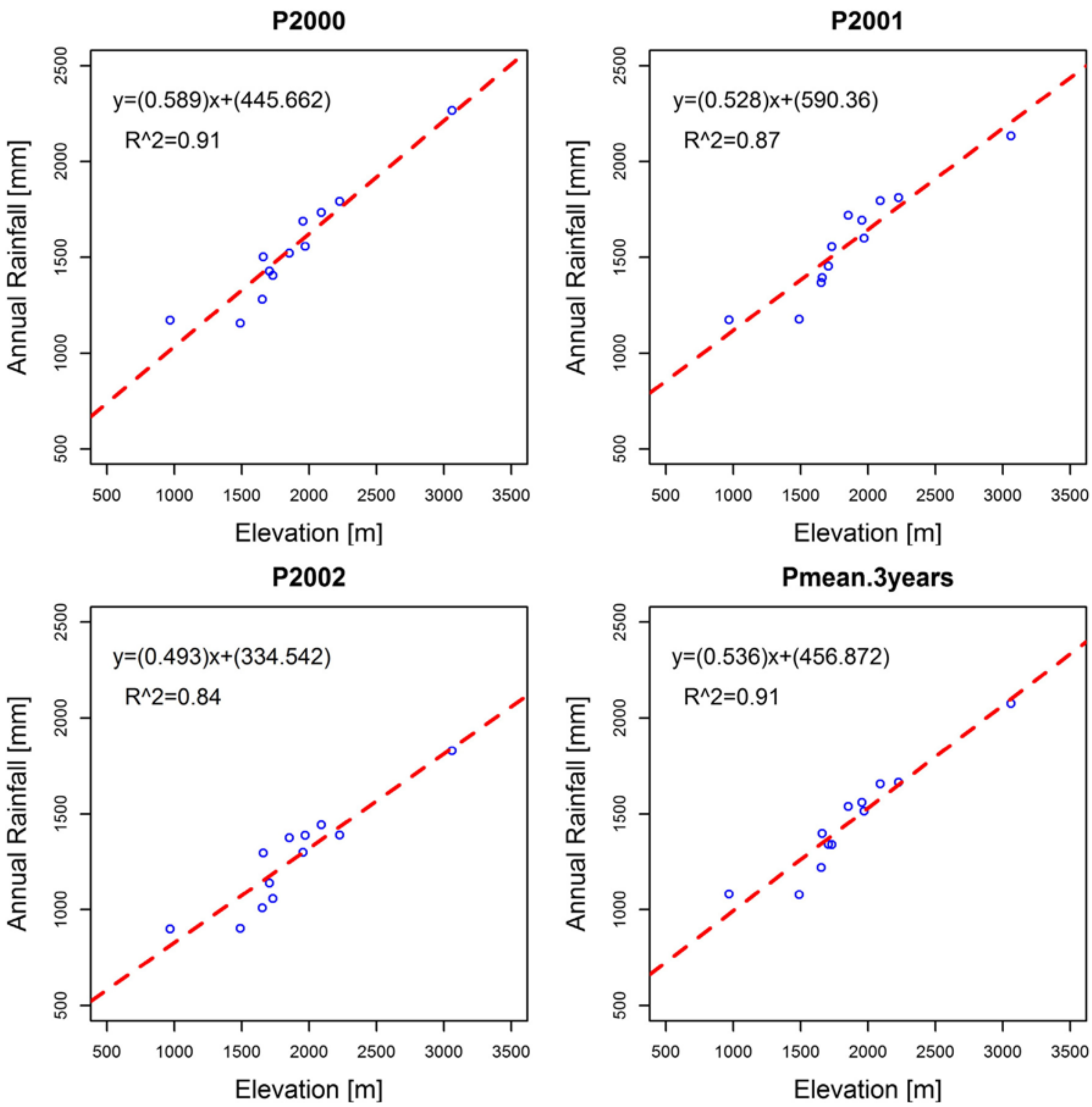

Fig. 6. The correlative relationship between the annual rainfall records and the corresponding elevation at the 12 sites in the years 2000, 2001, 2002 and over the period of 2000–2002 in the Kejie watershed.

annual R-factor in the Kejie watershed (Fig. 4). The power equation between annual rainfall and annual erosive rainfall from the 253-year dataset was:

$$RP = 0.055P^{1.348}, \quad R^2 = 0.94 \tag{13}$$

where *RP* is the annual erosive rainfall(mm), *P* is the annual rainfall (mm), and 0.055 and 1.348 are fitted parameters specific to the region.

The power equation between annual rainfall and annual R-factor from the 253-year dataset was:

$$R = 0.040P^{1.609}, \quad R^2 = 0.86 \tag{14}$$

where *R* is the annual R-factor (MJ.mm.ha^{-1}.h^{-1}.yr^{-1}), *P* is the annual rainfall(mm), and 0.040 and 1.609 are fitted parameters specific to the region.

Eq. (13) and Eq. (14) predicted annual erosive rainfall and annual R-factor with R^2 values of 0.94 and 0.86 respectively and at the statistical significant levels P < 0.001. Comparing the result from Eq. (14) with other studies, the values of α and β were close to Renard and Freimund (1994) with $\alpha = 0.048$, $\beta = 1.61$; and Yu and Rosewell (1996b) with $\alpha = 0.043$, $\beta = 1.61$. The results demonstrated Eq. (14) offered an acceptable means of estimating annual R-factor when high resolution data is not available.

During the 1965–2010 period, daily rainfall data was missing for five years at both the Kejie and Beimiaoshuiku sites. Thus the annual R-factor at these two sites from 2006 to 2010 was extrapolated using Eq. (14).

The Double Mass Curve of the monthly rainfall (Fig. 5) between the test site and the control sites illustrated the rainfall data from 12 sites was consistent. There is a high correlation between the short-term mean R-factor and long-term mean value with $R^2 = 0.84$ (Fig. 7a, 2000–2002 vs 1998–2002 at 11 sites) and $R^2 = 0.96$(Fig. 7b, 1998–2002 vs 1965–2010 at five sites), respectively. The mean annual R-factor of 1965-2010 at seven short-term sites was estimated by using the linear regression equations.

A significant linear regression between the elevation and annual rainfall records at the 12 sites over the period 2000–2002 ($R^2 = 0.84$–

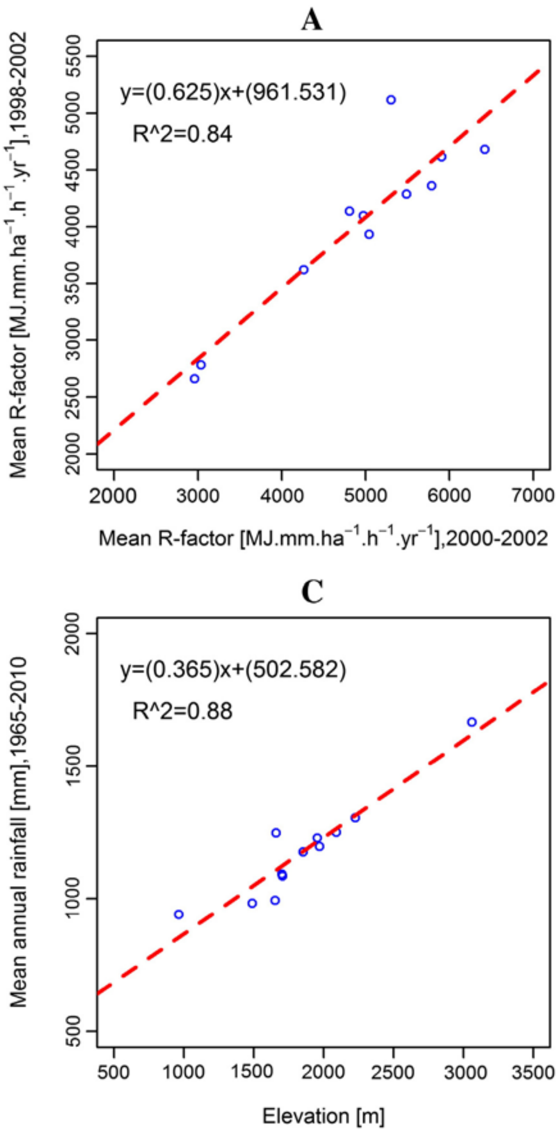

Fig. 7. The correlative relationship of the mean R-factor a) between the short-term (2000–2002) and the long-term (1998–2002) at 11 sites, and b) between the short-term (1998–2002) and the long-term (1965–2010) at 5 sites; the correlative relationship between c) the mean annual rainfall and the elevation, and d) the mean annual R-factor and the elevation at 12 sites in the Kejie watershed.

0.91, Fig. 6) was detected in the study area. It indicates there is high positive linear regression between the annual rainfall and the elevation in the Kejie watershed which was tested by Fig. 7c giving a linear regression equation between the mean rainfall and the elevation at the 12 sites with $R^2 = 0.88$ in the Kejie watershed. Fig. 7d discovered a similar relationship between the mean R-factor and the elevation at the 12 sites with $R^2 = 0.87$. The high correlative relation indicates the spatial distribution of rainfall and R-factor in the mountain area is highly influenced by the elevation.

The spatial distribution of average annual rainfall and R-factor which was produced by using cokriging method was shown in Fig. 8. The statistical indexes (Table 6) showed the value of MSDE in the prediction of R-factor and rainfall was quite less, close to zero; the value of ASDE is close to RMSE, a little greater than RMSE; and the value of RMSDE is less than 1 and close to 1. The indexes indicated the prediction error is less, and the variability in prediction is a little overestimated. So, based on these findings, the prediction from the cokriging technique is acceptable.

The mean annual rainfall map (Fig. 8a) and the mean annual R-factor map (Fig. 8b) showed a similar spatial distribution pattern. The mean value of rainfall was 1117 mm ranging from 941 to1667 mm. The mean value of R-factor was 3264 MJ.mm.ha^{-1}.h^{-1}.yr^{-1} ranging from 2505 to 5538 MJ.mm.ha^{-1}.h^{-1}.yr^{-1}. The highest values were distributed in the northwest parts followed by the southeastern parts; and the lowest values were distributed in the downstream area of the Kejie River and around the Longyang valley. According to the classes proposed by Silva (2004), the Kejie watershed has a medium, and medium-strong erosivity (criteria: 2452 to 4905 MJ.mm.ha^{-1}.h^{-1}.yr^{-1} for medium; 4905–7357 MJ.mm.ha^{-1}.h^{-1}.yr^{-1} for medium-strong).

4. Discussion

In our study, we used the RUSLE R-factor as an indicator of rainfall erosivity. The EI_{30} was an empirical equation to describe the R-factor in RUSLE which was widely used in China and other countries. The high intensity rainfall (10 min) at six sites over five years makes it possible to calculate the actual R-factor in the sub-watershed. The annual R-factor was ranging between 2474 MJ.mm.ha^{-1}.h^{-1}.yr^{-1} and 7014 MJ.mm.ha^{-1}.h^{-1}.yr^{-1} during the period 1998–2002, which showed there was medium and medium-strong rainfall erosivity in the Xizhuang sub-watershed. These R-factors are valuable for the Himalayan mountain area.

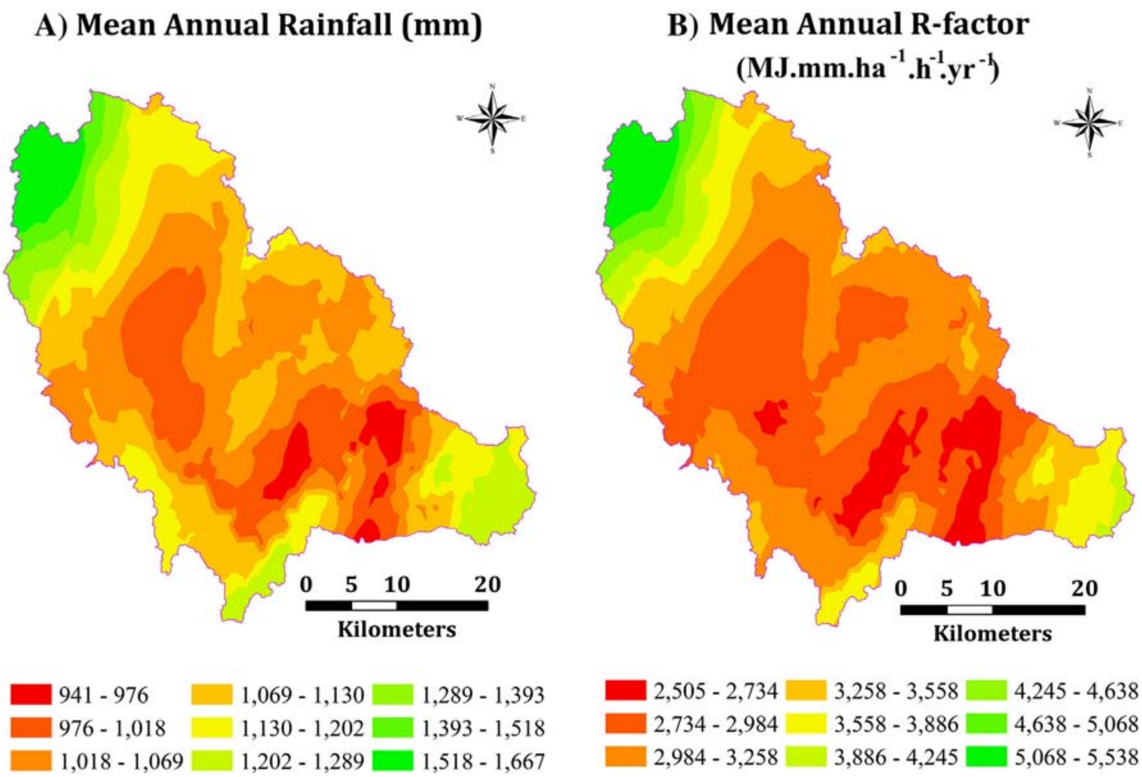

Fig. 8. Spatial distribution of mean annual rainfall and the R-factor in the Kejie watershed (1965–2010).

Because of the data constraint, many regression models were established to estimate EI_{30} worldwide which were summarized by Schonbrodt-Stitt et al. (2013). The regression models based on rainfall amount parameters or indexes gave different empirical coefficients from different places in the world. Consequently, the empirical models need to be localized. Three daily models used in Eastern China and Southwestern China were checked in our study, and the model 2 (Yu and Rosewell, 1996a) modified by Ning and Shi (2003) had the best performance with the advised β formula. The "model 2" can be used to estimate the monthly and annual R-factor in the Kejie watershed with satisfactory accuracy.

The temporary variability of monthly and annual R-factor was only analyzed at the five sites with long-term data. The five year period from 1998 to 2002 was a wetter period in terms of mean annual rainfall. The variability of annual R-factor in this same period is lower than the period of 1965 to 2010.

The simple power equation between annual rainfall and annual R-factor was derived from the estimated annual R-factor at 12 sites 253-years datasets in the Kejie watershed instead of the actual annual R-factor at six sites in the Xizhuang sub-watershed. The objective of the equation was to extrapolate the annual R-factor at the two sites (Kejie and Beimiaoshuiku) from 2006 to 2010. Meanwhile, it also can be applied to the sites where only annual rainfall data is available in the study area.

Table 6
Results of cross-validation of mapping average annual rainfall and R-factor by Cokriging in the Kejie watershed (1965–2010).

	ME	RMSE	MSDE	ASDE	RMSDE
Mean Rainfall	−32	143	−0.15	167	0.90
Mean R-factor	−65	605	−0.08	679	0.80

Note: ME stands for the mean errors; RMSE stand for the root-mean-squared errors; MSDE stands for the mean standardized errors; ASDE stands for the average standard errors; and RMSED stands for the root-mean-square standardized errors.

Unfortunately, it is a significant challenge to do spatial interpolation in the mountain areas with only sparse data available. Schonbrodt-Stitt et al. (2013) regionalized R-factor with the aid of elevation bands and the previous study results in the Xiangxi watershed. Goovaerts (1999) recommended the cokriging method to interpolate R-factor combining with the elevation from the digital elevation model. There is no further information related to elevation bands, thermal zones stratification, rainfall, and R-factor change rate in different zones in the study area, so it is difficult to apply the method recommended by Schonbrodt-Stitt. The high correlative regression equation built between the mean R-factor of 1965-2010 and the elevation (Fig. 7d) made it possible to interpolate the mean R-factor using cokriging. Meanwhile the linear regression model to predict R-factor for each pixel was not applied in our study for it cannot consider the effect from surrounding climatic sites.

During the procedure of the Cokrging, the mean R-factor was transformed to logarithm to fit the normal distribution, anisotropy was

Table 7
R-factor(MJ.mm.ha^{-1}.h^{-1}.yr^{-1}) for several locations of the Africa [a].

Country	Location	Climate[b]	R-factor	Reference
Ethiopia	Andit Tid	Cwb	5060	Haile et al. (2006)
	Anjeni	Csb	6330	
	Maybar	Cwa	4200	
Kenya	Nairobi Kabete	Cfb	3608	Moore (1979)
	Nakuru	Csb	2196	
	Narok	Csb	2621	
Zambia	Kabompo	Cwa	5120	Pauwelyn et al. (1988)
	Kabwe	Cwa	5600	
	Kafue Polder	Cwa	5250	
	Kasama	Cwa	7910	
	Mwinilunga	Cwa	8420	
	Ndola	Cwa	7980	
	Sesheke	Cwa	6553	

Note: [a] Source:Anton et al. (2010); [b] Koppen-Geiger climate codes(Peel et al., 2007).

considered, and the parameters of semivariogram (i.e. partial sill, nugget and lag size) were kept as the default value. A little adjust was done to change the number of Lags. Limited by the number of the sites, the accuracy of the interpolation map was still with some uncertainty although the evaluated indexes showing a good result. Comparing the result with the literature R-factors based on multi-year EI30 in Africa having temperate Koppen-Geiger climate (Peel et al., 2007), the range of R-factor (2505–5538 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$) in the Kejie watershed having a Cwb climate is similar to the range in Ethiopia and Kenya, and a little lower than the range in Zambia (Table 7). So this method is a good exploration exercise to get more accurate predictions based on very sparse data in the mountain areas.

5. Conclusions

The actual EI_{30} values calculated using 10-min data at the six sites with short-term dataset in the Xizhuang sub-watershed provide a background of R-factor for a Himalayan watershed. The model of Yu and Rosewell (1996a) with adjusted regression parameters was recommended to estimate the monthly and annual R-factor using daily rainfall data in the Kejie watershed, for the model yielded the best result with consistently-superior performance.

Intra-annual variation of the R-factor of the five sites with long-term dataset has clear pattern, with about 65% of the annual R-factor occurring in summer, and 26% in autumn. About 9% of annual R-factor is derived at the start of the rainy season in spring, when part of the land is bare and erosion risks are high. The highest monthly R-factor observed was in July, followed by August, June, and September, respectively.

The long-term changing trend analysis indicated there was no significant increasing or decreasing trend observed in annual R-factor series in the Kejie watershed as a whole, but an indication of an increasing trend observed in September at the Shidian and Baoshan sites, and in March at the Kejie site; as well as a decreasing trend in December at the Kejie site.

The mean annual R-factor in the Kejie watershed was in the class of medium and medium-strong erosivity according to established standards, with a mean value of 3264 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$ and a range from 2505 to 5538 $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$. The R-factor maps illustrated the potential areas prone to erosion if vegetation cover is poor. A simple power relation between the annual R-factor and the annual rainfall was established for the area. It is an acceptable means of estimating annual R-factor if high resolution data is limited. The R-factor maps and the simple power relation provided a useful tool for both land-use planning and agriculture management in the Kejie watershed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.catena.2014.05.017. These data include Google map of the most important areas described in this article.

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