Spatio-temporal Evolution Analysis of Rainfall Erosivity During 1901-2017 in Beijing, China

Yanlin Li

Northwest University

Yi He (✉ yihe@nwu.edu.cn)

Northwest University

Yaru Zhang

Northwest University

Liping Jia

Northwest University

Research Article

Keywords: Rainfall erosivity, Spatio-temporal evolution, Beijing, Soil erosion, MK trend test, R/S analysis method, Pettitt test, wavelet analysis

Posted Date: June 18th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-570992/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on August 9th, 2021. See the published version at <https://doi.org/10.1007/s11356-021-15639-y>.

Spatio-temporal evolution analysis of rainfall erosivity during 1901-2017 in Beijing, China

Yanlin Li^{1, 2, 3}, Yi He^{1, 2, 3,*}, Yaru Zhang^{1, 2, 3}, Liping Jia^{1, 2, 3}

1 Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity,
College of Urban and Environmental Sciences, Northwest University, Xi'an, 710127, China;

2 Institute of Qinling Mountains, Northwest University, Xi'an, 710127, China;

3 Yellow River Institute of Shaanxi Province, Xi'an 710127, Shaanxi, China;

*Correspondence to: yihe@nwu.edu.cn; Tel.: +86-29-8830-8342

Abstract Rainfall erosivity is regarded as one of the main factors affected soil erosion. Based on the 117 a monthly precipitation data of Beijing from 1901 to 2017, the temporal and spatial variation characteristics of rainfall erosivity in Beijing were analyzed by using Theil-Sen median analysis (Sen) and the Mann–Kendall (MK) trend test, R/S analysis method, cumulative anomaly method, MK mutation test method, Pettitt test, and wavelet analysis. The results showed that the average annual rainfall erosivity in Beijing ranged from 1080.6 to 6432.78 MJ • mm / (hm² • h • a), with an average value of 3465.06 MJ • mm / (hm² • h • a), showing a gradual decrease from southeast to northwest. In the seasonal distribution, 86% of rainfall erosivity was mainly concentrated in summer. In the past 117 years, the annual rainfall erosivity in most areas of Beijing had shown a downward trend, but its future trend also showed an increasing trend, indicating that Beijing, especially the northern part, was facing greater potential pressure of soil erosion. Through the cross validation of various methods, the abrupt change interval of rainfall erosivity in Beijing from 1901 to 2017 was from 1994 to 1997. The change of rainfall erosivity in Beijing has strong oscillation in 32 years and small periodic change in 15 and 7 years. The results will provide decision-making basis for soil erosion control and water/soil conservation planning. Additionally, they will be benefited to ensure the national agricultural and food security.

Keywords: Rainfall erosivity • Spatio-temporal evolution • Beijing • Soil erosion • MK trend test • R/S analysis method • Pettitt test • wavelet analysis

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials

The source of data used in this study is National Earth System Science Data Center, National Science & Technology Infrastructure of China. The dataset is the monthly precipitation data in China, with a spatial resolution of 0.0083333° (about 1km) and a time range of 1901.1-2017.12.

Competing interests

The authors declare that they have no competing interests or personal relationships.

Funding

This research was jointly supported by the Integrated Scientific Investigation of the North-South Transitional Zone of China (Grant No. 2017FY100904), China Postdoctoral Science Foundation (Grant No. 2018M633602), Postdoctoral Research Fund of Shaanxi Province (Grant No. 2017BSHEDZZ144), the Scientific Research Project of Education Department of Shaanxi Province (Grant No. 17JK0776) and the Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2021JQ-449).

Authors' contributions

Conceptualization—H.Y.; methodology—H.Y., and L.-Y.L.; Writing—original draft preparation, L.-Y.L.; Writing—review and editing, H.Y. All authors have read and agreed to the published version of the manuscript.

Acknowledgements

Acknowledgement for the data support from “National Earth System Science Data Center, National Science & Technology Infrastructure of China. (<http://www.geodata.cn>)”. We also would like to thank the anonymous reviewers and editors for their valuable comments and suggestions.

Spatio-temporal evolution analysis of rainfall erosivity during 1901-2017 in Beijing, China

Yanlin Li^{1, 2, 3}, Yi He^{1, 2, 3,*}, Yaru Zhang^{1, 2, 3}, Liping Jia^{1, 2, 3}

1 Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, College of Urban and Environmental Sciences, Northwest University, Xi'an, 710127, China;

2 Institute of Qinling Mountains, Northwest University, Xi'an, 710127, China;

3 Yellow River Institute of Shaanxi Province, Xi'an 710127, Shaanxi, China;

*Correspondence to: yihe@nwu.edu.cn; Tel.: +86-29-8830-8342

Abstract Rainfall erosivity is regarded as one of the main factors affected soil erosion. Based on the 117 a monthly precipitation data of Beijing from 1901 to 2017, the temporal and spatial variation characteristics of rainfall erosivity in Beijing were analyzed by using Theil-Sen median analysis (Sen) and the Mann–Kendall (MK) trend test, R/S analysis method, cumulative anomaly method, MK mutation test method, Pettitt test, and wavelet analysis. The results showed that the average annual rainfall erosivity in Beijing ranged from 1080.6 to 6432.78 MJ • mm / (hm² • h • a), with an average value of 3465.06 MJ • mm / (hm² • h • a), showing a gradual decrease from southeast to northwest. In the seasonal distribution, 86% of rainfall erosivity was mainly concentrated in summer. In the past 117 years, the annual rainfall erosivity in most areas of Beijing had shown a downward trend, but its future trend also showed an increasing trend, indicating that Beijing, especially the northern part, was facing greater potential pressure of soil erosion. Through the cross validation of various methods, the abrupt change interval of rainfall erosivity in Beijing from 1901 to 2017 was from 1994 to 1997. The change of rainfall erosivity in Beijing has strong oscillation in 32 years and small periodic change in 15 and 7 years. The results will provide decision-making basis for soil erosion control and water/soil conservation planning. Additionally, they will be benefited to ensure the national agricultural and food security.

Keywords: Rainfall erosivity • Spatio-temporal evolution • Beijing • Soil erosion • MK trend test • R/S analysis method • Pettitt test • wavelet analysis

94 Soil erosion is almost one of the most serious natural hazards which can affect
95 temporally nearly every region around the world. Soil erosion refers to the erosion of
96 the surface caused by the removal, migration and deposition of the geological parent
97 material or soil from one point on the surface due to the action of rainfall, irrigation
98 water, wind, ice or other natural and human factors (Soil Science Society of America).
99 The existence and constant acceleration of soil erosion have caused serious adverse
100 effects on the utilization of soil resources, soil fertility, soil quality, ecosystem stability
101 and sustainable development of agriculture. At the same time, they will aggravate flood
102 and waterlogging disasters, siltation of riverbed, and affect the development and
103 utilization of lakes and reservoirs. Among them, soil erosion is the most serious harm to
104 agricultural production. One potential threat currently existing in the agricultural
105 system is soil erosion, which damages the natural soil balance and results in a decline in
106 the productive potential of land, indirectly affecting the value of agricultural land, and
107 thus threatening national food security (Asfaw et al. 2020).

108 Soil erosion is a complex mechanical process that depends on the nature of the
109 soil, vegetation, ground slope, rainfall and rainfall intensity (Montgomery et al. 2007).
110 Under the background of global climate change, the soil erosion rate varies due to
111 various reasons, among which the most direct reason is the changes in rainfall erosivity
112 (Tsitsagi et al. 2018). The general soil loss equation (USLE) put forward by
113 Wischmeier and Smith (1978) and the revised USLE (Renard et al. 1991) are most
114 commonly used to calculate soil erosion rate. It is considered to be the best model to use
115 rainfall erosivity factor as the main parameter to estimate soil erosion (Kim et al.
116 2020).

117 Rainfall erosivity refers to a potential ability that caused soil erosion by rainfall. It
118 is a dynamic index for objective evaluation of soil separation and transport generated
119 by rainfall. Also, it is the dynamic source of soil erosion. Rainfall erosivity at the USLE
120 and RUSLE represents total EI_{30} , EI_{30} is the product of rainfall kinetic energy and 30
121 minutes maximum rainfall intensity (Huang et al. 2019). Although this method has
122 been widely accepted and used, it still requires high-temporal-resolution precipitation
123 data and a tedious process. Therefore, many scholars have studied and established a
124 simple algorithm to calculate rainfall erosivity. According to the different resolutions
125 of precipitation data, it is mainly based on daily rainfall (Talchabhadel et al. 2020,
126 Beguería et al. 2018, Liu et al. 2020), monthly rainfall (Vantas et al. 2020, Plangoen et

al. 2017, Panagos et al. 2017), annual rainfall (Liu et al. 2018, Petek et al. 2018) or other rainfall parameters to compute rainfall erosivity. The above calculation data of rainfall erosivity are mainly from precipitation data of meteorological stations, researchers only use the appropriate interpolation method to obtain complete precipitation data.

At present, most of the calculated data of rainfall erosivity mainly comes from meteorological sites with short time series, while with long time series of high resolution remote sensing data to calculate the rainfall erosivity relatively few, the main data used in this paper is the long time series of 1 km high-resolution monthly precipitation data. Compared with the data from meteorological stations, it has a higher spatial resolution and a longer time series, so its accuracy in calculating rainfall erosivity in regions, understanding spatio-temporal variability and determining areas vulnerable to rainfall erosivity will be greatly improved.

In China, there are few studies on rainfall erosivity, especially in Northeast and North China. Beijing is located in North China. As the administrative center and economic center of China, the population density of Beijing is comparatively higher than that of other surrounding areas; meanwhile, the social and economic development is rapid. Beijing is mountainous in the northwest and plain in the southeast, with heavy rainfall and serious soil erosion problems; therefore, the rainfall distribution in Beijing is uneven, and the temporal and spatial evolution of rainfall erosivity will also show certain rules. In addition, due to the influence of thermal dynamic factors and other factors, drought and flood disasters occur frequently in Beijing. Accordingly, the study of rainfall erosivity in Beijing from 1901 to 2017 can supply a theoretical reference for the comprehensive protection and management of soil erosion, and then have a profoundly impact on the ecosystem balance of Beijing.

The objective of this research was to (i) calculate the rainfall erosivity by using the monthly precipitation data to analyze the spatio-temporal differences and Hurst index of rainfall erosivity in Beijing from 1901 to 2017; (ii) use Sen and the MK trend method to analyze the variation trend of rainfall erosivity in Beijing; (iii) determine the abrupt transition point of rainfall erosivity in Beijing City by Multiple mutation detection methods; (iv) employ wavelet analysis to calculate the periodic change of rainfall erosivity in Beijing.

2 Materials and methods

2.1 Regional setting

The research area covers the whole city of Beijing, with an area of 16410.54 km², is situated at 115.7°-117.4°E, 39.4°-41.6°N; and is seated in the north of the North China Plain, contiguous to Tianjin in the East and Hebei Province in the rest (General situation of Beijing from Beijing Municipal People's government). The topography of Beijing is high in the West and low in the southeast. Beijing is Xishan Mountain in the southwest, and Jundu Mountain belongs to Yanshan Mountain in the north and northwest. Beijing is a semi humid and semi-arid monsoon climate in warm temperate zone. The frost free period of the whole year is 180-200 days, and the western mountainous area is short (Xu et al. 2006). The distribution of precipitation season is not average. The annual average rainfall is 520.11 mm (1901-2017). According to the spatial distribution of rainfall, the spatial and temporal differences are large. The soil types of Beijing are complex, mainly brown soil, which has obvious regional distribution law.

Fig. 1 Sketch of the study area

2.2 Monthly precipitation data

The source of data used in this study is National Earth System Science Data Center, National Science & Technology Infrastructure of China. The dataset is the monthly precipitation data in China, with a spatial resolution of 0.0083333° (about 1km) and a time range of 1901.1-2017.12. The data is a long-term series of monthly

precipitation data generated in China through the Delta spatial scaling scheme, according to the global 0.5° climate data released by CRU and the global high-resolution climate data released by WorldClim. The Delta space scale reduction scheme was used to generate the scale reduction in China. The data from 496 independent meteorological observation points are verified, and the verification results are reliable. The precipitation unit is 0.1 mm. We used ArcGIS to cut out the monthly precipitation data of Beijing, and used raster calculator to calculate the annual rainfall erosivity of Beijing from 1901 to 2017 (<http://www.geodata.cn>) (Peng et al. 2019).

2.3 Calculation and analysis method

2.3.1 Rainfall erosivity calculation method

Xu et al. (2007) extracted the starting and ending time and accumulated rainfall of erosive rainfall period, then calculated the rainfall intensity of each period, the maximum 30min rainfall of this rainfall and the secondary rainfall, and further calculated the corresponding daily, monthly and annual rainfall. A total of 2894 erosive rainfalls were extracted from 10 hydrological stations during the 25 years from 1980 to 2004. The number of erosive rainfalls varied from 234 to 368 in each station. These data are then used in the calculation of EI_{30} .

Station	Data used to build a simple model		
	longitude	latitude	Number of erosive rainfall
Yanchi	115.88°E	40.03°N	276
Fanzipai	116.88°E	40.73°N	266
Fengheyang	116.68°E	39.60°N	251
LuGou Bridge	116.22°E	39.87°N	296
Puwa	115.50°E	39.73°N	276
suzhuang	116.75°E	40.07°N	345
Tongxian	116.65°E	39.93°N	368
Yulinzhuang	116.78°E	39.80°N	308
Nangezhuang	116.40°E	39.50°N	234
Sanjiadian	116.10°E	39.97°N	274

Table 1 longitude and latitude and erosive rainfall frequency of 10 hydrological stations

$$R_{\text{time}} = EI_{30} \quad (1)$$

$$R = \sum_{r=1}^n (e_r \cdot P_r) \quad (2)$$

$$e_r = 0.29[1 - 0.72\text{Exp}(-0.054i_r)] \quad (3)$$

$$R_{\text{day}} = E' \cdot I_{30} \quad (4)$$

where: R —rainfall erosivity index ($\text{MJ} \cdot \text{mm} / (\text{hm}^2 \cdot \text{h})$); I_{30} —Maximum 30 min rainfall intensity (mm / h), E —total kinetic energy of rainfall (MJ/hm^2), i_r —breakpoint rainfall intensity (mm / h) in the r period of a rainfall process, which can be divided into n periods, —rainfall in the r period (mm), e_r —unit rainfall kinetic energy in the r period ($\text{MJ} / (\text{hm}^2 \cdot \text{mm})$). E' — the total kinetic energy of a day's rainfall (MJ / hm^2), which is a part of the total kinetic energy of a rainfall.

The simple formula was established in the form of power function. Based on the daily, monthly and annual EI_{30} values calculated at Fanzipai, Lugou Bridge, Yanchi, Puwa and Fengheying stations and the daily rainfall, monthly rainfall and annual rainfall, the simple estimation formulas of daily, monthly and annual rainfall erosivity are established as follows:

$$R_{\text{day}} = 1.38P^{1.453} \quad R^2 = 0.72 \quad (5)$$

$$R_{\text{month}} = 0.689P^{1.474} \quad R^2 = 0.72 \quad (6)$$

$$R_{\text{year}} = 0.440P^{1.463} \quad R^2 = 0.58 \quad (7)$$

The coefficient of determination of daily rainfall model and monthly rainfall model was 0.72, and the coefficient of determination of annual rainfall was 0.58. As the monthly rainfall data is used in this paper, the monthly rainfall model was adopted.

2.3.2 Theil-Sen median analysis and the Mann–Kendall trend test

Theil-Sen median trend analysis (Sen, 1968) linked with the Mann-Kendall test (Mann, 1945; Kendall, 1975) have been widely used to analyze the temporal variation of temporal trends of hydrological data (Qiao et al. 2020).

Theil-Sen Median method, also known as Sen Slope estimation method, is a trend calculation method that is used in non-parametric statistics. This method has high computational efficiency and is often used in trend analysis of hydrological elements of long time series data.

$$\beta = \text{mean} \left(\frac{x_j - x_i}{j - i} \right), \quad \forall j > i \quad (8)$$

Where: x_j and x_i are time series data. $\beta > 0$ indicates that it shows an upward trend in time series, $\beta < 0$ otherwise.

Mann-Kendall trend test (Huang et al. 2013) is a non-parametric statistical test method, which was first proposed by Mann in 1945 and has been widely used in the trend test of long time series data. Define the standardized test statistic Z .

At a given significance level α , if $|Z| > Z_{1-\alpha/2}$, the hypothesis showing no trend is rejected, and the time series data show significant trend changes. $Z_{1-\alpha/2}$ is the value corresponding to the distribution table of the standard normal function at the confidence level Z . When $|Z|$ is greater than 1.65, 1.96, and 2.58, it means that the trend has passed the significance test with reliability of 90%, 95% and 99%, respectively.

2.3.3 R/S analysis method

The R/S analysis method (Li et al. 2017) can be used to calculate The H signified by Hurst, and to qualitatively describe the sustainability of the future variation trend of time series. R/S method has a strong ability to predict the future development trend of time series. H is the Hurst index.

When $H = 0.5$, the time series is an independent process, showing no evident correlation with the future and the past; when $0 < H < 0.5$, it suggests that the trend of the future change of time series is anti-continuous with the past, and will be opposite to the past change trend. The smaller the value of H is, the stronger the anti-persistence is. Among them, $0.2 \leq H < 0.25$, $0 < H < 0.2$ respectively represent strong and strong anti-persistence.

Combined with the results of Mann-Kendall trend test and Hurst index analysis, the variation characteristics of long series climate data can be found and the future trend can be predicted.

Specific algorithm can refer to this article (Liu et al. 2018). In this paper, the methods were realized by MATLAB.

2.3.4 The cumulative anomaly method

The cumulative anomaly method (Duan et al. 2018) is a common method to judge the trend of change directly from the curve. The cumulative anomaly curve shows an upward trend, indicating that the anomaly value increases, while a downward trend indicates that the anomaly value decreases. For a sequence x , the cumulative anomaly of t at a certain time can be expressed as:

$$\hat{x} = \sum_{i=1}^t (x_i - \bar{x}) \quad (t = 1, 2, \dots, n) \quad (9)$$

Among them,

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (10)$$

According to the fluctuation of the curve, the long-term evolution trend of the time series and the approximate time of the abrupt change can be judged (Jiang et al. 2020). This method can be used to determine the characteristics of intra-annual variation of rainfall.

2.3.5 Manner-Kendall Mutation test

The MK test (He et al. 2013) is a climate diagnosis and prediction technology. It can be used to find if there is a climate mutation point in the climate sequence. If there is, the time of the mutation can be detected.

Analyze and draw out the UF and UB curve. If the value of $UF > 0$, it makes clear that the time sequence shows an upward trend; if the value of $UF < 0$, it shows that the time sequence represents a downward trend. When the value exceeds a critical line, they indicate a significant change trend. If there is an intersection point between UF and UB curves, and the intersection point is between the critical lines, then the start time of mutation is the time corresponding to the intersection point.

2.3.6 Pettitt test

The nonparametric Pettitt test was applied to ascertain the change point in the rainfall erosivity data (Du et al. 2020). It is a test based on rank sum and no distribution, which is used to find the significant changes of a time series mean when the exact time of changes is unsure (He et al. 2015).

If $p < \alpha$, x is regarded as a prominent change point at the significance level α . The Pettitt test has been widely used to estimate change points in the climatic and hydrological time series.

2.3.7 Wavelet analysis

Wavelet analysis is a kind of analysis method proposed by geologist Morlet in the 1980s, which can localize in both time domain and frequency domain at the same time (Ling et al. 2021). This method is known as "mathematical microscope" in academic circles (Salamalikis et al. 2016). Because it can reflect the periodic oscillation and multiple change periods of research variables in the time series. Wavelet analysis gives the change scales of Hydro meteorological elements in different levels of time series, and the periodicity of multiple time scales of rainfall

time series can be identified by wavelet coefficient analysis. In this paper, wavelet analysis is used to detect the periodic variation of rainfall erosivity in Beijing.

3 Results

3.1 Spatio-temporal changes of rainfall erosivity

3.1.1 Annual changes of rainfall erosivity

Results for average annual rainfall erosivity were presented in Fig. 2. The average annual rainfall erosivity from 1080.6 to 6432.78 MJ•mm / (hm²•h•a), and the multi-year average rainfall erosivity was 3465.06 MJ•mm / (hm²•h•a). The original statistical results indicated that the annual rainfall erosivity in Beijing had obvious oscillation and the high / low values were distributed in phases, which are related to the characteristics of rainfall change in Beijing. From the results of 5-year sliding average rainfall erosivity, the rainfall erosivity in Beijing presented the characteristics of fluctuation. It can be found that the average rainfall erosivity of Beijing had been declining since 1995.

Fig. 2 1901-2017 average annual rainfall erosivity and 5-year moving average annual rainfall erosivity

3.1.2 Spatial variation in rainfall erosivity

Results for average annual rainfall erosivity were shown in Fig. 3 from 1901 to 2017. It appeared that the average annual rainfall erosivity in province ranged from 2518.49 to 4602.93 MJ•mm / (hm²•h•a), with an average value of 3462.31 MJ•mm / (hm²•h•a). It was not difficult to find that the variation of the average rainfall erosivity in Beijing had a trend of gradual increase from northwest to southeast, showing an

obvious gradient. It indicated that there were obvious spatial variations of rainfall erosivity in Beijing. The research results of Jiao et al. (2020) showed that with the rapid development of urbanization in Beijing, the total amount of urban precipitation was on the rise and tended to be more extreme. The distribution of population density in Beijing is similar to that of rainfall erosivity: the population in the southeast is more than that in the northwest, mainly concentrated in Xicheng District and Dongcheng District. These two aspects confirmed the impact of human activities on climate and environment.

Fig. 3 Distribution of average annual rainfall erosivity

3.1.3 Seasonal variation of Rainfall Erosivity in Beijing

In order to analyze the annual variation of rainfall erosivity in Beijing more objectively, this study explored the annual rainfall erosivity in different seasons and makes a comparative analysis of them. On the basis of the geographical location, the climate of Beijing is a typical warm temperate semi humid continental monsoon climate. Tropical ocean air mass and polar continental air mass control and compete with each other in turn there. In spring, the cold and warm air activities are frequent, the temperature is changeable, and the daily range is large, so it is easy to have gale and dust weather; in summer, it is hot and rainy, which is the season of thunderstorm,

gale, heavy precipitation and other convective weather; in autumn, it is sunny and less rain, comfortable and pleasant; in winter, it is cold and dry, windy and less snow. The study season is divided into spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February).

It can be known from fig. 4 that the spatio-temporal distribution of rainfall erosivity in different seasons was quite different. 86% of the rainfall erosivity in Beijing was concentrated in summer, ranging from 1992.84 to 4152.47 MJ • mm / (hm² • h • a), and its spatial distribution was similar to that of the average rainfall erosivity in Beijing.

The range of rainfall erosivity in spring was 124.45 to 424.46 MJ • mm / (hm² • h • a), and the rainfall erosivity in the whole province was generally low, including the eastern and central parts of Beijing, and the areas of Jundu mountain and Xishan Mountain in the West were relatively high.

Rainfall erosivity in autumn is 206.25 to 448.35 MJ • mm / (hm² • h • a), which was close to that in spring, but there were differences in spatial distribution. In autumn, the rainfall erosivity in the north and west of Beijing was higher than that in the south. The warm and humid air in the southeast was uplifted by the Yanshan Mountain and Taihang Mountain, and formed a rain-bearing area on the windward slope and a rain-less area on the leeward slope. Therefore, the spatial distribution feature of rainfall erosivity was formed.

Compared with other seasons, the value of rainfall erosivity was the lowest in winter. The high value area was located in the urban area, where it can be saw that the urban heat island effect had a certain impact on the rainfall, so the rainfall erosivity was relatively high.

Fig. 4 Seasonal distribution of average annual rainfall erosivity

3.2 Time series analysis for rainfall erosivity

Sen, the MK trend test, and Hurst index were adopted to explore temporal evolution of rainfall erosivity.

3.2.1 Annual trends of rainfall erosivity

The variation trend results of rainfall erosivity in Beijing were displayed in the Fig. 5. In general, the rainfall erosivity of Beijing from 1901 to 2017 showed a downward trend characteristic. The rainfall erosivity in Beijing showed a decreasing trend in different degrees, and the decreasing trend in the East was more obvious than that in the west. This phenomenon benefited from the improvement of environmental quality caused by the management measures of the government and the promoting of people's comprehensive quality.

Fig. 5 Sen and MK trend test result of annual rainfall erosivity

3.2.2 Future trends of rainfall erosivity

The future trend of rainfall erosivity in Beijing from 1901 to 2017 was studied by RS analysis method, Fig. 6 showed that the Hurst index presented an obvious gradient from south to north. According to the principle and method, when Hurst index is at $0 < H \leq 0.25$, it means that the trend of future change of time series is anti-continuous with that of the past and will be opposite to the trend of the past. It was shown on the picture that Hurst index was between 0.17 and 0.24, it indicated that the change of rainfall erosivity in Beijing showed a trend contrary to the past. Combined to the results obtained by Sen and the MK trend test, the rainfall erosivity in Beijing showed an increasing trend. Therefore, relevant departments should take preventive measures to reduce the harm of social and economic problems caused by too much rainfall erosivity.

Fig. 6 Hurst index from 1901-2017

3.3 Abrupt changes analysis of rainfall erosivity

MK mutation test combined with cumulative anomaly method was mainly used to determine the abrupt transition point of rainfall erosivity in Beijing.

In the analysis of the change process of rainfall erosive accumulation anomaly curve (Fig. 7), the fluctuating rising stages were as follows: 1907-1917, 1921-1925, 1945-1979, 1993-1996, 2015-2017. The fluctuating decreasing stages as follows: 1901-1907, 1917-1921, 1925-1945, 1979-1984, 1996-2015. The rest stages show fluctuation state and the trend change was not obvious. Therefore, it can be inferred that 1907, 1917, 1921, 1925, 1945, 1979, 1996, 2015 may become the abrupt transition point.

Fig. 7 The results of cumulative anomaly method

The mutation point of rainfall erosivity was further examined by MK mutation test. The MK mutation test curve was shown in the Fig. 8. Analysis of statistical results showed that most of UF and UB statistical magnitude did not exceed the critical value. Accordingly, the trend change of rainfall erosivity in Beijing was not evident. From the MK mutation test curve we can get, the UF and UB statistical magnitude intersect in 1902 and 1994.

Fig. 8 The results of MK mutation test

The absolute value of the intersection point obtained by MK mutation test was less than 1.96, which didn't pass the significance level test of 0.05, indicating that there wasn't significant mutation point or mutation interval in the inter annual variation of rainfall erosivity in Beijing.

In order to further determine whether the rainfall erosivity in Beijing was mutated, the Pettitt test was adopted. The following fig. 9 showed the test results of Pettitt test. The conclusion can be drawn from the figure was that the abrupt change of Rainfall Erosivity in Beijing from 1901 to 2017 occurred in 1997, and passed the significance test of 0.05.

Fig. 9 The test results of Pettitt test

From the results of the three, there was no common mutation point, indicating that there wasn't significant mutation point in the inter annual variation of rainfall erosivity in Beijing. However, from the common points of the three, it can be concluded that the abrupt change range of rainfall erosivity in Beijing from 1901 to 2017 was from 1994 to 1997.

3.4 Periodic analysis

In order to better study the evolution characteristics of rainfall erosivity in Beijing, we used wavelet analysis to detect its periodic variation. From the wavelet variance diagram (Fig. 10), it can be found that there were three peaks, which corresponded to the time scales of 7 years, 15 years and 32 years respectively. Among them, the largest peak value corresponds to the 32 year time scale, which indicated that the cycle oscillation was the strongest on the 32 year time scale, and it was the first main cycle of rainfall erosivity in Beijing; the second and third peaks corresponded to 15 years and 7 years, which were the second and third main cycles respectively. The fluctuation of the above three periods controlled the variation characteristics of annual rainfall erosivity in the whole time domain in Beijing.

Fig. 10 Wavelet Variogram

4 Discussions

4.1 Correction of El Niño and La Niña events with rainfall erosivity

First of all, according to the (El Niño/La Niña criterion), we determined all El Niño and La Niña events from 1901 to 2017, as well as the duration of time, and calculated the size of rainfall erosivity in the corresponding period, as well as the value of rainfall erosivity in non El Nino and La Nina events, as shown in the following table (Table 2). This paper studied the correlation between El Niño/La Niña events and rainfall erosivity in Beijing. In the correlation analysis, the relative changes of annual average rainfall erosivity in Beijing and El Niño/La Niña events were analyzed by comparison.

As can be seen from the table below, the average annual rainfall erosivity during El Niño events was $178.09 \text{ MJ} \cdot \text{mm} / (\text{hm}^2 \cdot \text{h} \cdot \text{a})$, the average annual rainfall erosivity during La Niña events was $294.18 \text{ MJ} \cdot \text{mm} / (\text{hm}^2 \cdot \text{h} \cdot \text{a})$, the non El Niño/La Niña

456 events was 302.62 MJ•mm / (hm²•h•a), the El Niño/La Niña events was 230.77 MJ•
457 mm / (hm²•h•a), and the erosivity of annual average rainfall was 288.53 MJ•mm /
458 (hm²•h•a). The rainfall erosivity in the case of El Niño/La Niña events was greater
459 than that in the case of El Niño events and lower than that in the case of non El
460 Niño/La Niña events. However, in the case of non El Niño/La Niña events, the
461 rainfall erosivity was greater than that in the case of La Niña events and El Niño
462 events. From the numerical variation, it can be summarized that the range of rainfall
463 erosivity between El Niño/La Niña events was no obvious pattern. The influence of
464 cold and hot events formed by El Niño/La Niña events on rainfall and rainfall
465 erosivity in Beijing did not show strong regularity. ENSO and rainfall erosivity in
466 Beijing were not stable. El Niño events did not strictly correspond to high values
467 whereas La Niña event did not strictly correspond to a low value.

number	El Niño/La Niña	time	time span	Average monthly rainfall erosivity	number	El Niño/La Niña	time	time span	Average monthly rainfall erosivity
1	El Niño	1902.6-1903.3	10	96.04	25	La Niña	1970.7-1972.1	19	319.36
2	La Niña	1903.11-1904.4	6	181.99	26	El Niño	1972.6-1973.3	10	197.82
3	El Niño	1905.5-1906.3	11	224.50	27	La Niña	1973.5-1974.7	15	523.42
4	La Niña	1909.6-1911.6	25	297.02	28	La Niña	1975.3-1976.3	13	204.22
5	El Niño	1911.11-1912.4	6	10.92	29	El Niño	1976.9-1977.2	6	50.68
6	La Niña	1916.7-1917.3	9	231.11	30	El Niño	1977.10-1978.2	5	41.41
7	La Niña	1917.12-1918.4	5	15.38	31	El Niño	1982.5-1983.6	14	287.83
8	El Niño	1918.10-1919.6	9	63.63	32	La Niña	1983.9-1984.2	6	37.35
9	La Niña	1924.5-1924.9	5	1126.24	33	La Niña	1984.10-1985.7	10	291.04
10	El Niño	1925.7-1926.7	13	445.87	34	El Niño	1986.9-1988.1	17	237.72
11	El Niño	1930.7-1931.5	11	266.79	35	La Niña	1988.5-1989.6	14	319.35
12	La Niña	1933.6-1934.3	10	315.02	36	El Niño	1991.10-1992.6	9	56.05
13	La Niña	1938.10-1939.3	6	19.03	37	El Niño	1994.10-1995.2	5	5.72
14	El Niño	1940.11-1942.2	14	138.90	38	El Niño	1997.5-1998.5	13	182.55
15	La Niña	1942.6-1943.4	11	321.73	39	La Niña	1998.7-2000.7	25	234.14
16	La Niña	1945.6-1945.10	5	554.36	40	La Niña	2000.10-2001.2	5	19.14
17	La Niña	1949.9-1951.3	19	276.10	41	El Niño	2002.6-2003.2	9	204.20
18	El Niño	1951.7-1951.12	6	249.60	42	El Niño	2004.8-2005.1	6	182.26
19	La Niña	1954.5-1957.1	33	462.51	43	El Niño	2006.9-2007.1	5	18.15
20	El Niño	1957.6-1958.3	10	324.16	44	La Niña	2007.8-2008.5	10	123.20
21	El Niño	1963.7-1964.2	8	429.41	45	El Niño	2009.7-2010.4	10	189.88
22	La Niña	1964.3-1965.1	10	563.74	46	La Niña	2010.6-2011.5	12	213.04
23	El Niño	1965.7-1966.4	10	207.15	47	La Niña	2011.8-2012.2	7	117.56
24	El Niño	1968.11-1969.3	5	10.68	48	El Niño	2015.4-2016.4	13	189.00
Overall average monthly erosivity El Niño				178.09	Overall average monthly erosivity Non-ENSO				302.62
Overall average monthly erosivity La Niña				294.18	Overall average monthly erosivity 1901–2017				288.53

Table 2 Average monthly rainfall erosivity for El Niño/La Niña events from 1901 to 2017

4.2 Comparison with previous studies

The data used in this paper were monthly precipitation grid data with resolution of 1km, and the data used by previous scholars (Xu et al. 2007, Xu et al. 2007) were all the data recorded by meteorological stations, in contrast, the grid rainfall data might deviate from the data of meteorological stations, so the calculation results of the model obtained by Xu et al. (2007) might lead to the underestimation of rainfall erosivity. In order to carry out further research, comprehensive analysis should be carried out in combination with topography, land use data and other factors.

Then we will analyze the reason why the evolution of rainfall erosivity in Beijing showed this characteristic from two aspects.

On the one hand, the algorithm used to calculate rainfall erosivity only involves rainfall. From the perspective of rainfall variation characteristics in Beijing and even North China, Yang et al. (2020) concluded that the precipitation intensity showed an increasing trend in space, the temporal distribution of precipitation was more concentrated, moderate rain and heavy rain increased, but the total amount of rainfall increased by 3.2% each ten years from 1961 to 2017. Therefore, it can be used to explain why the trend of rainfall erosivity in Beijing was not obvious.

On the other hand, the change of rainfall erosivity is impacted by terrain height difference, mountain range trend, vegetation and other climate factors (Xu et al. 2007), not limited to rainfall. The single variable of rainfall was applied to describe the change of rainfall erosivity. It was unable to reflect how other factors affect rainfall erosivity and the degree of influence on rainfall erosivity in detail. There was a certain one-sided influence on the change of rainfall erosivity.

However, despite the above limitations, the results of this study can still be used as a reference for soil erosion research under climate change in the future.

4.3 Measures to deal with the influence of rainfall erosivity on soil erosion

Compared with other static factors, rainfall erosivity can show the potential changes of soil erosion more dynamically (Zhong et al. 2015). Therefore, this paper mainly studied the spatial and temporal evolution mechanism of rainfall erosion in

Beijing and its trend change regular pattern. The results showed that the distribution of rainfall erosion power in Beijing was very unbalanced. Although it has declined in recent years, there are still rising risks in the future. Therefore, we have put forward some suggestions for reducing rainfall erosivity, coping with extreme climate change, weakening soil erosion and improving the quality of living environment.

First of all, it is necessary to carry out ecological greening, especially for the densely populated urban areas with relatively high rainfall erosivity and high degree of urbanization. It is necessary to expand the green area and strengthen the construction of sponge city to prevent urban waterlogging. Second, it is necessary to strengthen the slope management to prevent the occurrence of debris flow and landslide in the northern mountainous areas. Then, it is necessary to standardize the development of agriculture, no tillage and so on.

5 Conclusions

Beijing is the political and cultural center of China and has a dense population. Extreme rainfall in this area can lead to urban floods, landslides and debris flows in mountainous areas, as well as loss of people's lives and property, so we should attach great importance to it (zhong et al. 2017). As an important factor of soil erosion, the research on rainfall erosivity will provide scientific data support for soil erosion monitoring, soil and water conservation research and comprehensive control in Beijing. Through the study, we draw the following conclusions.

(1)The average annual rainfall erosivity ranged from 1080.6 to 6432.78 MJ•mm / (hm²•h•a), and the multi-year average rainfall erosivity was 3465.06 MJ•mm / (hm²•h•a). The rainfall erosivity fluctuated obviously, the fluctuation range had decreased in recent years, and the rainfall erosivity value had shrunk.

(2)The spatial distribution of rainfall erosion in Beijing: the rainfall erosivity in southeast was high, and the rainfall erosion in northwest was low, and it displayed a downward trend from southeast to northwest.

(3)From the perspective of seasonal change, the rainfall erosivity of Beijing was concentrated in summer and the smallest mainly occurred in winter, which was related to the rainfall characteristics of Beijing with large and concentrated rainfall and dry and less rain in winter.

(4) The trend change of rainfall erosivity in Beijing showed a decreasing trend as a whole. Combined with Hurst index, the rainfall erosivity in Beijing still had the risk of rising, so it should be prevented.

(5) Through the cross validation of various methods, the abrupt change interval of rainfall erosivity in Beijing from 1901 to 2017 was from 1994 to 1997.

(6) The change of rainfall erosivity in Beijing has strong oscillation in 32 years and small periodic change in 15 and 7 years.

(7) The influence that El Niño/La Niña events caused on rainfall and rainfall erosivity in Beijing did not show strict regularity. ENSO and rainfall erosivity in Beijing were not stable. El Niño events did not strictly correspond to high values whereas La Niña event did not strictly correspond to a low value.

References

Asfaw S, Pallante G, Palma A (2020) Distributional impacts of soil erosion on agricultural productivity and welfare in Malawi. *Ecol. Econ.* 177:106764.

Beguería S, Serrano-Notivol R, Tomas-Burguera M (2018) Computation of rainfall erosivity from daily precipitation amounts. *Sci. Total Environ.* 359:637.

Duan N, Yang GY, You JJ (2020) Temporal and spatial evolution of precipitation in Wuzhishan City in recent 60 years. *South-to-North Water Transfers and Water Science & Technology* 16:60.

Du HH, Wang YM, Wang ZZ, Liu KL, Cheng L (2020) Spatial and temporal characteristics of the daily precipitation concentration index over China from 1979 to 2015, *Hydrology Research* 51:562–582.

General situation of Beijing from Beijing Municipal People's government. Available online: <http://www.beijing.gov.cn/renwen/bjgk>.

He W, Bu RC, Xiong ZP, Hu YM (2013) Characteristics of temperature and precipitation in Northeastern China from 1961 to 2005. *Acta Ecologica Sinica* 33:0519.

He Y, Ye J, Yang X (2015) Analysis of the spatio-temporal patterns of dry and wet conditions in the Huai River basin using the standardized precipitation index. *Atmos. Res.* 166:120–128.

562 Huang J, Zhang F, Hu Z, Chen ST (2019) Climatology of rainfall erosivity during
563 1961–2012 in Jiangsu Province, southeast China. *Nat Hazards* 98:1155.

564 Huang J, Zhang JC, Zhang ZX, Xu CY (2013) Spatial and temporal variations in
565 rainfall erosivity during 1960–2005 in the Yangtze River basin. *Stoch. Env. Res. Risk*
566 *A.* 27:337.

567 Jiang Y, Xu ZX, Wang J (2020) Comparison among five methods of trend detection
568 for annual runoff series. *Shuili Xuebao* 51:845.

569 Jiao YM, Zhao N, Yue TX, Deng JY (2020) The effect of urbanization on extreme
570 climate events in Beijing. *Geographical Research* 39:461-472.

571 Kendall MG (1975) Rank Correlation Method. Charless Griffin, London.

572 Kim J, Han H, Kim B, Chen HN, Lee JH (2020) Use of a
573 high-resolution-satellite-based precipitation product in mapping continental-scale
574 rainfall erosivity: A case study of the United States. *CATENA* 193:104602.

575 Li RB, Wei P, Ji CG, Wang BQ (2017) Analysis of runoff tendency characteristics of
576 Yalong River for past 6 decades. *Yangtze River* 48:38.

577 Ling MH, Han HB, Wei XL, Lv CM (2021) Temporal and spatial distributions of
578 precipitation on the Huang-Huai-Hai Plain during 1960–2019, China. *Journal of*
579 *Water and Climate Change*.

580 Liu SY, Huang SZ, Xie YY, Leng GY (2018) Spatial-temporal changes of rainfall
581 erosivity in the loess plateau, China: Changing patterns, causes and implications.
582 *CATENA* 166:279.

583 Liu Y, Li LH, Chen X, Zhang R (2018) Temporal-spatial variations and influencing
584 factors of vegetation cover in Xinjiang from 1982 to 2013 based on
585 GIMMS-NDVI3g. *Glob Planet Change* 169:145.

586 Liu Y, Zhao WW, Liu YX, Pereira P (2020) Global rainfall erosivity changes between
587 1980 and 2017 based on an erosivity model using daily precipitation data. *CATENA*
588 194:104768.

589 Mann HB (1945) Nonparametric tests against tren. *Econometrica* 13:245.

590 Montgomery DR (2007) Soil erosion and agricultural sustainability. *PNAS*
591 104:13268.

592 Nearing MA, Yin SQ, Borrelli P (2017) Rainfall erosivity: An historical review.
 593 *CATENA* 157:357-362.

594 Panagos P, Ballabio C, Meusburger K, Spinoni J (2017) Towards estimates of future
 595 rainfall erosivity in Europe based on REDES and WorldClim datasets. *J. Hydrol.* 548:
 596 251.

597 Peng S, Ding Y, Liu W, Li Z (2019) 1 km monthly temperature and precipitation
 598 dataset for China from 1901 to 2017. *Earth Syst. Sci. Data* 11:1931.

599 Petek M, Mikos M, Bezak N (2018) Rainfall erosivity in Slovenia: Sensitivity
 600 estimation and trend detection. *Environ. Res.* 167:528.

601 Plangoen P, Udmale P (2017) Impacts of Climate Change on Rainfall Erosivity in the
 602 Huai Luang Watershed, Thailand. *Atmos.* 8:143.

603 Qiao YN, Chen H, Jiang YJ (2020) Quantifying the impacts of lithology on
 604 vegetation restoration using a random forest model in a karst trough valley, China.
 605 *Ecol. Eng.* 156:105973.

606 Renard KG, Foster GR, Weesies GA, Porter JP (1991) RUSLE: Revised universal soil
 607 loss equation. *Soil. Water. Conserv.* 46:30–33.

608 Salamalikis V, Argiriou A, Dotsika E (2016) Periodicity analysis of delta O-18 in
 609 precipitation over Central Europe: time-frequency considerations of the isotopic
 610 ‘temperature’ effect. *Journal of Hydrology* 534:150–163.

611 Sen PK (1968) Estimates of the regression coefficient based on Kendall’s tau. *Publ.*
 612 *Am. Stat. Assoc.* 63:1379.

613 Soil Science Society of America. Available online:
 614 <https://www.soils.org/publications/soils-glossary>.

615 Talchabhadel R, Nakagawa H, Kawaike K, Prajapati R (2020) Evaluating the rainfall
 616 erosivity (R-factor) from daily rainfall data: an application for assessing climate
 617 change impact on soil loss in Westrapti River basin, Nepal. *Model. Earth Syst.*
 618 *Environ.* 6:1741.

619 Tsitsagi M, Berdzenishvili A, Gugeshashvili M (2018) Spatial and temporal variations
 620 of rainfall-runoff erosivity (R) factor in Kakheti, Georgia. *Annals of Agrarian Science*
 621 16:226.

622 Vantas K, Sidiropoulos E, Loukas A (2020) Estimating Current and Future Rainfall
623 Erosivity in Greece Using Regional Climate Models and Spatial Quantile Regression
624 Forests. *Water* 12:687.

625 Wischmeier WH, Smith DD (1978) Predicting Rainfall Erosion Losses: A Guide to
626 Conservation Planning. Department of Agriculture, Science and Education
627 Administration.

628 Xu L, Xie Y, Fu SH, Liu BY, Lu BJ, Yuan AP (2007) Simple Method of Estimating
629 Rainfall Erosivity Under Different Rainfall Amount of Beijing. *Research of Soil and*
630 *Water Conservation* 14:398-402.

631 Xu ZX, Zhang L, Ruan BQ (2006) Analysis on the spatio-temporal distribution of
632 precipitation in Beijing. *Arid Land Geogr.* 29:186–192.

633 Yang RZ, Xing P, Du WP (2020) Climatic characteristics of precipitation in North
634 China from 1961 to 2017. *Scientia Geographica Sinica* 40:1573-1583.

635 Zhang YQ, Gong HL, Zhao WJ (2007) Study on Calculation Method and
636 Characteristics of Rainfall Erosivity of Beijing. *Soil and Water Conservation In China*
637 5:23-26.

638 Zhong LZ, Mu R, Zhang DL (2015) An observational analysis of warm-sector rainfall
639 characteristics associated with the 21 July 2012 Beijing extreme rainfall event. *J.*
640 *Geo-phys. Res. Atmos.* 120:3274-3291.

641