Spatial and temporal variation of precipitation characteristics in the semiarid region of Xi’an, northwest China

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ABSTRACT
Precipitation variations mostly affect the water resource planning in semi-arid regions of northwest China. The objective of this study is to quantitatively explore the spatial and temporal variations of precipitation in different time scales in Xi’an city area. The Mann–Kendall test and wavelet analysis methods were applied to analyze the precipitation variability. In terms of temporal variation of precipitation, the results indicated that the annual precipitation exhibited a significant decreasing trend during 1951–2018. Except for summer precipitation representing a slightly increasing trend, the other seasonal precipitations had a similar decreasing trend to annual precipitation throughout 1951–2018. The monthly precipitation had different change trends, showing the precipitation from June to September could account for 58.4% of the total annual precipitation. In addition, it was clear that annual precipitation had a significant periodic change, with the periods of 6, 13, 19, and 27 years. For the spatial variation of precipitation during 1961–2018, the results showed that annual and seasonal precipitation exhibited obvious spatial differences, indicating an increasing spatial trend from north to south. Thus, understanding the precipitation variation in Xi’an city can provide a theoretical foundation of future water resources management for other cities in semi-arid regions of northwest China.

Key words | Mann–Kendall test, periodicity analysis, precipitation, spatial and temporal variations, wavelet analysis, Xi’an city

HIGHLIGHTS
● There were different variation trends in annual, seasonal and monthly precipitation at a temporal scale.
● The annual precipitation in Xi’an city had a significantly increasing trend during 1951–2018.
● The annual and seasonal precipitation exhibited obvious spatial differences during 1961–2018.
● Findings could guide future water resource management and allocation of other cities in semiarid regions of northwest China.

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INTRODUCTION

Precipitation is the essential element to explore hydrological processes (Emmanuel et al. 2012), showing significant variability in terms of frequency, duration, intensity, and trend (Sang et al. 2019). As well as precipitation having significant impacts on the hydrological cycle and human life, precipitation changes may result in natural disasters, loss of biodiversity, agricultural productivity, and soil erosion change (Li et al. 2010; Sayemuzzaman & Jha 2014; Yang et al. 2017; Jiang et al. 2018). In particular, frequent precipitation extremes could cause the increase of flood hazards with the rapid development of urbanization (Nguyen et al. 2019). Precipitation has shown significant changes in many regions around the world in recent years (Jones et al. 2015; Mahmood et al. 2015; Yan et al. 2017; Yang et al. 2017; Bedaso et al. 2020; Han et al. 2020). Moreover, the spatial and temporal variability of precipitation can significantly affect runoff generation in urban catchments (Segond et al. 2007; Emmanuel et al. 2012; Zhang et al. 2012). It is important to identify its driving potential of extreme events to affect socioeconomic conditions to evaluate the spatial and temporal variation of precipitation (Sharma et al. 2020). Meanwhile, the identification of the periodic variability of precipitation is of most importance for rainfall modeling and forecasting (Sang et al. 2019). Thus, it is necessary to explore quantitatively precipitation variation characteristics in urban areas. In recent years, the periodicity, spatial and temporal characteristics of precipitation change have received wide attention from government regulators and many scholars (Li et al. 2010; Xing et al. 2015; Thomas & Prasannakumar 2016; Yang et al. 2017; Ding et al. 2019). For instance, China’s sponge city development policy was put forward to solve many urban waterlogging issues which are due to frequent extreme precipitation events (Ding et al. 2019; Ma et al. 2020). In all, it is important to systematically evaluate the spatial and temporal variations of precipitation to help us upgrade the understanding of precipitation variability.

Xi’an city was not only the site of four of the world’s ancient civilizations, but is also a large industrial city and a typical megacity in the semi-arid region in northwest China (Wang et al. 2018). Precipitation variation is potentially challenging the sustainable utilization of water resources in the semi-arid region of Xi’an. Meanwhile, with the rapid development of urbanization, the spatial and temporal variation of rainfall distribution has become uneven and significant in Xi’an (Chen et al. 2015). In addition, urban waterlogging has become an increasingly serious natural hazard under the changing environment in Xi’an city in recent years, while it has been affected by the factor of precipitation change (Wang et al. 2020). Therefore, quantitative analysis of the spatial and temporal variation of precipitation distribution can provide a good
reference for urban flood mitigation and water resource planning.

At present, some studies have evaluated the characteristics of precipitation variations in semi-arid regions of Xi’an (Liu et al. 2013; Chen et al. 2015; Jiang et al. 2016; Yang et al. 2016; Li et al. 2020; Wang et al. 2020). However, most previous studies do not systematically analyze characteristics of precipitation variations in Xi’an at both spatial and temporal scales (Liu et al. 2013; Jiang et al. 2016; Yang et al. 2016; Li et al. 2020; Wang et al. 2020). These studies have focused mainly on temporal variation of precipitation at different time scales and have ignored spatial variation of precipitation distribution. A recent study by Wei et al. (2019) analyzed the characteristics of temporal distribution and periodicity just in the urban central area of Xi’an, but the study did not systematically examine the spatial variation of precipitation for Xi’an city at a whole area scale. Moreover, a few studies have emphasized the periodicity and spatial characteristics of precipitation distribution in Xi’an city (Chen et al. 2015; Wei et al. 2019; Wang et al. 2020). Thus, a study of the spatial characteristic of precipitation distribution needs to be further strengthened in this area. It is necessary to systematically investigate the spatial and temporal variation characteristics of precipitation, providing a comprehensive perspective to understand precipitation variation characteristics in Xi’an city.

Some previous studies on precipitation variations were mainly based on data obtained from precipitation stations and meteorological stations (Wei et al. 2019; Li et al. 2020; Wang et al. 2020). However, the spatial distribution of these stations was very irregular and heavily biased towards more populated areas (Jurković & Pasarić 2013). In addition, the reliable gridded precipitation data are important for water resources management applications and flood monitoring (Salimi et al. 2019; Sharifi et al. 2019). The application of gridded precipitation datasets has created new possibilities for analyzing spatial characteristic precipitation variations (Jurković & Pasarić 2013; Duan et al. 2016). For instance, Chen et al. (2015) carried out the assessment of precipitation variations for the Guanzhong Plain (includes Xi’an) with an April–June gridded precipitation dataset for the period 1800–2009, which revealed that a gridded precipitation dataset can be better used to analyze the precipitation distribution, but it just focused on changes in monthly precipitation of Xi’an city. As mentioned above, there was still the need to investigate the spatial variation of precipitation with the gridded precipitation data in the semi-arid region of Xi’an, northwest China.

Moreover, choosing the appropriate method is of great importance to explore the spatial and temporal variation of precipitation. The statistical and graphical methods can be effectively used to detect long-term time series responses to various disturbances (Zhang et al. 2016). The Mann–Kendall test method is an important nonparametric statistical method widely used to detect the changing trend for a time series (Liang et al. 2010; Pingale et al. 2014; Han et al. 2020). The wavelet analysis method is an effective tool for examining nonstationary and multiscale time series and transient phenomena (Labat 2005). Meanwhile, the wavelet analysis method has also been used to identify periodic oscillations of object, distinguishing the multi-periodical features of a time series (Nalley et al. 2012; Hermida et al. 2015; Tian et al. 2019). In addition, ArcGIS, as a leading GIS (geographic information system) software platform, has been successfully applied to analyze and visualize gridded datasets in climatological and meteorological studies (Xu et al. 2016). Thus, it can provide a better understanding of precipitation spatial visualization with the gridded precipitation data based on ArcGIS. The above-mentioned analysis methods can provide a better advantage for the precipitation variations’ exploration in this work.

Therefore, the aim of this study is to quantitatively investigate the spatial and temporal variations of precipitation based on the employed methods in Xi’an city. The entire urban region scale was selected in this work. It will provide a guide for managing regional water resources effectively and improving the capability for urban inundation disaster prevention and mitigation. The remainder of the paper is organized as follows. Details of the study area are described in the section below. This is followed by a section providing a description of the data resources and methods, including the linear analysis, Mann–Kendall test, and wavelet analysis method. Analysis results of the spatial and temporal variation of precipitation are presented in the next section, which also provides a detailed discussion about this work. Lastly, brief conclusions of this paper are drawn in the final section.
STUDY AREA

Xi’an city is located in the hinterland of Shaanxi province in northwest China, the ninth National Central City in China. It is an important node city of the Belt and Road Initiative with an urbanization rate of 74.01% (Hu et al. 2020). As shown in Figure 1, the urban area lies between 107°30’ and 110°E and between 33°30’ and 35°N, covering a total area of approximately $1.1 \times 10^4$ km$^2$, and its southern and eastern parts are the Qinling Mountains and the Loess Plateau in the north. The terrain gradually rises from west to east, north to south, and the river flows from southeast to northwest. The urban climate is characterized by sub-humid warm temperate continental monsoon with four distinct seasons and abundant rainfall. The annual precipitation has a remarkable seasonal variability affected by the continental monsoon in Xi’an city (Bai & Wang 2014). The average annual precipitation in Xi’an city is 522.4 to 719.5 mm, with roughly 60% of it concentrated in the four months from July to October with an obvious seasonal change (Hu et al. 2020). In the past ten years, the duration of rainstorm and heavy rain has shown an increased trend, and thus the short-term heavy rainfall causes serious urban water-logging events with high frequency occurrence in Xi’an city (Wei et al. 2019). Hence, Xi’an city was selected as the case study to analyze the precipitation variations in this paper.

DATA AND METHODS

Data

The monthly precipitation from Xi’an meteorological station during 1951–2008 was obtained from the National Climate Center of China Meteorological Administration (CMA) (http://data.cma.cn/). This station was used to collect data from 1951 to 2008 as the national station. The location of the Xi’an meteorological station is shown in Figure 1. Therefore, the seasonal precipitation data and annual precipitation data were obtained from the monthly precipitation data. In order to better examine precipitation change, maintain data continuity and long-time data acquisition, it is necessary to add the numbers of annual precipitation and monthly precipitation time series data. The annual and monthly precipitation

Figure 1 | Location of the study area.
data from 2009 to 2018 could also be collected from the Shaanxi Statistical Yearbook (2009–2018) (http://tjj.shaanxi.gov.cn/tjj/ndsji/tjnj/), and this was provided by Shaanxi Provincial Bureau of Statistics (SPBS), China. Based on the above, the long-time monthly and annual precipitation data were obtained from 1951 to 2018.

Additionally, the dataset of gridded monthly precipitation in China (Version 2.0) (http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_PRE_MON_GRID_0.5.html) was adopted in this study. The gridded monthly precipitation dataset with a resolution of 0.5°×0.5° from 1961 to 2018 within Xi’an city was released by the CMA. Meanwhile, the gridded seasonal and annual precipitation data were obtained from the gridded monthly precipitation. Each grid cell contained monthly precipitation data in these grid cells’ region. The above-mentioned collected precipitation data were strictly controlled by CMA and SPBS without missing any values.

Method

In this study, we applied the Mann–Kendall test method to analyze the trends of annual, seasonal, and monthly precipitation in Xi’an city during 1951–2018, and it was also used to identify the abrupt change year of the precipitation. Then, spatial distribution of precipitation was explored in different time scales based on the spatial analysis and interpolation of ArcGIS. In addition, the wavelet analysis method was applied to better examine the periodicity of precipitation. Linear regression and Durbin–Watson (DW) test were employed to carry out linear trend analysis and check data autocorrelation, respectively.

Linear regression and Durbin–Watson test

In order to test autocorrelation of precipitation data, the DW test method can be used to check data autocorrelation in this work. Moreover, linear regression was applied to analyze trend change of variables. The general form of the linear regression equation is as follows (Yin 2020):

\[
Y = \beta_0 + \beta X + \varepsilon
\]

where \(Y\) represents response variable, \(X\) is annual precipitation data in this work; \(\omega\) represents the frequency; \(\beta_0\) represents the constant term, \(\beta\) represents the linear regression coefficient vector; \(X\) represents the independent variable, \(X\) is year in this work; \(\varepsilon\) represents a random error.

The linear regression coefficient is less than zero and greater than zero, indicating the precipitation data series decreasing and increasing linear trend. The DW test method is the most famous test for series autocorrelation (Yin 202). The DW test statistic \((d)\) is based on the residuals from a linear regression equation. The statistic \(d\) was computed as (Koseman & Bamgboy 2021):

\[
d = \frac{\sum_{i=2}^{n} (e_i - e_{i-1})^2}{\sum_{i=1}^{n} e_i^2}
\]

where \(d\) represents number of observations; \(e_i\), \(e_{i-1}\) represents residual of observations.

The Mann–Kendall test method

The Mann–Kendall test method was used to examine the nonlinear trend of precipitation in different time scales, and abrupt change year of precipitation in Xi’an city.

(1) The Mann–Kendall trend test analysis: The Mann–Kendall test is a nonparametric test method (Nyikadzino et al. 2020). The Mann–Kendall test method can be used to detect the changing trend of a time series for hydrologic data and meteorological data (Liu et al. 2015; Pingale et al. 2014; Tian et al. 2019). In recent years, the Mann–Kendall test has been widely applied to characterize the trend of precipitation data (Song et al. 2014; Jones et al. 2015; Zhao et al. 2017; Wang et al. 2019; Nyikadzino et al. 2020).

The formula of the Mann–Kendall test, the statistic \(S\) value, was defined by (Wang et al. 2016):

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)
\]

where \(\text{sgn}(x) = \begin{cases} 
1, & \text{if } x_j - x_i > 0 \\
0, & \text{if } x_j - x_i = 0 \\
-1, & \text{if } x_j - x_i < 0 
\end{cases}
\]
\[ \text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \]  

\[ Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0 \\
0, & \text{if } S = 0 \\
\frac{S + 1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0 
\end{cases} \]  

where the statistic \( S \) obeys the normal distribution with a mean of zero; \( x_i \) and \( x_j \) are two sequential data values of the variable; \( n \) is the length of the data series; and \( Z \) is the test statistic value.

Based on the results of the Mann–Kendall trend test, \( Z > 0 \) and \( Z < 0 \) indicate that the time series of precipitation displays an increasing trend and decreasing trend, respectively (Wang et al. 2020). In addition, the time series of the variables have a significant trend if \( |Z| > Z_{1-\alpha/2} \) under a certain confidence level of \( \alpha \). \( Z_{1-\alpha/2} \) can be obtained from the standard normal cumulative distribution tables.

(2) Mann–Kendall change-point test analysis: The Mann–Kendall test method was also applied to examine the abrupt change-point time. Thus, the calculation process was:

\[ S = \sum_{i=1}^{k} \sum_{j=i}^{n} \alpha_q(k = 2, 3, 4, \ldots, n) \]  

\[ \alpha_q = \begin{cases} 
1, & x_i > x_j \\
0, & x_i \leq x_j 
\end{cases} \]  

\[ UF = \frac{S_k - E(S_k)}{\sqrt{\text{Var}(S_k)}} \]  

\[ E(S_k) = \frac{k(k-1)}{4} \]  

\[ \text{Var}(S_k) = \frac{k(k-1)(2k+5)}{72} \]  

where \( UF \) is the forward statistic sequence; and \( UB \) is the backward sequence with a reversed series of data.

In the case of \( UF > 0 \) and \( UF < 0 \), it shows that the time series present an increasing trend and decreasing trend, respectively. If there is an intersection point of the two curves (\( UF \) and \( UB \)) and the trend of the time series is statistically significant, the corresponding time of intersection point would be regarded as the abrupt change time point (Zhao et al. 2017).

**Wavelet analysis method**

The wavelet analysis method was used to study the multiscale of time series, revealing the periodic features of non-stationary variance in different time scales (Yi & Shu 2012; Jones et al. 2015). In addition, the wavelet analysis was proven as a powerful tool for the analysis and synthesis of data (Nayak et al. 2013). Wavelet analysis was also an effective means to reveal the change trend and distinguish the periodicity for a temporal sequence (Luo et al. 2019). Therefore, wavelet analysis has seen increasing application in atmospheric sciences, particularly in meteorological data processing and climatology (Hermida et al. 2015). Wavelet analysis can be performed based on the two approaches of discrete wavelet transform (DWT) and continuous wavelet transform (CWT). CWT was proven to be suitable for exploratory scale analysis and a better approach for feature extraction purposes such as that in Furon et al. (2008). Thus, CWT was employed to extract the periodicity of precipitation in this paper.

CWT for the temporal sequence \( f(t) \) was defined by Luo et al. (2019) as in Equation (12):

\[ W_i(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) e^{i(b/2)(c/2)} \frac{e^{i(a/2) t}}{c} \frac{d}{c} \]  

where \( W_i(a, b) \) represents the wavelet coefficient; \( a \) is the scale factor, reflecting the periodic scale of wavelet; \( b \) is the time factor; \( i \) represents the imaginary number; \( c \) is a constant.

In addition, the Morlet wavelet in CWT was applied to detect the periodicity of precipitation in this study. The reason is that the Morlet wavelet has the clear advantage in that it allows detection of time-dependent amplitude and phase for different frequencies with its complex nature (Hermida et al. 2015). The Morlet wave was given by Jones et al. (2015) as:

\[ \tilde{\psi}_\omega(s, t) = \pi^{1/4} H(\omega) e^{-i(\omega t + \phi)} \]  

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*Corrected Proof*

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where $s$ represents the wavelet scale; $\omega$ represents the frequency; $H(\omega)$ represents the Heaviside step function; $\omega_0$ represents the non-dimensional frequency.

After finishing the Morlet wavelet transform analysis, the real part of precipitation indicates that a positive value and negative value can represent an increasing trend and decreasing trend for precipitation during the research period (Luo et al. 2019).

RESULTS AND DISCUSSION

This section described the temporal and spatial variation trends of precipitation in different time scales, and explores the abrupt change and periodicity change.

**Variation trends and abrupt change analysis of precipitation in Xi’an city**

**Variation trends of precipitation**

Figure 2 shows the linear trend of annual precipitation in Xi’an city from 1951 to 2018. It is obvious that the annual precipitation exhibited a decreasing trend of $-1.0133$ mm yr$^{-1}$ according to the linear regression coefficient value. A similar conclusion was also reported by Wang et al. (2019), which indicated the significant decreased trend changes of annual precipitation. The DW test value for Equation (2) was 2.41, suggesting that there was no significant auto-correlation in annual precipitation (a significance level of 5%).

![Figure 2](https://example.com/image2.png)

**Table 1** The statistics of annual precipitation in Xi’an city during different periods

| Average annual precipitation (mm) | Maximum annual precipitation (mm) | Minimum annual precipitation (mm) | Period time |
|-----------------------------------|-----------------------------------|-----------------------------------|-------------|
| 628.38                            | 839                               | 384.4                             | 1951–1959   |
| 573.25                            | 782.3                             | 408.9                             | 1960–1969   |
| 547.01                            | 671.6                             | 346.1                             | 1970–1979   |
| 609.23                            | 903.2                             | 402.8                             | 1980–1989   |
| 516.02                            | 713.4                             | 312.2                             | 1990–1999   |
| 570.26                            | 883.2                             | 405.9                             | 2000–2009   |
| 547.57                            | 723.6                             | 426.7                             | 2010–2018   |
| 569.72                            | 903.2                             | 312.2                             | 1951–2018   |
Mann–Kendall trend test analysis in the next section. The average seasonal precipitation was presented in descending order of precipitation value, as summer precipitation (234.19 mm), autumn precipitation (184.06 mm), spring precipitation (128.34 mm), and winter precipitation (23.14 mm) (Table 2). However, seasonal precipitation variation was more significant than that of annual precipitation (the smallest \(C_v\) of 21%). In addition, the coefficient of variance of the winter precipitation (\(C_v\) is 63%) is larger than that of the other seasonal precipitations and annual precipitation (Table 2). This indicated that the data sequence of winter precipitation was more significant with a high discrete degree from 1951 to 2018, as shown in Table 2. This phenomenon was possibly because the temporal distribution of precipitation was uneven, and may be affected by climate change.

Figure 4 shows the distribution of average monthly precipitation in Xi’an city during 1951–2018. The average

| Variable       | Average precipitation (mm) | \(C_v\) of average precipitation (%) | Period time   |
|----------------|-----------------------------|------------------------------------|---------------|
| Spring precipitation | 128.34                      | 34                                 | 1951–2018     |
| Summer precipitation    | 234.19                      | 35                                 | 1951–2018     |
| Autumn precipitation    | 184.06                      | 41                                 | 1951–2018     |
| Winter precipitation    | 23.14                       | 63                                 | 1951–2018     |
| Annual precipitation    | 569.72                      | 21                                 | 1951–2018     |
monthly precipitation was obtained by the average value of monthly precipitation during 1951–2018. The bar chart reveals the distribution of monthly precipitation, and the line chart with some series values shows the proportion of monthly precipitation to annual precipitation. The highest monthly precipitation (98.3 mm) in September was 15.8 times higher than the lowest monthly precipitation (6.23 mm) in December during 1951–2018. The distribution of monthly precipitation was also uneven, indicating the most precipitation focus on the period from June to September, accounting for 58.4% of the total annual precipitation (Figure 4).

**Abrupt change analysis of precipitation**

Abrupt change analysis can reflect the significant trend change for long-term precipitation series. Figures 5 and 6 show the Mann–Kendall trend change test results of annual and seasonal precipitation in Xi’an city during 1951–2018. It is clear that the abrupt change year was in 1965 for the annual precipitation, identified by just one intersection point of the UF curve and the UB curve under the significance level of 0.05. The result of abrupt change point in this study was consistent with other studies such as Yang et al. (2017) and Wang et al. (2019). Therefore, analysis of the abrupt change year in 1965, with the large difference value (70.8 mm) between average annual precipitation was 625.9 mm (during 1951–1964) and 555.1 mm (during 1966–2018). This abrupt change year occurred because of the transition from the wetter period to the dry period after 1965. Figure 7 illustrates the Z statistic value trend of the sequential Mann–Kendall trend test of precipitation in Xi’an city at the 5% significance level from 1951 to 2018. Additionally, the results of the Mann–Kendall test show a decreasing trend from the perspective of annual precipitation with the Z statistic value of −1.7 (Figure 7).

As shown in Figure 6, there were different abrupt change points in the four seasonal precipitations determined by some intersection points of the UF and UB curves using the Mann–Kendall trend test method. While these intersections for change points detected throughout the urban area ranged from zero to four, there were more than three intersections between the UF and UB curves in Figure 6(a)–6(d), showing that the number of abrupt change year of seasonal precipitation is greater than that of annual precipitation (Figure 5). The result indicated that seasonal precipitation had a higher frequency of abrupt change than annual precipitation, and the most significant abrupt variation appears in autumn with the largest number of intersection points (Figure 6(c)). It is clear that the seasonal precipitation has significant decreasing trends, with a slight increasing trend in summer precipitation according to the results of the Mann–Kendall trend test (see Figure 7). It is therefore important that the verification of summer precipitation should exhibit a slight increasing trend. The Mann–Kendall trend test values of the seasonal precipitation indicated that the decreased precipitation was more significant in spring and there were smaller declines in winter and autumn. During 1951–2018, the absolute value of the Mann–Kendall test of the spring precipitation ($Z = −2.1$) was higher than 1.96 ($Z_{0.05} = 1.96$), indicating that the trend in spring precipitation dropped significantly. The related departments should pay high attention to the fact that the growth of crops in spring will be affected due to the spring precipitation continuing to decline. The above-mentioned results indicated that a significant temporal variation was observed in the seasonal precipitation in the study area. For the Z test values in monthly precipitation, an increasing variation trend was shown in June and August and a decreasing variation trend in other months, especially the reduction amplitude and increased
Figure 6 | The Mann–Kendall trend test of the seasonal precipitation in Xi’an city at the 5% significance level (1951–2018). (a) Spring (b) Summer (c) Autumn (d) Winter.

Figure 7 | The Mann–Kendall trend test values in precipitation.
amplitude of precipitation remained highest in April and June, respectively. Some of the explanations for the decreasing trend in annual precipitation of Xi’an city are that it could be affected by the Southern Oscillation Index (Jiang et al. 2019), sunspot (Wang et al. 2020), El Niño–Southern Oscillation, and Arctic Oscillation (Li et al. 2018). Therefore, these factors could affect the annual precipitation in Xi’an city.

Spatial distribution variation of precipitation

The spatial distribution variations of the average annual precipitation and average seasonal precipitation in Xi’an city are illustrated in Figures 8 and 9. The results show that there existed significant regional differences in the spatial distribution of the precipitation during different time scales. The average annual and average seasonal precipitation for each grid corresponds to the average values of annual precipitation and seasonal precipitation of these grids from 1961 to 2018 in the study region. For the spatial distribution of the average annual precipitation, it is clear that there was an increasing precipitation gradient from north (<600 mm) to south (>1,000 mm) during 1961–2018 (Figure 8). The precipitation of the urban center region was less than precipitation in the southern region (between 33°30’ and 34°N) and eastern region (109°30’ and 110°E). At the regional scale, the highest average annual precipitation in the southwest was higher than that of the other regions. While the precipitation was less in the western and northern regions, the higher precipitation was in the eastern and southern regions of Xi’an urban area, suggesting that the Qinling Mountains region in the eastern and southern regions had the higher precipitation. In addition, the spatial distribution patterns of the average seasonal precipitation were similar to those of the average annual precipitation (Figure 9), showing that the spatial distributions of the average seasonal precipitation increased from the north to the south. Compared to the spatial distribution of the average precipitation in spring, autumn, and winter, there was a significant distribution difference in average summer precipitation (Figure 9(b)). In addition, it was obvious that both the average annual and seasonal precipitation in the eastern and western wings of the urban southern region were quite different.

Figure 10 shows the distribution of trends of the average annual precipitation during different periods in Xi’an city.
Variations of precipitation for six periods all exhibited a similar trend to the average annual precipitation of the entire period (1961–2018) in spatial distribution, expressing that precipitation increased from north to south in the entire study area. However, spatial distribution of average precipitation exhibited smaller differences identified by the distribution of different colored areas during the six periods (Figure 10). Among these periods, the average annual precipitation in the southeast region of the entire urban area during the periods of 1980–1989 and 2010–2018 was over 1,000 mm (Figure 10(c) and 10(f)), indicating that it had the most abundant precipitation for these two periods. The above-mentioned results indicated that the spatial distribution variations of the average annual precipitation and average seasonal precipitation were scattered. Analysis of spatial variation differences of precipitation, the climate change, complex topography and geomorphology resulted in the spatial differences of precipitation in the Guanzhong Plain described by Zhang et al. (2020).

Periodicity analysis of annual precipitation

The periodicity variation characteristic of annual precipitation was examined using Morlet wavelet analysis method in this section. The calculated real part of wavelet coefficients was used to analyze the wavelet variability in the different time scales. In general, for the real part periodic change map of precipitation, the lower scale changes complexly nested into the higher scales (Li et al. 2009). Figure 11 shows the contour map for the real part of wavelet coefficient of annual precipitation in Xi’an city during 1951–2018. The red regions, blue regions, and other color regions represent higher, lower, and middle values of annual precipitation, respectively. As seen in Figure 11, it is shown...
that there was obvious periodic change for annual precipitation on a 25- to 30-year scale. In the case of the real part coefficients of annual precipitation there were positive values and negative values, suggesting that the annual precipitation series exhibited a higher value and lower value, respectively.

Figure 10 | The spatial distribution of the average annual precipitation in Xi’an city in different periods. (a) 1961–1969 (b) 1970–1979 (c) 1980–1989 (d) 1990–1999 (e) 2000–2009 (f) 2010–2018.
The result of wavelet variance of annual precipitation in Xi’an city was computed, as plotted in Figure 12. There exist 6-, 13-, 19-, and 27-year periods and the 13 and 27 years are the main periods. In particular, the 27-year period was significantly obvious with the largest wavelet variance value. Compared to the result of the real part of wavelet coefficient and wavelet variance of annual precipitation (Figures 11 and 12), it indicated that the same significant appearance year for annual precipitation ranged from 25 to 30 years. In order to analyze the change character of annual precipitation, the real part of wavelet coefficients change of annual precipitation on a 27-year scale is illustrated in Figure 13. The variety of annual precipitation of Xi’an city had obvious plentiful and declining circulation periods. Real part values of wavelet coefficient of annual precipitation were positive in the periods of 1951–1954, 1963–1972, 1982–1989, 1999–2007, and 2017–2018, indicating high annual precipitation for these periods in the entire area. Meanwhile, the low annual precipitation periods with negative wavelet coefficient values were 1955–1962, 1973–1981, 1990–1998, and 2008–2016, suggesting the stronger periodic oscillation variability. As can be seen from the above results, the annual precipitation had obvious periodic variability in Xi’an city, which agrees well with the findings of the studies of Zhang & Zhao (2008) and Wang et al. (2019). In addition, some studies have investigated the effects of the El Niño–Southern Oscillation (ENSO), Arctic Oscillation (AO), Southern Oscillation Index (SOI), and sunspot on the precipitation periodic periods in Xi’an city, indicating that these factors have an impact on precipitation (Zhang & Zhao 2008; Chen et al. 2015; Jiang et al. 2016; Wang et al. 2019). For instance, SOI has been found to have a positive climatic impact on the precipitation, whereas ENSO and sunspot exhibited a negative impact on the precipitation. Among them, sunspot exerted the greater impact on precipitation periodic periods in this study area.

**Comparison with previous studies**

The spatial and temporal variation of precipitation is a crucial issue related to water resource management and planning in Xi’an city. In this study, we have shown a detailed assessment of the temporal variation trend in annual, seasonal, and monthly precipitation. It showed a decreasing trend in annual precipitation, with the regression
coefficient of −1.0133 and Mann–Kendall test statistic value of −1.7 (Figures 2 and 7). A number of previous studies have identified a decrease in annual precipitation in Xi’an city (Yang et al. 2016; Wang et al. 2019). The finding of this study’s annual precipitation change trend analysis was consistent with those studies. In the meantime, the year 1965 was identified as the abrupt change year for annual precipitation. In addition, the temporal variation of annual precipitation revealed significant interannual and interdecadal variability, which existed in the change periods of 6, 13, 19, and 27 years based on wavelet periodicity analysis (Figure 12). A similar variation trend characteristic was found by Zhang & Zhao (2008), indicating the obvious change periods of 3, 6, 13, 21, and 27 years.

There were different increasing and decreasing variation trends in seasonal and monthly precipitation. The results showed that seasonal precipitation had a decreasing trend based on linear trend analysis in Xi’an city; however, the trend of summer precipitation does not agree well with the result of Mann–Kendall trend analysis. The Mann–Kendall test method can better examine trend and abrupt change of precipitation (Liu et al. 2015). The comprehensive analysis of summer precipitation trend based on the linear trend analysis method and Mann–Kendall trend analysis method was discussed, indicating a slight decreasing trend in summer precipitation; the same result was found by Yang et al. (2016). Except for the summer precipitation, the precipitation in spring, autumn, and winter exhibited a decreasing trend.

Although most studies have explored the variations in precipitation at the annual scale and seasonal scale, few researchers have investigated variations in monthly precipitation considering long-term time series in the study area. Therefore, this study evaluated the detailed variations in monthly precipitation. The temporal distribution and Mann–Kendall test statistic values of monthly precipitation are plotted in Figures 4 and 7, respectively. Monthly precipitation, except for June and August, shows the decreasing trends and a significant change was observed in April.

Most of the previous studies have been devoted mainly to describing the precipitation variations at temporal scale in Xi’an city, but few studies have been concerned with the precipitation variations at the spatial scale. Wei et al. (2019) analyzed the spatial distribution characteristic of precipitation considering only the urban central district scale from 2009 to 2015. The spatial variation distribution in average annual precipitation and average seasonal precipitation in Xi’an city during 1961–2018 was systematically investigated in this work. Meanwhile, compared to the precipitation data of a few meteorological stations and hydrologic stations, the gridded precipitation data were applied to assess the spatial variation considering different time scales, which was useful for analyzing variability of precipitation of the urban area in all directions. On the basis of the spatial variation in precipitation analysis, there was obvious spatial difference, and the spatial difference changes were affected by climate change, complex topography, and geomorphology. The multiple barriers that moisten water vapor were blocked by Qinling Mountains (south and east) and the Loess Plateau (north), resulting in the spatial differences of precipitation in Xi’an city as described by Zhang et al. (2020). Moreover, Gu et al. (2019) emphasized the significant impact of rapid urbanization on variations of annual precipitation and seasonal precipitation in China. Therefore, it is important to further examine spatial and temporal variations of precipitation at the urban regional scale.

**CONCLUSIONS**

Based on the long-term measured precipitation data (1951–2018), this study investigated the spatial and temporal variations of precipitation in Xi’an city. The Mann–Kendall test and wavelet analysis method were applied to quantitatively detect temporal variations of precipitation in different time scales, while spatial variations characteristic of the average annual precipitation and average seasonal precipitation were explored using gridded data. Through analyzing the calculated results, four main conclusions are drawn as follows:

- To further reveal the variations of measured annual precipitation in the entire Xi’an urban region from 1951 to 2018, the results showed that annual precipitation exhibited significant decreasing trend, and it also showed an abrupt change feature with an abrupt change point in the year 1965. Also, the higher annual precipitation was in the periods of 1951–1959 and 1980–1989. In addition, the annual precipitation had an obvious periodic
variability during 1951–2018, with the periods of 6, 13, 19, and 27 years being detected by Morlet wavelet analysis. Among them, the 27-year period was more obvious based on wavelet variance analysis of annual precipitation.

- Evaluation of the temporal variability and abrupt change of seasonal precipitation based on both linear trend analysis and Mann–Kendall trend test method indicated that spring, autumn, and winter precipitations were dominated by decreasing trends, and summer precipitation was slightly dominated by increasing trend. This phenomenon indicated that spring, autumn, and winter precipitation all contributed highly to reduction change for annual total precipitation. The abrupt change feature of the seasonal precipitation with more than two abrupt change years was different to annual precipitation change, showing the obvious variation in the seasonal precipitation.

- The trends of increasing and decreasing monthly precipitation were different based on Mann–Kendall trend analysis. The precipitation from June to September played a major role in the annual total precipitation in Xi’an city during 1951–2018, with the contribution rate of 58.4%. In addition, it showed an increasing trend for precipitation in June and August. By contrast, the other monthly precipitations have a decreased trend.

- The spatial distributions of annual precipitation and seasonal precipitation were investigated in Xi’an city, indicating the regional precipitation had significant spatial variation characteristics. The spatial distribution of the seasonal precipitation was similar to the annual precipitation during 1961–2018, showing a spatial trend of increasing precipitation gradient from north to south, and the highest precipitation was mainly concentrated in the southwest region. Similarly, the precipitation for six separate periods exhibited the same spatial variation trend.

In summary, the obvious temporal variations and spatial distribution characteristics of precipitation in Xi’an city were discussed in this work. The results from this study will help to achieve better comprehensive understanding of the precipitation variations in Xi’an city, and can provide guidance for future water resource management and planning, and water resources optimal allocation under changing climate in other cities in semi-arid regions. Meanwhile, this study could also provide basic references for investigating the spatial and temporal variations in other urban regions in China. In addition to the above-mentioned results, the effect of climate change and human activity on precipitation also requires further investigation in future research.

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DATA AVAILABILITY STATEMENT

All relevant data are available from [http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_PRE_MON_GRID_0.5.html](http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_PRE_MON_GRID_0.5.html) and [http://tjj.shaanxi.gov.cn/tjsj/ndsj/tjnj/](http://tjj.shaanxi.gov.cn/tjsj/ndsj/tjnj/).

REFERENCES

Bai, L. & Wang, Z. L. 2014 Anthropogenic influence on rainwater in the Xi’an City, Northwest China: constraints from sulfur isotope and trace elements analyses. Journal of Geochemical Exploration 137, 65–72. [https://doi.org/10.1016/j.gexplo.2013.11.011](https://doi.org/10.1016/j.gexplo.2013.11.011).

Bedaso, Z. K., DeLuca, N. M., Levin, N. E., Zaitchik, B. F., Waugh, D. W., Wu, S. Y., Harman, C. & Shanko, D. 2020 Spatial and temporal variation in the isotopic composition of
Ethiopian precipitation. *Journal of Hydrology** 585, 124364. https://doi.org/10.1016/j.jhydrol.2019.124364.

Chen, F., Yuan, Y., Wei, W., Fan, Z., Zhang, R. & Yu, S. 2015 April–June precipitation reconstruction for Xi’an and drought assessment for the Guanzhong Plain from tree rings of Chinese pine. *Journal of Water and Climate Change* 6 (3), 638. https://doi.org/10.2166/wcc.2014.245.

Ding, L., Ren, X., Gu, R. & Che, Y. 2019 Implementation of the ‘sponge city’ development plan in China: an evaluation of public willingness to pay for the life-cycle maintenance of its facilities. *Cities* 93, 13–30. https://doi.org/10.1016/j.cities.2019.04.007.

Duan, Z., Liu, J., Tuo, Y., Chiogna, G. & Disse, M. 2016 Evaluation of eight high spatial resolution gridded precipitation products in Adige Basin (Italy) at multiple temporal and spatial scales. *Science of the Total Environment* 573, 1536–1553. https://doi.org/10.1016/j.scitotenv.2016.08.213.

Emmanuel, I., Andrieu, H., Leblois, E. & Flahaut, B. 2012 Temporal and spatial variability of rainfall at the urban hydrological scale. *Journal of Hydrology* 430–431, 162–172. https://doi.org/10.1016/j.jhydrol.2012.02.013.

Furon, A. C., Wagner-Riddle, C., Smith, C. R. & Warland, J. S. 2008 Wavelet analysis of wintertime and spring thaw CO2 and N2O fluxes from agricultural fields. *Agricultural and Forest Meteorology* 148 (8–9), 1305–1317. https://doi.org/10.1016/j.agrformet.2008.03.006.

Gu, X., Zhang, Q., Li, J., Singh, V. & Sun, P. 2019 Impact of urbanization on nonstationarity of annual and seasonal precipitation extremes in China. *Journal of Hydrology* 575, 638–653. https://doi.org/10.1016/j.jhydrol.2019.05.070.

Han, H., Hou, J., Huang, M., Li, Z., Xu, K., Zhang, D., Bai, G. & Wang, C. 2020 Impact of soil and water conservation measures and precipitation on streamflow in the middle and lower reaches of the Hulu River Basin, China. *Catena* 195, 104792. https://doi.org/10.1016/j.catena.2020.104792.

Hermida, L., López, L., Merino, A., Berthet, C., García-Ortega, E., Sánchez, J. L. & Descans, J. 2015 Halifall in southwest France: relationship with precipitation, trends and wavelet analysis. *Atmospheric Research* 156, 174–188. https://doi.org/10.1016/j.atmosres.2015.01.005.

Hu, D., Zhang, C., Ma, B., Liu, Z., Yang, X. & Yang, L. 2020 The characteristics of rainfall runoff pollution and its driving factors in Northwest semi-arid region of China – A case study of Xi’an. *Science of the Total Environment* 726, 138384. https://doi.org/10.1016/j.scitotenv.2020.138384.

Jiang, R., Xie, J., Zhao, Y., He, H. & He, G. 2016 Spatiotemporal variability of extreme precipitation in Shaanxi province under climate change. *Theoretical and Applied Climatology* 130 (3–4), 831–845. https://doi.org/10.1007/s00704-016-1910-y.

Jiang, Y., Zevenbergen, C. & Ma, Y. 2018 Urban pluvial flooding and stormwater management: a contemporary review of China’s challenges and ‘sponge cities’ strategy. *Environmental Science & Policy* 80, 132–143. https://doi.org/10.1016/j.envsci.2017.11.016.

Jiang, R., Wang, Y., Xie, J., Zhao, Y., Li, F. & Wang, X. 2019 Assessment of extreme precipitation events and their teleconnections to El Niño Southern Oscillation, a case study in the Wei River Basin of China. *Atmospheric Research* 218, 372–384. https://doi.org/10.1016/j.atmosres.2018.12.013.

Jones, J. R., Schwartz, J. S., Ellis, K. N., Hathaway, J. M. & Jawdy, C. M. 2015 Temporal variability of precipitation in the Upper Tennessee Valley. *Journal of Hydrology: Regional Studies* 3, 125–138. https://doi.org/10.1016/j.jhr.2014.10.006.

Jurković, R. S. & Pasaric’ Z. 2013 Spatial variability of annual precipitation using globally gridded data sets from 1951 to 2000. *International Journal of Climatology* 33 (3), 690–698. https://doi.org/10.1002/joc.3462.

Kosemanii, B. S. & Bamboyie, A. I. 2021 Modelling energy use pattern for maize (Zea mays L) production in Nigeria. *Cleaner Engineering and Technology* 2, 100051. https://doi.org/10.1016/j.clet.2021.100051.

Labat, D. 2005 Recent advances in wavelet analyses: part 1. A review of concepts. *Journal of Hydrology* 314 (1–4), 275–288. https://doi.org/10.1016/j.jhydrol.2005.04.003.

Li, C., Yang, Z., Huang, G. & Li, Y. 2009 Identification of relationship between sunspots and natural runoff in the Yellow River based on discrete wavelet analysis. *Expert Systems with Applications* 36 (2), 3309–3318. https://doi.org/10.1016/j.eswa.2008.01.083.

Li, Z., Zheng, F., Liu, W. & Flanagan, D. C. 2020 Spatial distribution and temporal trends of extreme temperature and precipitation events on the Loess Plateau of China during 1961–2007. *Quaternary International* 226, 92–100. https://doi.org/10.1016/j.quaint.2010.03.003.

Li, Y., Huang, S., Ma, L., Huang, Q., Wu, L., Hou, B. & Leng, G. 2018 Spatiotemporal changes in extreme wet and dry conditions and linkages with planetary oscillations. *Journal of Coastal Research* 84, 134–143. https://doi.org/10.2112/SI84-0191.1.

Li, X., Lu, A., Feng, Q., Li, Z., Liu, W., Wang, S., Tripathee, L., Wang, X. & Cao, J. 2020 Recycled moisture in an enclosed basin, Guanzhong Basin of Northern China, in the summer: contribution to precipitation based on a stable isotope approach. *Environmental Science and Pollution Research* 27 (22), 27926–27936. https://doi.org/10.1007/s11356-020-09099-z.

Liang, L., Li, L. & Liu, Q. 2020 Temporal variation of reference evapotranspiration during 1961–2005 in the Taer River basin of Northeast China. *Agricultural and Forest Meteorology* 150 (2), 298–306. https://doi.org/10.1016/j.agrformet.2009.11.014.

Liu, W., Zhang, M., Wang, S., Wang, B., Li, F. & Che, Y. 2013 Changes in precipitation extremes over Shaanxi Province, northwestern China, during 1960–2011. *Quaternary International* 313–314, 118–129. https://doi.org/10.1016/j.quaint.2013.06.033.

Luo, J., Zheng, Z., Li, T., He, S., Wang, Y., Zhang, X., Huang, H., Yu, H. & Liu, T. 2019 Characterization of runoff and sediment associated with rill erosion in sloping farmland
during the maize-growing season based on rescaled range and wavelet analyses. Soil and Tillage Research 195, 104359. https://doi.org/10.1016/j.still.2019.104359.

Ma, Y., Jiang, Y. & Swallow, S. 2020 China’s sponge city development for urban water resilience and sustainability: a policy discussion. Science of the Total Environment 729, 139078. https://doi.org/10.1016/j.scitotenv.2020.139078.

Mahmood, R., Babel, M. S. & Jia, S. 2015 Assessment of temporal and spatial changes of future climate in the Jhelum river basin, Pakistan and India. Weather and Climate Extremes 10, 40–55. https://doi.org/10.1016/j.wace.2015.07.002.

Nalley, D., Adamowski, J. & Khalil, B. 2012 Using discrete wavelet transforms to analyze trends in streamflow and precipitation in Quebec and Ontario (1954–2008). Journal of Hydrology 475, 204–228. https://doi.org/10.1016/j.jhydrol.2012.09.049.

Nayak, P. C., Venkates, B., Krishna, B. & Jain, S. K. 2015 Rainfall-runoff modeling using conceptual, data driven, and wavelet based computing approach. Journal of Hydrology 493, 57–67. https://doi.org/10.1016/j.jhydrol.2013.04.016.

Nguyen, T. T., Ngo, H. H., Guo, W., Wang, X. C., Ren, N., Li, G., Ding, J. & Liang, H. 2019 Implementation of a specific urban water management-Sponge City. Science of the Total Environment 652, 147–163. https://doi.org/10.1016/j.scitotenv.2018.10.168.

Nyikadzino, B., Chitakira, M. & Muchururu, S. 2020 Rainfall and runoff trend analysis in the Limpopo river basin using the Mann Kendall statistic. Physics and Chemistry of the Earth 117, 102870. https://doi.org/10.1016/j.pce.2020.102870.

Pingale, S. M., Khare, D., Jat, M. K. & Adamowski, J. 2014 Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan, India. Atmospheric Research 138, 73–90. https://doi.org/10.1016/j.atmosres.2013.10.024.

Salimi, A. H., Samakosh, J. M., Sharifi, E., Hassanvand, M. R., Noori, A. & Rautenkranz, H. 2019 Optimized artificial neural networks-based methods for statistical downscaling of gridded precipitation data. Water 11 (8), 1653. https://doi.org/10.3390/w11081653.

Sang, Y. F., Fu, Q., Singh, V. P., Sivakumar, B., Zhu, Y. & Li, X. 2019 Does summer precipitation in China exhibit significant periodicities? Journal of Hydrology 581, 124289. https://doi.org/10.1016/j.jhydrol.2019.124289.

Sayemuzzaman, M. & Jha, M. K. 2014 Seasonal and annual precipitation time series trend analysis in North Carolina, United States. Atmospheric Research 137, 183–194. http://dx.doi.org/10.1016/j.atmosres.2013.10.012.

Segond, M. L., Wheeler, H. S. & Onof, C. 2007 The significance of spatial rainfall representation for flood runoff estimation: a numerical evaluation based on the Lee catchment, UK. Journal of Hydrology 347, 116–131. https://doi.org/10.1016/j.jhydrol.2007.09.040.

Sharif, E., Eitzinger, J. & Dorigo, W. 2009 Performance of the state-of-the-art gridded precipitation products over mountainous terrain: a regional study over Austria. Remote Sensing 11 (17), 2018. https://doi.org/10.3390/rs11172018.

Sharma, S., Khadka, N., Hamal, K., Baniya, B. & Luintel, N. 2020 Spatial and temporal analysis of precipitation and its extremes in seven provinces of Nepal (2001–2016). Applied Ecology and Environmental Sciences 8 (2), 64–73. https://doi.org/10.12691/aees-8-2-4.

Song, X., Zhang, J., Aghakouchak, A., Roy, S., Xuan, Y., Wang, G. & Liu, C. 2014 Rapid urbanization and changes in spatiotemporal characteristics of precipitation in Beijing metropolitan area. Journal of Geophysical Research 119 (19), 11250–11271. https://doi.org/10.1002/2014JD022084.

Thomas, J. & Prasannakumar, V. 2016 Temporal analysis of rainfall (1871–2012) and drought characteristics over a tropical monsoon-dominated state (Kerala) of India. Journal of Hydrology 534, 266–280. https://doi.org/10.1016/j.jhydrol.2016.01.013.

Tian, S., Xu, M., Jiang, E., Wang, G., Hu, H. & Liu, X. 2019 Temporal variations of runoff and sediment load in the upper Yellow River, China. Journal of Hydrology 568, 46–56. https://doi.org/10.1016/j.jhydrol.2018.10.033.

Wang, H., Chen, L. & Yu, X. 2016 Distinguishing human and climate influences on streamflow changes in Luan River basin in China. Catena 136, 182–188. https://doi.org/10.1016/j.catena.2015.02.013.

Wang, L., Zhang, S., Wang, L., Zhang, W., Shi, X., Lu, X., Li, X. & Li, X. 2018 Concentration and risk evaluation of polycyclic aromatic hydrocarbons in urban soil in the typical semi-arid city of Xi’an in northwest China. International Journal of Environmental Research and Public Health 15 (4), 607. https://doi.org/10.3390/ijerph15040607.

Wang, X., Jiang, R., Xie, J., Zhao, Y., Li, F. & Zhu, J. 2019 Multiscale variability of precipitation and their teleconnection with large-scale climate anomalies: a case study of Xi’an City, China. Journal of Coastal Research 93, 417–426. https://doi.org/10.2112/SI93-055.1.

Wang, X., Jiang, R., Xie, J. & Zhao, Y. 2020 Study on the variation characteristics and driving mechanism of precipitation during flood season in Xi’an City. Journal of Natural Disasters 29 (2), 138–148. https://doi.org/10.13577/j.jnd.2020.0214. (in Chinese).

Wei, N., Sun, X., Bi, X., Wang, J. M. & Li, X. 2019 The spatial characteristics of precipitation and water-logging disaster during rainy season for urban planning in Xi’an. Indoor and Built Environment 28 (9), 1–9. https://doi.org/10.1177/1420326X19856662.

Xing, Z. Q., Yan, D. H., Zhang, C., Wang, G. & Zhang, D. D. 2011 Assessment of temporal and bivariate frequency analysis of precipitation and runoff in the upper Huai River Basin, China. Water Resources Management 25, 3291–3304. https://doi.org/10.1007/s11269-015-0997-8.

Xu, H., Abdul-Kadar, F. & Gao, P. 2016 An information model for managing multi-dimensional gridded data in a GIS. IOP Conference Series: Earth and Environmental Science 34, 012041. https://doi.org/10.1088/1755-1315/34/1/012041.

Yan, T., Shen, Z. & Bai, J. 2017 Spatial and temporal changes in temperature, precipitation, and streamflow in the Miyun Reservoir Basin of China. Water 9 (2), 78. https://doi.org/10.3390/w9020078.
Yang, J., Qian, H., Gao, Y. & Huo, C. 2016 Multi-year precipitation characteristics analysis and precipitation forecast of Xi’an city. *South-to-North Water Transfers and Water Science & Technology* **14** (3), 30–35. https://doi.org/10.13476/j.cnki.nsbdqk.2016.03.006. (in Chinese).

Yang, P., Xia, J., Zhang, Y. & Hong, S. 2017 Temporal and spatial variations of precipitation in Northwest China during 1960–2013. *Atmospheric Research* **183**, 283–295. https://doi.org/10.1016/j.atmosres.2016.09.014.

Yi, H. & Shu, H. 2012 The improvement of the Morlet wavelet for multi-period analysis of climate data. *Comptes Rendus Geoscience* **344** (10), 483–497. https://doi.org/10.1016/j.crte.2012.09.007.

Yin, Y. 2020 Model-free tests for series correlation in multivariate linear regression. *Journal of Statistical Planning and Inference* **206**, 179–195. https://doi.org/10.1016/j.jspi.2019.09.011.

Zhang, Y. & Zhao, J. 2008 Multiple time scale analysis of precipitation in Xi’an city over last 55 year. *Chinese Journal of Agrometeorology* **29** (4), 406–410. (in Chinese).

Zhang, Q., Singh, V. P., Peng, J., Chen, Y. D. & Li, J. 2012 Spatial-temporal changes of precipitation structure across the Pearl River Basin, China. *Journal of Hydrology* **440–441**, 113–122. https://doi.org/10.1016/j.jhydrol.2012.03.037.

Zhang, H., Huang, Q., Zhang, Q., Gu, L., Chen, K. & Yu, Q. 2016 Changes in the long-term hydrological regimes and the impacts of human activities in the main Wei River, China. *Hydrological Sciences Journal* **61** (6), 1054–1068. https://doi.org/10.1080/02626667.2015.1027708.

Zhang, Y., Chao, Y., Fan, R., Ren, F., Qi, B., Ji, K. & Xu, B. 2020 Spatial-temporal trends of rainfall erosivity and its implication for sustainable agriculture in the Wei River Basin of China. *Agricultural Water Management* **245**, 106557. https://doi.org/10.1016/j.agwat.2020.106557.

Zhao, X. K., Li, Z. Y. & Zhu, Q. K. 2017 Change of precipitation characteristics in the water-wind erosion crisscross region on the Loess Plateau, China, from 1958 to 2015. *Scientific Reports* **7**, 8048. https://doi.org/10.1038/s41598-017-08600-y.

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