

# Copulas-Based Drought Evolution Characteristics and Risk Evaluation in a Typical Arid and Semi-Arid Region

Shengzhi Huang · Qiang Huang · Jianxia Chang ·  
Yutong Chen · Li Xing · Yangyang Xie

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**Abstract** The Wei River Basin, a typical arid and semi-arid region, is frequently attacked by droughts, which heavily limits its sustainable development of society and economy. Therefore, the main motivation of this study is to investigate the drought evolution characteristics and risk evaluation in the basin, which is crucial for drought warning, water resources management as well as agricultural development. The modified Mann-Kendall test trend method was used to capture the trend of the severity and duration of historical drought events, and the persistence of droughts was analyzed based on the Rescaled Range (R/S) analysis. Additionally, the Morlet wavelet analysis was utilized to calculate the period of dry and wet condition, and copulas were applied to calculate the joint return period of two typical scenarios. The main results are as follows: (1) the whole basin has an obviously dry trend, especially in autumn and winter; furthermore, the months with a wet trend are primarily concentrated in July and August; (2) the persistence of droughts is strong, indicating that droughts in the near future may be persistent; (3) the average “or” and “and” joint return periods under scenario (1) where drought duration is 6 months and drought severity is 4 are approximately 15.6 and 28.9 years, respectively, while those under scenario (2) where drought duration is 8 months and drought severity is 6 are approximately 34.9 and 53.1 years, respectively. In general, the drought risk of the northwestern basin is larger than that of the southeastern basin.

**Keywords** Drought evolution characteristics · Drought risk assessment · Copula · The Bayesian copula selection method · The Wei River Basin

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S. Huang (✉) · Q. Huang · J. Chang · Y. Chen · Y. Xie  
State Key Laboratory Base of Eco-Hydraulic Engineering in Arid Area, Xi'an, China  
e-mail: huangshengzhi7788@126.com

S. Huang · Q. Huang · J. Chang · Y. Chen · Y. Xie  
Xi'an University of Technology, Xi'an 710048, China

L. Xing  
Department of Atmospheric and Oceanic Sciences and Laboratory for Climate and Ocean-atmosphere  
Studies, School of Physics, Peking University, Beijing 100871, China

## 1 Introduction

Over the past century, the global climate and environment have witnessed a significant change. They are primarily characterized by global warming, which leads to accelerating water circulation, thereby resulting in high-frequency extreme events such as droughts and floods on a global scale (Roy and Balling 2004; Beniston and Stephenson 2004; Kunkel 2003; Christensen and Christensen 2004). The societal influences of such natural hazards are increasingly intensifying and the development of society and economy tends to be more and more vulnerable (Zhang et al. 2012a). Therefore, it is becoming a focus on investigating extreme weathers and their related societal effects (Mudelsee et al. 2003; Leng et al. 2014).

Drought is a kind of natural hazards, and it can cause considerable losses in the environment, agriculture and social economy (Wilhite 2000). According to Heim (2002), environmental droughts were mainly cataloged as hydrological droughts, meteorological droughts, agricultural droughts and socioeconomic droughts. Compared with any other kinds of natural hazards, droughts affect more areas and have longer durations, and they have the most frequent occurrence (WMO 1997). Additionally, droughts have a great effect on society, economy and environment, and have a strong impact on agriculture and water supply, thus resulting in profound impacts on society. According to Wilhite (2000), it was evaluated that the global economic losses due to droughts reached up to 6~8 billion US dollars every year, which is far more than other types of meteorological hazards. Droughts are regarded as a most expensive but least understood natural hazards. Therefore, the risk assessment and changing characteristics of droughts have been attached much importance in recent decades (e.g., Lei and Duan 2010; Liroyd-Hughes 2010).

Droughts usually start as meteorological droughts induced by precipitation deficits. Subsequently, a lasting meteorological drought can lead to a deficit in soil moisture, surface water and groundwater supply, thereby resulting in agricultural and hydrological drought. Many indices are used to characterize meteorological drought, and the Reconnaissance Drought Index (RDI) which contains the deficit between precipitation and evaporative demand of the atmosphere is an ideal index to depict meteorological drought due to its sound physical meaning (Tsakiris et al. 2007). However, it is intensive computation and data demanding. The SPI is widely applied to reveal meteorological droughts and has been proven to be an effective tool in assessing the duration and severity of droughts due to its simplicity and effectiveness (Angelidis et al. 2012; Raziie et al. 2013; Huang et al. 2014b). Wilhite and Glantz (1985) used SPI with various timescales to monitor drought variations. Livada and Assimakopoulos (2007) applied SPI to analyze drought events in Greece. Morid et al. (2006) indicated that SPI could identify the onset of a drought and should be applied to operational drought monitoring. Thus, this study investigated meteorological drought across a region based on the Standardized Precipitation Index (SPI).

The Wei River Basin, a typical arid and semi-arid region, is an important region for China, especially after the establishment of the Guanzhong-Tianshui Economic Zone, which is a national key economic development zone and acts as a direct stimulus to the rapid economic development of the whole western region in China. The Guanzhong Plain which is located in the southeastern basin is also a very important national agricultural production region, and the local government attempts to build it as a core area of grain production ensuring stable yields despite of drought or excessive rain. However, the available water resources in the basin are extremely limited. Per capita and acre possessions of river runoff in the basin are only 308 and 174 m<sup>3</sup>, respectively, which only account for 13 % and 9 % of the corresponding national average values, respectively. To make matters worse, within the recent decades, the runoff in the basin had a significantly decreasing trend caused by climate changes and human activities

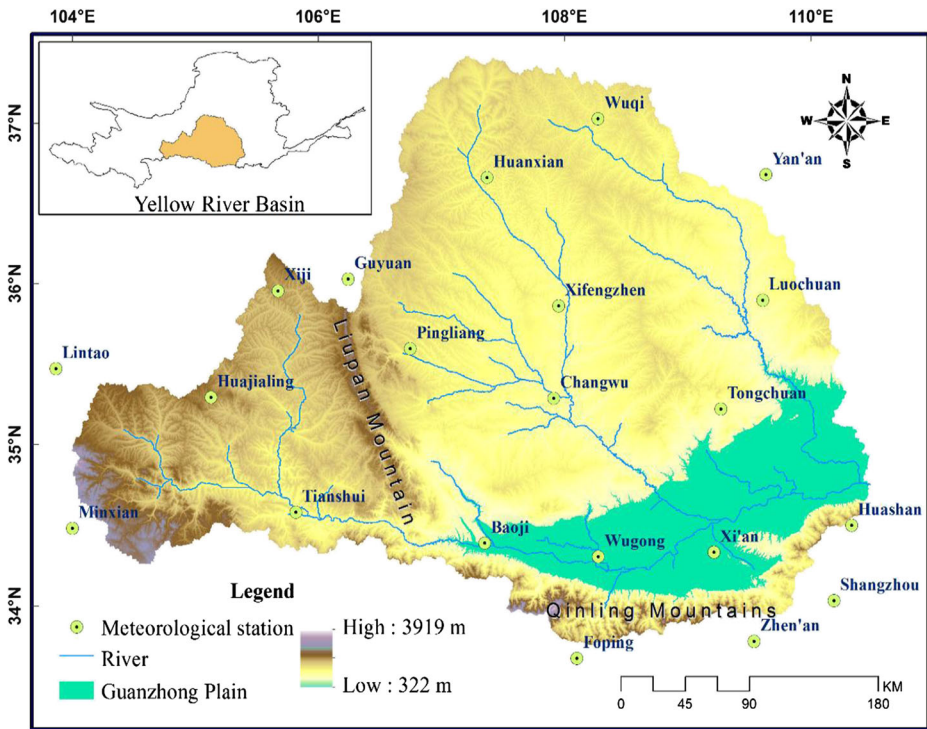
(Huang et al. 2014a), which heavily restricted local economic and social development. It should be emphasized that natural hazards often occur in this basin, amongst these natural hazards, droughts have the highest frequency and their damages are largest. Additionally, droughts play an important role in affecting regional economic structure adjustment and local utilization of water resources. Based on what outlined above, it is of great importance to investigate drought evolution characteristics and risk evaluation in the Wei River Basin, which is useful in drought prediction, reducing the adverse effect of drought as well as taking effective hazard prevention and mitigation measures.

Some studies have been conducted to investigate the drought of the Wei River Basin. Zhang et al. (2008a, b) used the Mann-Kendall trend test method to analyze the trend of hydrological drought and agricultural drought in the Wei River Basin. Ma and Song (2012) conducted a research concerning the spatial distribution of drought indices and found that the drought in this basin had a seasonal characteristic. However, these studies only placed emphasis on one or two of the trend, space-time distribution, frequency analysis and risk assessment of droughts and lacked a comprehensive and systematic investigation, which is greatly important to regional agricultural production, ecology health and economic development. Therefore, this study aims to comprehensively and systematically reveal meteorological drought evolution characteristics and risk evaluation in the Wei River Basin. The main objectives of this study are to: (i) investigate the spatio-temporal changes of drought properties; (ii) analyze the persistence of drought and the period of wet and dry condition; (iii) assess the drought risk in the Wei River Basin. The overall objective of this study is to shed light on the drought evolution and its risk in the Wei River Basin and to provide a solid foundation for local water resources planning and management. The findings of this research will be helpful for reasonable water resources management and agricultural development under the background of changing climate.

## 2 Study Area and Data

### 2.1 Introduction of the Wei River Basin

The Wei River Basin, as shown in Fig. 1, is selected in this research. The Wei River lies between 103.5°E~110.5°E and 33.5°N~37.5°N, covering a total area of  $1.35 \times 10^5$  km<sup>2</sup>. Located in a continental monsoon climate zone, the basin is characterized by relatively abundant precipitation and high temperature in summer, and dominated by sparse precipitation and low temperature in winter. Annual precipitation of the basin is approximately 559 mm (Zhang et al. 2008a, b). Precipitation varies monthly and annually, which in flood season (from June to September) generally accounts for approximately 60 % of total annual precipitation. Annual precipitation also varies greatly due to the unstable characteristic of the intensity, duration and influencing area of the subtropical high pressure belt over the northern Pacific. The subtropical high pressure belt has a great effect on local precipitation, and easily triggers highly frequent droughts and floods. Topographically, the altitude decreases from the highest northwest mountainous areas to the lowest Guanzhong Plain in the southeast and southern portion of the basin. In addition, the Guanzhong Plain is a very important agricultural production zone, and agriculture plays an important role in local economy. Additionally, many industrial parks are also built in this plain. These industrial parks require a large amount of water to support their normal operations. However, in recent decades, the precipitation of the basin has a decreasing trend, thus, the available water resources in this basin are shortage, failing to satisfy the water demand of local socioeconomic development and eco-environmental requirement. In view of the significance of water security in the basin, a further



**Fig. 1** The locations of the Wei River Basin and related meteorological stations in the Yellow River Basin, China

investigation is very necessary to understand the drought evolution characteristics and risk evaluation in the Wei River Basin, which is crucial to local water resources management, economic development and agricultural practices under the backdrop of global climate changes.

**2.2 Study Data**

Daily precipitation data collected from 21 meteorological stations in the Wei River Basin were used in this study, whose locations are presented in Fig. 1 and their details are exhibited in Table 1. Each station has daily precipitation data covering January 1, 1960~December 31, 2010, which were acquired from the National Climate Center (NCC) of the China Meteorological Administration (CMA).

**3 Methodologies**

Section 3.1 will introduce the characteristic and calculation of SPI, Section 3.2 and 3.3 will introduce the modified Mann-Kendall (MMK) trend test method and Rescaled Range Analysis, respectively, which can be used to compute the trend and persistence of time series. Then, Copula function including their parameter estimation and selection will be introduces. Finally, how to calculate the joint return period of droughts will be introduced.

**Table 1** Information on meteorological stations analyzed in this study

Station	Station No.	Longitude (E)	Latitude (N)	Elevation (m)	Hurst index
Lintao	1	103.85	35.35	1893.8	0.67
Minxian	2	104.02	34.043	2315	0.66
Huajialin	3	105	35.38	2450.6	0.67
Xiji	4	105.72	35.97	1916.5	0.66
Tianshui	5	105.75	34.58	1141.7	0.69
Guyuan	6	106.27	36	1753	0.65
Pingliang	7	106.67	35.55	1346.6	0.65
Baoji	8	107.13	34.35	612.4	0.68
Huanxian	9	107.3	36.58	1255.6	0.70
Xifengzhen	10	107.63	35.73	1421	0.63
Changwu	11	107.8	35.2	1206.5	0.67
Foping	12	107.98	33.52	827.2	0.68
Wuqi	13	108.17	36.92	1331.4	0.67
Wugong	14	108.22	34.25	447.8	0.68
Xi'an	15	108.93	34.3	397.5	0.66
Tongchuan	16	109.07	35.08	978.9	0.68
Zhen'an	17	109.15	33.43	693.7	0.67
Yan'an	18	109.5	36.6	958.5	0.67
Luochuan	19	109.5	35.82	1159.8	0.66
Shangzhou	20	109.97	33.87	742.2	0.68
Huashan	21	110.08	34.48	2064.9	0.66

The source of data comes from the National Climate Center (NCC) of the China Meteorological Administration (CMA)

### 3.1 Standardized Precipitation Index (SPI)

The SPI was first proposed by McKee et al. (1993) to estimate drought conditions in Colorado. It has the ability to monitor precipitation conditions in a desired period in a long time series and reflects the precipitation deficits corresponding to the period. Since the SPI can easily capture the features of droughts with different time scales (1, 3, 6, 12, 24, 48 months), it has been broadly applied to study droughts (Zhang et al. 2012c; Logan et al. 2010). The SPI can monitor the short-term water supplies, which is very importance to water management and agricultural production. Short-term shortage of soil moisture may exert a great influence on agricultural production, thereby triggering an agricultural drought (Mishra and Singh 2010). Thus, the droughts in this study are described by a SPI with a timescale of 3 months.

SPI can be formulated as follows:

$$SPI = S \frac{t - (c_2 t + c_1)t + c_0}{((d_3 t + d_2)t + d_1)t + 1.0}, \quad t = \sqrt{\ln \frac{1}{H(x)^2}} \tag{1}$$

$$G(x) = \frac{1}{\beta^\gamma \Gamma(\gamma)_0} \int_0^x x^{\gamma-1} e^{-x/\beta} dx, x > 0, \quad \Gamma(\gamma) = \int_0^\infty x^{\gamma-1} e^{-x} dx \tag{2}$$

where,  $x$  denote precipitation value;  $\beta$  and  $\gamma$  represent the scale parameter and shape parameter of the  $\Gamma$  function;  $S$  denotes positive and negative coefficients;  $c_0, c_1, c_2$  and  $d_1, d_2, d_3$  are constants (Ma and Song 2012). Their values are as follows:

$c_0=2.515517, c_1=0.802853, c_2=0.010328, d_1=1.432788, d_2=0.189269, d_3=0.001308$  (Ma and Song 2012).  $G(x)$  denotes the probability distribution of precipitation. When  $G(x) > 0.5$ , then  $H(x)=1- G(x)$  and  $S=1$ ; otherwise,  $H(x)=G(x)$  and  $S=-1$ .

Furthermore, the classification of droughts based on SPI is presented in Table 2.

### 3.2 The Modified Mann–Kendall (MMK) Trend Test Method

The modified Mann–Kendall trend test method (MMK) (Mann 1945; Kendall 1955; Hamed and Rao 1998) was utilized to capture the trend of the meteorological variables in the Wei River Basin. The initial Mann–Kendall (MK) test recommended by the World Meteorological Organization (Mitchell et al. 1966; Zhang et al. 2012b) is a nonparametric approach. However, the MK test results are affected by the persistence of time series. Therefore, Hamed and Rao (1998) made an improvement on the MK test by taking into account the lag- $i$  autocorrelation to eliminate the persistence.

For a time series of  $n$  observations  $X=x_1, x_2, \dots, x_n$ , the MK trend statistic  $S$  is computed as follows (Kendall 1955):

$$S = \sum_{i < j} \text{sgn}(x_j - x_i) \tag{3}$$

where

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & x_j > x_i \\ 0 & x_j = x_i \\ -1 & x_j < x_i \end{cases} \tag{4}$$

The variance of  $S$  is proposed by (Kendall 1955):

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{5}$$

Then, the standardized test statistic  $Z = \frac{S}{\sqrt{\text{Var}(S)}}$  with the standard normal variable at the desired significance level is calculated to test the significance of the time series trend. Hamed and Rao (1998) indicated that the significant temporal autocorrelations of a time series disturbs the evaluation of the variance of  $S$ . For removing the persistence influences, Hamed and Rao (1998) suggested extracting a nonparametric trend estimator from the original time series to

**Table 2** Drought and wet period classification according to the SPI index

Index value	Category
Extreme drought	$\text{SPI} \leq -2.00$
Severe drought	$-1.99 < \text{SPI} \leq -1.50$
Moderate drought	$-1.49 < \text{SPI} \leq -1.00$
Near normal	$-0.99 < \text{SPI} \leq 0.99$
Moderately wet	$1.00 < \text{SPI} \leq 1.49$
Very wet	$1.49 < \text{SPI} \leq 1.99$
Extremely wet	$\text{SPI} \geq 2.00$

The source of data is derived from Zhang et al. (2012c)

estimate the autocorrelation coefficients of the new time series ranked by size. Autocorrelation coefficients ( $\rho_s(i)$  at lag ( $i$ )) which are significantly different from zero at the 5 % level are then used to estimate the modified variance of  $S$ ,  $V^*(S)$  as follows (Hamed and Rao 1998):

$$V^*(S) = Var(S)Cor \tag{6}$$

where  $Cor$  denotes a correction due to the autocorrelation in the time series, which is calculated as follows (Hamed and Rao 1998):

$$Cor = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-1)(n-i-1)(n-i-2)\rho_S(i) \tag{7}$$

### 3.3 Rescaled Range Analysis (R/S analysis)

The basic thought of R/S analysis is to change the timescale of sample series and investigate the statistical law at different scales. Its basic principle is as follows (Oliver and Ballester 1996):

For an original precipitation series of  $n$  observations  $X=x_1, x_2, \dots, x_n$ , its average series is calculated as follows:

$$y(\tau) = \frac{1}{\tau} \sum_{t=1}^{\tau} x(t) \quad \tau = 1, 2, \dots \tag{8}$$

Its deviation is computed as follows:

$$F(t, \tau) = \sum_{t=1}^{\tau} x(t) \quad 1 \leq t \leq \tau \tag{9}$$

Its range is computed as follows:

$$R(\tau) = \max_{1 \leq t \leq \tau} F(t, \tau) - \min_{1 \leq t \leq \tau} F(t, \tau) \tag{10}$$

And its standard deviation is expressed as:

$$S(\tau) = \left| \frac{1}{\tau} \sum_{t=1}^{\tau} (x(t) - y(\tau)) \right|^{1/2} \tag{11}$$

There is a certain link between its range and standard deviation:

$$R(\tau)/S(\tau) = (C\tau)^H \tag{12}$$

where  $C$  is constant, and  $H$  denotes Hurst index (Oliver and Ballester 1996).

The different Hurst index denotes different types of time series. When  $H=0.5$ , it indicates that this series is completely independent, when  $0 < H < 0.5$ , it means that the future trend of the series will be opposite to that of the past series, and a smaller  $H$  value denotes a stronger persistence. Whilst  $H > 0.5$ , it indicates that the future trend of precipitation will be consistent with that of the past series, and a larger  $H$  value denotes a stronger persistence. Therefore, this method can be applied to analyze the trend of drought in the near future.

### 3.4 Copula Function and Their Parameter Estimation and Selection

Copula function can build various variables with different marginal distributions as a joint distribution. There are many kinds of copula functions, the archimedean copulas were utilized in this study due to their simple structure and strong representativeness. Their expression is as follows:

$$C(u, v) = \varphi^{-1}(\varphi(u), \varphi(v)) \quad (13)$$

where  $\varphi$  denote a generator, it is continuously decreasing within its range, and  $\varphi(1)=0$ , additionally,  $\varphi$  is a convex function. Given all of the archimedean copulas (Gumbel Copulas, Clayton Copulas and Frank Copulas) have these advantages outlined above, thus, the three sorts of copulas function were used in this study. A nonparametric estimation method proposed by Genest and Rivest (1993) was used to calculate the copulas function. Regarding the joint distribution of drought duration and drought severity, the three kinds of archimedean copulas were used for fitting joint distribution, and the Bayesian copula selection method proposed by Huard et al. (2006) was used to evaluate their fitting effects and choose the best appropriate copula function. The existing methods for selecting the appropriate copula family pose considerable difficulties and none is completely satisfied. The Bayesian copula selection method is a reliable and simple approach to select the best copula. The corresponding program code can be free downloaded in this website: <http://code.google.com/p/copula/>.

### 3.5 Return Period of Droughts

The bivariate return period of a drought can be calculated by replacing the univariate cumulative density function (CDF) with the bivariate CDF. For instance, the bivariate return periods of the drought with drought duration ( $D$ ) and severity ( $S$ ) whose definitions are based on the theory of run (Zhang et al. 2012c) are expressed as follows:

$$T_{(S>s\cup D>d)} = \frac{1}{\theta P(S > s \cup D > d)} = \frac{1}{\theta(1-F(s, d))} \quad (14)$$

$$T_{(S>s\cap D>d)} = \frac{1}{\theta P(S > s \cap D > d)} = \frac{1}{\theta(1-F(s)-F(d) + F(s, d))} \quad (15)$$

where  $\cup$  denotes union, and  $\cap$  represents intersection.  $F(s)=P(S\leq s)$ ,  $F(d)=P(D\leq d)$ , and  $F(s, d)$  stands for the joint distribution. For the sake of convenience, the joint bivariate return period of drought event  $(S>s\cup D>d)$  and  $(S>s\cap D>d)$  are called as bivariate “or” and “and” return period, respectively.

## 4 Results and Discussion

### 4.1 The Trend Analysis of Dry and Wet Condition in the Wei River Basin

When the absolute value of the statistic of the MMK is larger than 1.96, it means that the trend of the time series is significant at the 95 % significance level. If this value is positive, it denotes that wet trend is significant. Conversely, if this value is negative, it means that dry tendency is

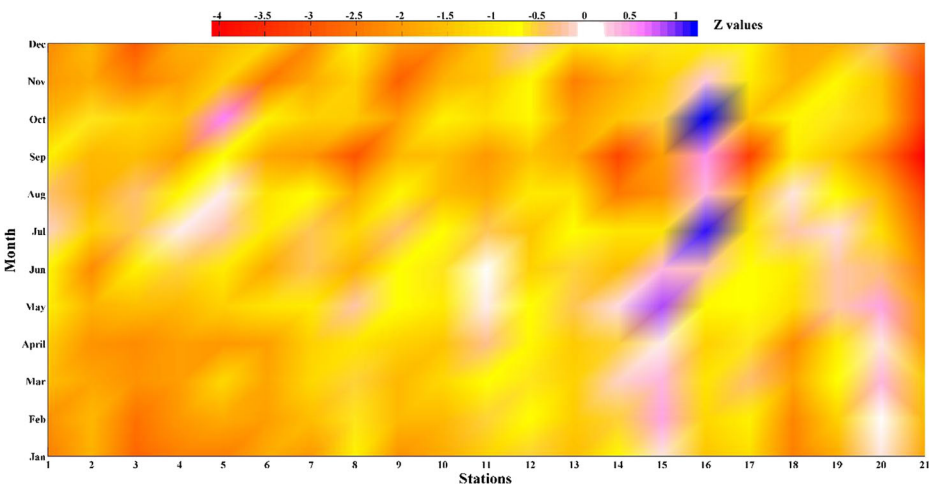


significant. The trends of SPI covering 1960–2010 of the 12 months at each station in the basin are exhibited in Fig. 2. The meteorological stations in Fig. 2 are arranged according to their magnitude of longitudes, from west to east. Thus, the results of the SPI trends can reflect the spatio-temporal changes characteristics of dry and wet conditions in the Wei River Basin.

It can be seen from Fig. 2 that the whole basin has a noticeably dry trend, especially for the central and western part of the basin where almost all the SPI values of every month have a downward trend. As regards the eastern basin, the SPI values of May, June, July, September and October at Xi'an and Tongchuan stations have a non-significantly upward trend. In general, amongst all the seasons, the SPI values of autumn and winter in the whole basin have an obviously decreasing trend, implying that this basin have an remarkably dry trend in autumn and winter. It should be noted that autumn and winter are the seasons of winter wheat cultivation in the basin, which needs considerable water to satisfy its normal growing demand. Thus, the drought trend has a heavily adverse effect on local agricultural development, and the relevant department should take some effective measures in advance to relieve the damage of possible drought. Furthermore, the months with a wet trend are primarily concentrated in July and August. Note that July and August are the flood season in the Wei River Basin. However, the wet tendency further increases local flood control pressure. Therefore, under the background of climate changes and intensifying human activities, the hydrological response in the basin is that the flood season has a wet trend and the non-flood season has a dry trend. This response not only increase drought risk, but also has an exceedingly adverse effect on water resources management. These findings are similar to Li et al. (2005), who found that the precipitation in summer has a non-significantly increasing trend in the Guanzhong Plain, but that in autumn has a significantly decreasing trend. It should be emphasized that the geomorphology of many areas in the Wei River Basin belongs to the loess plateau, whose ecological environment is greatly fragile. Hence, the dry trend in these areas has a large resistance to the improvement and recovery of local ecological environment.

#### 4.2 The Spatio-temporal Changes in Historical Drought Events

Based on the statistics of MMK concerning the severity and duration of historical drought events in the basin, the Inverse Distance Weighted method based on ArcGIS software was used to obtain the spatial patterns of the severity and duration of the historical drought events.



**Fig. 2** The trend of SPI in 12 months at each station in the Wei River Basin

The spatial patterns of the severity and duration of the historical drought events are exhibited in Fig. 3.

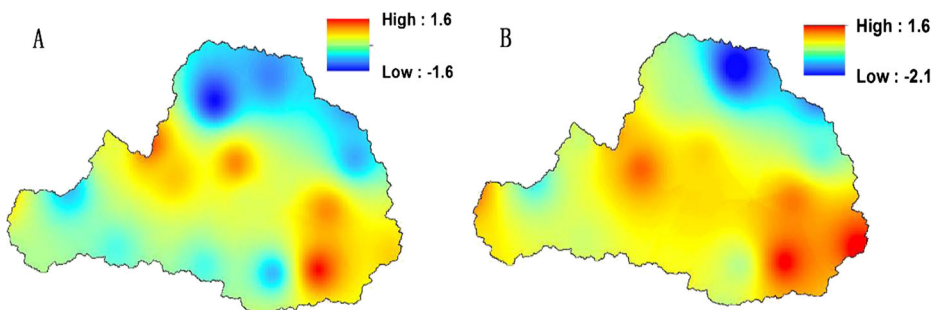
Figure 3a shows that the statistics of the MMK values of drought severity in the whole basin range from  $-1.6$  to  $1.6$ , indicating that all the trends of drought severity in this basin are not statistically significant. Drought severity in the northern and western part of the basin has a decreasing trend, whilst that in the central and eastern basin has an increasing trend, which may imply a slightly intensifying drought. It should be stressed that the central basin is mainly located in the loess plateau, where soil erosion are serious and ecological environment is very fragile, whereas the eastern basin is an economically developed area. Therefore, the intensifying drought events have an extremely adverse impact on local ecological environmental protection and economic development. The spatial pattern of drought duration in the basin is exhibited in Fig. 3b. The statistics of the MMK values of drought duration in the whole basin is in the range of  $-2.1 \sim 1.6$ . The Wuqi station in the northern basin has a significantly downward trend at the 95 % significance level. Similarly, the central and eastern basin has a non-significantly upward trend. Overall, the spatial pattern of drought severity is slightly similar to that of drought duration.

#### 4.3 The Trend of Drought in the Near Future in the Wei River Basin

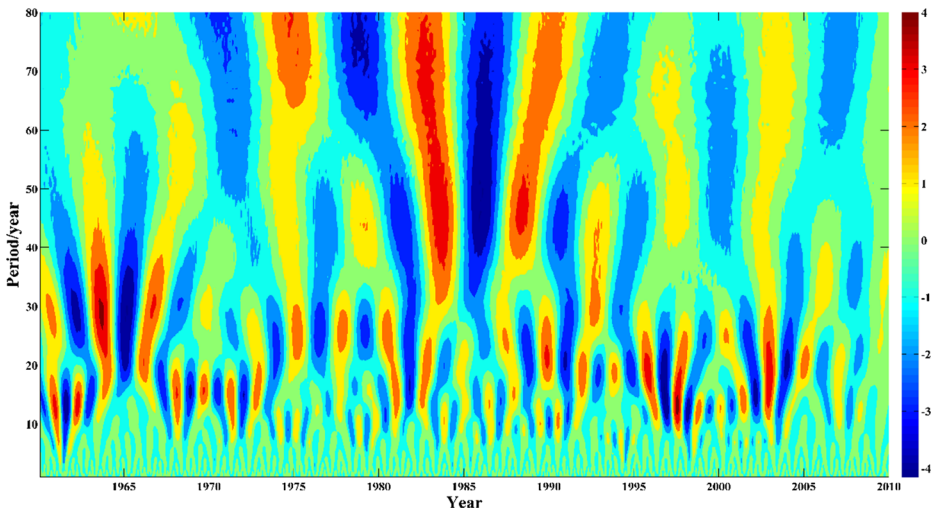
In order to obtain possible change trend of drought in the Wei River Basin in the near future, which is very important to local water resources management and agricultural development, the R/S analysis was used to calculate the persistence of droughts. The specific procedures of computing the persistence of droughts are according to what outlined in Section 3.3, and the Hurst index of the SPI values at each station are shown in Table 1. It can be observed from Table 1 that the Hurst index of the SPI at each station range from 0.63 to 0.70, which implies that the droughts in the basin have a strongly positive persistence. Therefore, the trend towards droughts may continue in the near future, and the drought control pressure of related department may further increase. Thus, some effective measures to control droughts should be taken in advance in order to reduce the damage caused by droughts.

#### 4.4 The Period of Dry and Wet Condition in the Wei River Basin

To obtain the period of dry and wet conditions in the Wei River Basin, the wavelet analysis based on the Morlet wavelet was used in this study and the time-frequency distribution of SPI values is illustrated in Fig. 4.



**Fig. 3** The spatial patterns of drought severity (a) and drought duration (b) of the historical drought events in the Wei River Basin



**Fig. 4** The time-frequency distribution of SPI values in the Wei River Basin

The red color in Fig. 4 denotes positive phase, and the blue color represents negative phase. The striking alternation of positive and negative phase denotes the alternation of dry and wet condition. Therefore, it can be observed from Fig. 4 that multiple periods exist during 1960–2010. During 1960–1975, a primary period of approximately 11 years and a secondary period of approximately 32 years are found in this figure, whilst a primary period of approximately 22 years is detected during 1975–2010. All of the periods identified in Fig. 4 may be linked to the 11-year Schwabe sunspot cycles (range of 8–17 years) and 22-years solar Hale cycles, respectively (Weedon 2003). The Schwabe sunspot cycles is the periodic change in the appearance and activity of the Sun. Solar variation plays an important role in affecting changes in weather, space weather and climate on Earth (Camp and Tung 2007). Some researches (Qu et al. 2004; Cong et al. 1995) indicated that the sun activities influence the condition of climate and atmosphere by way of radiation changes and inspiring the magnetic field change in the earth, thus affecting the climate in the earth. The two ways are closely related to the magnetic field changes in the sunspot activities. Cong et al. (1995) indicated that the dramatic change period of magnetic factors was closely associated with the striking climate changes in the Yellow River Basin. The period of its low intensity was related to the high-frequency occurrence of flood, whilst the period of its high intensity was associated with high-frequency occurrence of drought. Therefore, the sun activities caused by the sunspot activities have a great effect on the alteration of dry and wet to some extent. However, the details need to be further studied.

#### 4.5 The Joint Return Period Analysis of Typical Drought

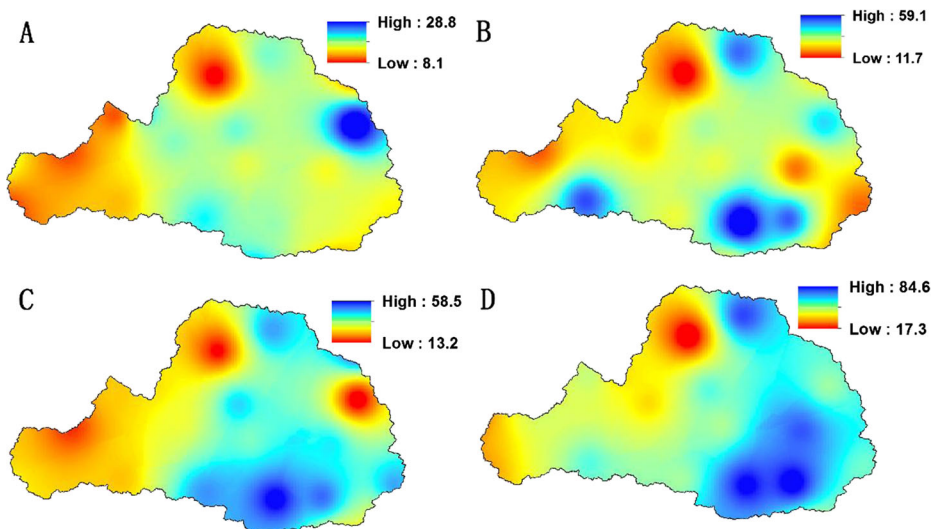
Exponential distribution and geometric distribution were used to fit drought duration distribution, whilst Gamma distribution, lognormal distribution and generalized Pareto distribution were applied to fit drought severity distribution. Regarding drought duration, exponential distribution passed the Kolmogorov-Smirnov (K-S) test at all the stations. As regards drought severity, Gamma distribution and lognormal distribution passed the K-S test at all stations, whilst generalized Pareto distribution passed the K-S test at approximately 53 % of all the

stations. The distribution used to fit the marginal distribution depends on their goodness of fitting. Furthermore, the Bayesian copula selection method was used to choose the appropriate copula function, the Gumbel Copula has the best goodness of fitting at approximately 80 % of all stations, and the Clayton Copula has the best goodness of fitting at the rest of stations.

For the sake of convenience, the joint bivariate return periods of drought events expressed as  $(S > s \cup D > d)$  and  $(S > s \cap D > d)$  are called as the joint “or” and “and” return periods, respectively. According to formula (14)–(15), the two types of joint return periods in the Wei River Basin were calculated, the spatial patterns of the joint return periods in the whole basin were obtained based on the Inverse Distance Weighted method. Based on the historical drought events, two typical drought scenarios were defined: (1) drought duration is selected as 6 months and drought severity is selected as 4, which is regarded as a typically moderate drought in this study; (2) drought duration is selected as 8 months and drought severity is selected as 6, which is regarded as a typically severe drought in this study.

The spatial patterns of the joint return periods under the two scenarios are exhibited in Fig. 5. Regarding scenario (1), the average “or” joint return period in this basin is approximately 15.6 years (see Fig. 5a), and the average “and” joint return period is approximately 28.9 years (see Fig. 5b). In general, the possibility of moderate drought in the basin is high, and the drought return period of northwestern basin is smaller than that of southeastern basin, which implies that the drought risk of northwestern basin is larger than that of southeastern basin. The “or” joint return periods are smaller than the “and” joint return periods. For the “or” return periods, there is an area with a low frequency of drought located around Luochuan station in the eastern basin. Regarding the “and” return periods, there is an area with a low frequency of drought located around Wugong station in the southern basin.

As regards scenario (2), the average “or” joint return period in this basin is approximately 34.9 years (see Fig. 5c), and the average “and” joint return period is approximately 53.1 years (see Fig. 5d). Whether for the “or” return periods or “and” return periods, the return periods of northwestern basin are far smaller than those of southeastern basin. The lowest return period



**Fig. 5** The joint return periods under two typical drought scenarios, **a** “or” joint return periods under scenario (1), **b** “and” joint return periods under scenario (1), **c** “or” joint return periods under scenario (2), and **d** “and” joint return periods under scenario (2)

belongs to Huanxian station, whose “or” and “and” joint return periods are 13.2 and 17.3 years, respectively. The areas around Huanxian station have a higher drought risk compared with the central, eastern and southern basin. Additionally, for the “or” joint return periods, there is an area located around Luochuan station with a high drought risk. Overall, whether for moderate drought or severe drought, the northwestern basin has a higher drought risk than other regions. Moreover, as regards the southeastern basin, the probability of moderate drought is greatly larger than that of severe drought. These findings are similar to Ma and Song (2012a), who indicated that the probability of drought in the northwestern basin is larger than that of the southeastern basin. The primary cause of this phenomenon is that the northwestern basin is located in the mainland hinterland and far away from oceans, local natural conditions determine its drought characteristic. Therefore, the drought in this region belongs to “absolute drought”. If the precipitation in this region has a small reduction, it easily results in a drought. Conversely, the precipitation of the southeastern basin is far more than that of the northwestern basin, this region primarily suffers droughts due to the inter-annual or intra-annual uneven distribution of precipitation, in this case, the drought of this region belongs to “relative drought”. Essentially, the drought risk of the northwestern basin is larger than that of the southeastern basin. Therefore, the relevant department should enhance drought monitoring efforts of the northwestern basin and prepare for hazard prevention and mitigation in advance.

## 5 Conclusions

Investigating drought evolution characteristics and risk evaluation is crucial for drought warning, water resources management and agricultural development. The spatio-temporal changes in the severity and duration of historical drought events in the Wei River Basin were investigated based on the modified Mann-Kendall trend test method, and the persistence of droughts was acquired based on the R/S analysis. Additionally, the period of dry and wet condition was obtained by the Morlet wavelet analysis. Furthermore, the joint return periods of two typical drought scenarios in the basin were calculated by copula-based method. The main conclusions are as follows:

- (1) The whole basin has an obviously dry trend, especially in autumn and winter when are the seasons of winter wheat cultivation. Therefore, the dry trend exerts an extremely adverse effect on regional agricultural development. Additionally, the months with a wet trend are primarily concentrated in July and August when are the flood season in the basin, thus, the wet trend further increases local flood control pressure.
- (2) The drought severity and duration in the central and eastern basin have an increasing trend, whilst those in other region have a decreasing trend. In general, the spatial pattern of drought severity is slightly similar to that of drought duration.
- (3) The positive persistence of droughts in the Wei River Basin is strong, indicating that droughts in this basin in the near future may be persistent.
- (4) Multiple periods are found, a primary period of approximately 11 years and a secondary period of approximately 32 years are found during 1960–1975, whilst a primary period of approximately 22 years is identified during 1975–2010. All the periods may be closely associated with the sunspot activities.
- (5) The average “or” and “and” joint return periods under scenario (1) are approximately 15.6 and 28.9 years, respectively, those under scenario (2) are approximately 34.9 and 53.1 years, respectively. In general, the drought risk of the northwestern basin is larger than that of the southeastern basin.

The Wei River Basin is a typical arid and semi-arid area with limited water resources. Frequent occurrence of droughts will inevitably further intensify local contradiction between supply and demand of water resources. Therefore, these findings in this study will be helpful in water resources management, agricultural development and drought warning.

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