J Arid Land (2016) 8(2): 157–171
doi: 10.1007/s40333-015-0022-3

Science Press Springer-Verlag

Spatio-temporal variation of hydrological drought under climate change during the period 1960–2013 in the Hexi Corridor, China

GAO Liming[1,2,3], ZHANG Yaonan[1,2*]

[1] Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China;
[2] Gansu Data Engineering and Technology Research Center for Resources and Environment, Lanzhou 730000, China;
[3] University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: In recent years, climate change has been aggravated in many regions of the world. The Hexi Corridor is located in the semiarid climate zone of Northwest China, which is particularly affected by climate change. Climate change has led to the spatial and temporal variations of temperature and precipitation, which may result in hydrological drought and water shortage. Thus, it is necessary to explore and assess the drought characteristics of river systems in this area. The patterns of hydrological drought in the Hexi Corridor were identified using the streamflow drought index (SDI) and standardized precipitation index at 12-month timescale (SPI12) from 1960 to 2013. The evolution of drought was obtained by the Mann–Kendall test and wavelet transform method. The results showed that both the mean annual SDI and SPI12 series in the Hexi Corridor exhibited an increasing trend during the study period. According to the results of wavelet analysis, we divided the study period into two segments, i.e. before and after 1990. Before 1990, the occurrence of droughts showing decreased SDI and SPI12 was concentrated in the northern part of the corridor and shifted to the eastern part of the corridor after 1990. The probability of drought after 1990 in Shule River basin decreased while increased in Shiyang River basin. The wavelet analysis results showed that Shiyang River basin will be the first area to go through the next drought period. Additionally, the relationships between drought pattern and climate indices were analyzed. The enhanced westerly winds and increased precipitation and glacier runoff were the main reasons of wet trend in the Hexi Corridor. However, the uneven spatial variations of precipitation, temperature and glacier runoff led to the difference of hydrological drought variations between the Shule, Heihe and Shiyang River basins.

Keywords: Hexi Corridor; streamflow drought index; standardized precipitation index; westerly index; glacier runoff; temperature

Citation: GAO Liming, ZHANG Yaonan. 2016. Spatio-temporal variation of hydrological drought under climate change during the period 1960–2013 in the Hexi Corridor, China. Journal of Arid Land, 8(2): 157–171. doi: 10.1007/s40333-015-0022-3

Drought is a natural phenomenon characterized by a significant decrease of water availability for a considerable period of time over a large area (Nalbantis and Tsakiris, 2009; Bahramand, 2014). Drought has significant effects on socio-economic activities and environments (Zamani et al., 2015). As there is no universal definition of drought, scientists of various disciplines measure this phenomenon in terms of meteorological drought, hydrological drought, agricultural drought and socioeconomic drought (Wilhite and Glantz, 1985; American Meteorological Society, 2004;

*Corresponding author: ZHANG Yaonan (E-mail: yaonan@lzb.ac.cn)
Received 2015-03-31; revised 2015-10-26; accepted 2015-11-04

Livada and Assimakopoulos, 2007; Tabari et al., 2013). The simplest way to monitor drought conditions is using drought indices, because these indices provide a quantitative method for determining the onset or end of a drought event and the level of drought severity. Numerous drought indices have been developed over the past decades to identify and quantify drought events (Buttafuoco et al., 2015). These include the Palmer Hydrological Drought Index (PHDI; Karl and Knight, 1985), the Surface Water Supply Index (SWSI; Shafer and Dezman, 1982), the Standardized Precipitation Index (SPI; McKee et al., 1993), the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010), the Reconnaissance Drought Index (RDI; Tsakiris et al., 2007), the Rainfall Anomaly Index (RAI; Moron, 1994), the Palmer Drought Severity Index (PDSI; Palmer, 1965), the Standardized Palmer Drought Index (SPDI; Ma et al., 2014) and the Streamflow Drought Index (SDI; Nalbantis and Tsakiris, 2009).

China is a drought-prone country and suffered frequent severe drought during the second half of the 20th century (Zou et al., 2005). Statistical data showed that 60% of the total area in China affected by all types of meteorological disasters (He et al., 2011). Under the background of global warming, the drought occurrence frequency and drought-affected area are still increasing (Li et al., 2003). Many studies had shown that much of northern China has experienced droughts since the 1950s, in which the most severe and prolonged droughts had occurred since 1990 (Zhai et al., 2010; Wang et al., 2011). Global warming makes wet regions wetter and dry regions drier (Liu and Allan, 2013). In arid and semi-arid regions of northwestern China, due to population growth and unreasonable environmental exploitation, the mainstreams and tributaries of many rivers are drying up (Chen et al., 2011). Thus, droughts are receiving an increasing attention in these areas, where greater demand on water supply has emerged due to increasing population (Wang et al., 2015).

The Hexi Corridor is a transition zone of humid and dry climate in Northwest China. Moreover, it is the commodity grain base of Gansu province. Because of its geographical position, drought is the dominant hazard in this area (Zhai and Feng, 2009). Chen et al. (2012) used three drought indices to determine the drought condition from the data of five meteorological stations in the Hexi Corridor and found the areas of Jiuquan and Gaotai were serious drought while the droughts of Zhangye, Shandan and Wuwei areas were relative light. Guo et al. (2011) analyzed the drought condition of the Hexi Corridor by using *Z* index and found drought in the central and western regions had a high degree of consistency. Zhai and Feng (2009) analyzed the spatial and temporal pattern of drought by using SPI in the Hexi Corridor and proposed severe drought differed among different regions. However, these studies mainly focused on the meteorological droughts according to the data of precipitation. However, these indices are inapplicable for the Hexi Corridor because of the low annual precipitation (Wang et al., 2009). Wang et al. (2009) first proposed the runoff drought index for hydrological drought, but only used data from three hydrologic stations in their study, which could not represent the spatial and temporal pattern of the whole region. Water shortages have become an increasingly serious problem in Northwest China (Kang, 2000; Ji et al., 2005). Hydrological drought challenges the management of water resources, as drought decreased water supplies while demand for water is continuously increasing due to population growth. So it is crucial to identify hydrological drought in the Hexi Corridor.

The drought indices used in this study were SDI and SPI. SDI is a very effective index for hydrological drought and SPI at long-term scales is also suitable for water resources management (Bonaccorso et al., 2003). The aims were to identify the hydrological drought dynamics and its related factors in the Hexi Corridor. The results of this study may provide references for the planning and management of water resource systems in this area.

1 Materials and methods

1.1 Study area and data collection

The Hexi Corridor located in the eastern part of arid areas of northwestern China (37°17′–42°48′N, 93°23′–104°12′E; Fig. 1). This region stretches from the Wushaoling in the east to the Dunhuang in the west and from the Qilian Mountains in the south to the Mazong, Heli and Longshou mountains in the north (Wang et al., 2009). Influenced by a continental climate and terrain, the water and heat distribution in the Hexi Corridor is uneven. On one hand, the annual average temperature, sunshine time and aridity generally increase from north to south and from east to west. On the other hand, annual precipitation and average relative humidity decrease from north to south and from east to west. The Hexi Corridor lies in the convergence area of two climate systems, the monsoon and the westerlies (Ji et al., 2005). The eastern part is mainly influenced by the monsoon climate system and the central and western regions are mainly affected by the westerlies. The Qilian Mountains are located in the border area between the monsoon and the westerlies. Therefore, the annual precipitation in this region has obvious spatial differences from less than 100 mm in the northern desert to more than 500 mm in the southern mountains (Ji et al., 2006). The evaporation capacity in most years is 2,000–3,000 mm (Ding and Zhang, 2004).

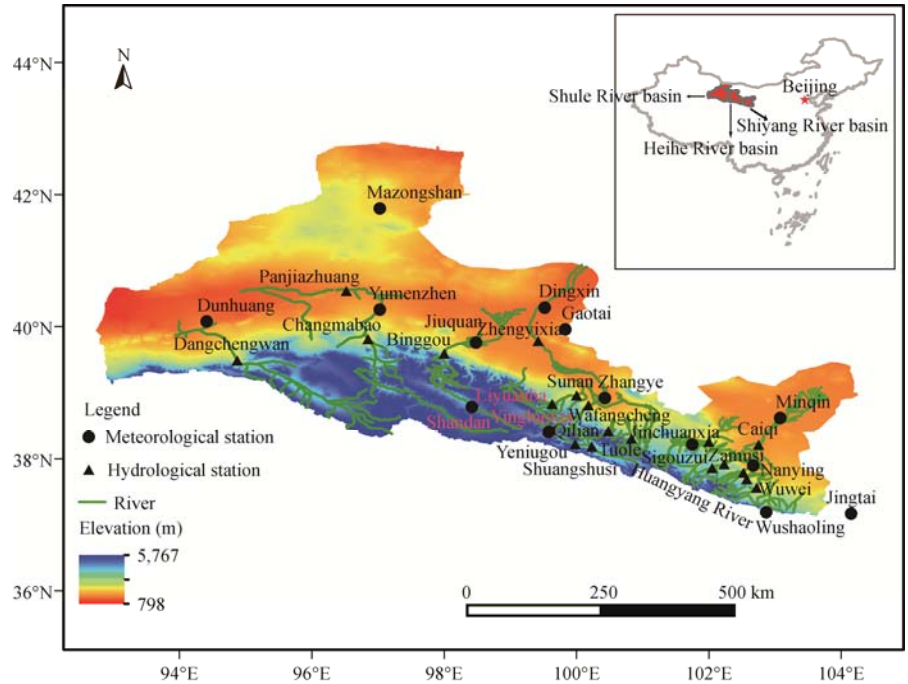

Fig. 1 Location of the Hexi Corridor and the typical hydrological and meteorological stations

The main rivers of the Hexi Corridor, from west to east, are the Shule, Heihe and Shiyang rivers. All of them originate from the Qilian Mountains. The average water volumes in the Shiyang, Heihe and Shule basins are 17.46×10^8, 41.59×10^8 and 22.78×10^8 m^3, respectively, with a total of 81.83×10^8 m^3 (Li et al., 2002). The total groundwater volume in the Hexi Corridor is 4.94×10^8 m^3, of which the Shiyang River basin contains 1.32×10^8 m^3, the Heihe River basin has 2.49×10^8 m^3 and Shule River basin has 1.13×10^8 m^3 (Gao et al., 2002). The utilization ratios of water resources have reached 154%, 112% and 76.4%, respectively, much higher than 40%, the internationally recognized alarm line (Falkenmark and Carl, 1992). Thus, the water problems in the Hexi Corridor became the focus (Wang and Cheng, 1999; Fang et al., 2007; Zhang, 2007; Wang, 2009).

In this work, the meteorological data were obtained from the Chinese Meteorological Data Sharing Service System (http://data.cma.gov.cn). Runoff data were collected from the Water Resources Department of Gansu province. The glacier runoff data were offered by the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences.

In order to reduce the impacts of human activities, we only choose the hydrological stations in the mountains and upstream regions for analysis. In addition, stations without continuous time series were all eliminated. At the end of the data processing, a total of 19 hydrological and 15 meteorological stations (Table 1) for the period of 1960–2013 were finally available for the analysis.

Table 1 Details of the hydrological and meteorological stations in the study area

Station	River basin	Category	Latitude	Longitude	Elevation (m)	Period
Dangchengwan	Shule River	Hydrological	39.50°N	94.87°E	2,176	1966–2013
Changmabao	Shule River	Hydrological	39.82°N	96.85°E	2,080	1960–2013
Panjiazhuang	Shule River	Hydrological	40.55°N	96.52°E	1,355	1960–2013
Dunhuang	Shule River	Meteorological	40.09°N	94.41°E	1,139	1960–2013
Yumenzhen	Shule River	Meteorological	40.27°N	97.03°E	1,526	1960–2013
Mazongshan	Shule River	Meteorological	41.08°N	97.03°E	1,770	1960–2013
Binggou	Heihe River	Hydrological	39.60°N	98.00°E	2,040	1960–2013
Liyuanbao	Heihe River	Hydrological	38.97°N	100.00°E	1,760	1960–2013
Yingluoxia	Heihe River	Hydrological	38.82°N	100.18°E	1,700	1960–2013
Zhamashenke	Heihe River	Hydrological	38.23°N	99.98°E	2,810	1960–2013
Qilian	Heihe River	Hydrological	38.20°N	100.23°E	3,020	1968–2013
Wafangcheng	Heihe River	Hydrological	38.43°N	100.48°E	2,440	1960–2013
Shuangshusi	Heihe River	Hydrological	38.32°N	100.83°E	2,570	1960–2013
Zhengyixia	Heihe River	Hydrological	39.79°N	99.42°E	1,280	1960–2013
Sunan	Heihe River	Hydrological	38.84°N	99.63°E	2,312	1962–2013
Jiuquan	Heihe River	Meteorological	39.77°N	98.48°E	1,477	1960–2013
Tuole	Heihe River	Meteorological	38.8°N	98.42°E	3,367	1960–2013
Gaotai	Heihe River	Meteorological	39.97°N	99.83°E	1,332	1960–2013
Dingxin	Heihe River	Meteorological	40.03°N	99.52°E	1,177	1960–2013
Yeniugou	Heihe River	Meteorological	38.42°N	99.58°E	3,320	1960–2013
Shandan	Heihe River	Meteorological	38.08°N	98.42°E	1,764	1960–2013
Zhangye	Heihe River	Meteorological	38.93°N	100.43°E	1,482	1960–2013
Jinchuanxia	Shiyang River	Hydrological	38.27°N	102.00°E	1,920	1960–2013
Jiutiaoling	Shiyang River	Hydrological	37.87°N	102.05°E	2,270	1960–2013
Sigouzui	Shiyang River	Hydrological	37.93°N	102.23°E	1,980	1960–1972
Nanyingshuiku	Shiyang River	Hydrological	37.80°N	102.52°E	1,940	1960–2013
Zamusi	Shiyang River	Hydrological	37.70°N	102.57°E	2,010	1960–2013
Huangyanghe	Shiyang River	Hydrological	37.57°N	102.72°E	2,070	1960–2013
Caiqi	Shiyang River	Hydrological	38.22°N	102.75°E	1,520	1960–2013
Yongchang	Shiyang River	Meteorological	38.23°N	101.75°E	1,976	1960–2013
Wuwei	Shiyang River	Meteorological	37.91°N	102.67°E	1,531	1960–2013
Wushaoling	Shiyang River	Meteorological	37.02°N	102.86°E	3,045	1960–2013
Minqin	Shiyang River	Meteorological	38.63°N	103.08°E	1,367	1960–2013
Jingtai	Shiyang River	Meteorological	37.18°N	104.15°E	1,631	1960–2013

1.2 Methods

We used the SDI to evaluate hydrological drought based on cumulative streamflow volumes. SDI was first developed by Nalbantis and Tsakiris (2009) for characterizing hydrological drought in Greece, and was also tested in the other regions including United States, India, Iran, Iraq and Taiwan of China (Madadgar and Moradkhani, 2013; Tabari et al., 2013; Al-Faraj et al., 2014; Manikandan and Tamilmani, 2015; Yeh et al., 2015). The computational process is as follow and also detailed introduced in previous research (Tabari et al., 2013):

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j}\ ,\ i=1, 2, \ldots; j=1, 2, \ldots, 12; k=1, 2, 3, 4. \quad (1)$$

Where *i* refers to the hydrological year, *j* is the month of that year, *k* refers to the time duration of the period, $V_{i,k}$ is the cumulative streamflow volume for the i^{th} hydrological year and the k^{th} reference period. Based on cumulative streamflow volume $V_{i,k}$, we defined the SDI for each reference period *k* of the i^{th} hydrological year as follows:

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V_k}}{S_k}\ ,\ i=1, 2, \ldots; k=1, 2, 3, 4. \quad (2)$$

Where $\overline{V_k}$ and S_k are, respectively, the mean and the standard deviations of the cumulative streamflow volumes of reference period *k* as these volumes are estimated over each period of time.

In Eq. 2, the streamflow volumes data for analysis must follow a normal or log-normal distribution. However, in small basins, streamflows might follow a skewed probability distribution, whose distribution pattern is similar to that of the Gamma distribution (Yeh et al., 2015). Therefore, when calculating SDI, the first step is to transform the statistical distribution. In this study, the two-parameter log-normal distribution was used for transformation, and natural logarithms of the streamflow data were taken. The SDI index was redefined as follow (Yeh et al., 2015):

$$SDI_{i,k} = \frac{y_{i,k} - \overline{y_k}}{S_{y,k}}\ ,\ i=1, 2, \ldots; k=1, 2, 3, 4. \quad (3)$$

$$y_{i,k} = \ln(V_{i,k})\ ,\ i=1, 2, \ldots; k=1, 2, 3, 4. \quad (4)$$

Where the values of $y_{j,k}$ are the natural logarithms of cumulative streamflow with mean y_k and standard deviation $S_{y,k}$. According to the hydrological situation in the Hexi area, we defined one complete hydrological year as from December to November next year. The aim was to analyze the long-term changes of hydrological drought in the Hexi Corridor, so the SDI series of the whole hydrological year were used for analysis.

Another index chosen for drought monitoring was SPI (standardized precipitation index), whose computation is based on the long-term precipitation record accumulated over the selected time scale (Buttafuoco et al., 2015). The long-term record is fitted to a probability distribution, usually a Gamma distribution, which is then transformed into a normal distribution through an equal-probability transformation (Guttman, 1999). Lloyd-Huhes and Saunders (2002) described in detail the calculation of SPI. It is generally agreed that the SPI at longer-term scales will be suitable for water resource management (Bonaccorso et al., 2003; Buttafuoco et al., 2015). Azareh et al. (2014) investigated the relationship between hydrological and meteorological droughts in Karaj dam basin, and also found SPI and SDI were in good agreement. Bahramand (2014) also found high correlation between SPI as a meteorological index with hydrologic index (SDI) in Halilrud Basin of Iran. In this study, SPI12 was also calculated for hydrological drought monitoring. In order to compare the two indices of SDI and SPI12, we averaged SPI12 values from December to November next year to get the series of hydrological years. Based on the SDI and SPI, we defined five grades of hydrological droughts, which are denoted by an integer from 0 (non-drought) to 4 (extreme drought). These grades of hydrological drought are defined by the criteria given in Table 2.

Table 2 Drought grades as classified with the SPI (standardized precipitation index) and SDI (streamflow drought index)

Grade	Description	SPI value	SDI value
0	Non-drought	SPI>–0.5	SDI≥0
1	Mild drought	–1.0<SPI≤–0.5	–1.0≤SDI<0
2	Moderate drought	–1.5<SPI≤–1.0	–1.5≤SDI<–1.0
3	Severe drought	–2.0<SPI≤–1.5	–2.0≤SDI<–1.5
4	Extreme drought	SPI≤–2.0	SDI<–2.0

Two statistical methods, Mann–Kendall nonparametric test (MK test) and wavelet analysis were used to analyze the spatial variations and temporal trends of SDI and SPI12 series. MK test is one of the most popular trend detection methods (Mann, 1945; Kendall, 1975). This test can cope with missing values below a detection limit and is therefore highly recommended for general use by the World Meteorological Organization (Mitchell et al., 1966). *Z* value of MK test is used to test the variation trend. When *Z* is greater than 0, the trend is increasing. If $Z>1.96$, the trend is also significant. When *Z* is smaller than 0, the trend is decreasing and the trend is significant when *Z* is smaller than –1.96. Wavelet analysis has been shown to be a powerful technique for multiple-scale analysis of earth surface processes such as temperature, precipitation or hydrological time series (Nakken, 1999; Labat, 2005; Xu et al., 2009). Wavelet analysis provides for multiple-resolution evaluations of time series. When the analyzed function is multiplied by the mother wavelet, wavelet coefficients at various scales can be calculated. When the wavelet scale is larger, macro-scale characteristics of the time series can be discerned, and when the wavelet scale is fine, micro-scale characteristics of the time series can be detected. The principle for choosing the mother wavelet is the self-similarity of wave forms between the mother wavelet and the analyzed time series. The similarity of wave forms can effectively decrease the amount of calculation required. Based on the principle of wavelet analysis, we chose the Morlet wavelet as the mother wavelet to conduct continuous wavelet analysis in this study.

The Westerly Index (WI) was calculated by the method of Wang et al. (2005):

$$WI = \sum_{K} u_{500hPa} / K \cdot \quad (5)$$

Where u_{500hPa} is the east-west component of wind at 500 hPa height, *K* is the total number of grid point in the study area (40°–55°N, 50°–85°E). The wind data are obtained from National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR), which can be downloaded from http://www.esrl.noaa.gov.

2 Results

2.1 Variation of runoff in the Hexi Corridor

Firstly, the variation of runoff in the Hexi Corridor was analyzed. The ensemble average ($\overline{x}$) and coefficient of variation (CV) were used for quantitative describing the characteristics of the runoff:

$$\overline{x} = \sum_{i=1}^{n} x_i , \quad (6); \qquad V_{i,k} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(k_i - 1)^2} \cdot \quad (7)$$

In Eqs. 6 and 7, *n* is the number of sample, x_i denotes the runoff volume in different years, $k_i = x_i/x$. Furthermore, *Z* values of the MK trend test were used for determining the variation tendency of runoff. All of the results were shown in Table 3. It can be seen that the station with the largest runoff was Yingluoxia in Heihe River basin and the smallest was Liqiaoshuiku, also in Heihe River basin. The average coefficient of variation in Shiyang River basin was 0.25, which was larger than Shule and Heihe River basins (Table 3). That implies the inter-annual variability of runoff in Shiyang River basin was larger than Shule and Heihe River basins. The results of MK trend test showed that the runoff in nine stations showed obvious rising trend while only two stations appeared obvious downward trend. That meant the runoff volume in the Hexi Corridor was increasing in recent decades.

Table 3 The ensemble average ($\overline{x}$), coefficient of variation (CV) and Z values of MK (Mann–Kendall) trend test of runoff series in the Hexi Corridor

River basin	Station	$\overline{x}$ (1×10^8 m^3)	CV	Z
Shule River	Changmabao	9.94	0.27	4.49
	Dangchengwan	3.57	0.13	4.28
	Panjiazhuang	2.72	0.25	0.91
Heihe River	Binggou	6.21	0.14	–0.54
	Liyuanbao	2.49	0.22	0.64
	Yingluoxia	16.14	0.17	3.97
	Qilian	4.57	0.17	2.42
	Shuangshusi	1.23	0.23	–0.51
	Zhamashenke	7.42	0.18	2.50
	Sunan	1.79	0.22	3.39
	Zhengyixia	10.05	0.24	–0.51
	Liqiaoshuiku	0.62	0.25	–4.78
	Wafangcheng	0.89	0.15	2.70
Shiyang River	Jiutiaoling	3.16	0.19	–0.01
	Zamusi	2.30	0.20	0.21
	Jinchuanxia	1.45	0.20	6.52
	Nanyingshuiku	1.27	0.20	–1.50
	Sigouzui	9.95	0.27	4.50
	Caiqi	2.56	0.47	–6.31
	Huangyanghe	1.25	0.25	–1.81

2.2 Variability of the SDI series in the Hexi Corridor

2.2.1 Trend analysis

Figure 2 showed the mean annual SDI series in the whole Hexi Corridor and Shule, Heihe and Shiyang River basins. In the whole Hexi Corridor, the SDI values were mainly negative before 2001, which meant the corridor was in a relatively drier period. After 2002, all of the SDI values were positive, which implied the corridor was in a relatively wetter period in the last dozen years. The variations of the three river basins were similar to the whole corridor, although there were little differences. Before 1998, the frequency of negative SDI values in the Shule River basin was significantly higher than that in the Heihe or Shiyang River basin. The SDI values in the Shule River region became positive after 1999, which was obviously earlier than the case in the Heihe and Shiyang River basins, which became positive after 2001 and 2002, respectively. Based on the MK test method, we found significant upward trend in the whole Hexi Corridor and in the Heihe River and Shule River basins, which showed Z values of 2.89, 2.02 and 4.02, respectively. The trend of SDI series in the Shiyang River was increasing but insignificant. This suggested that the hydrological drought had improved over the whole Hexi region.

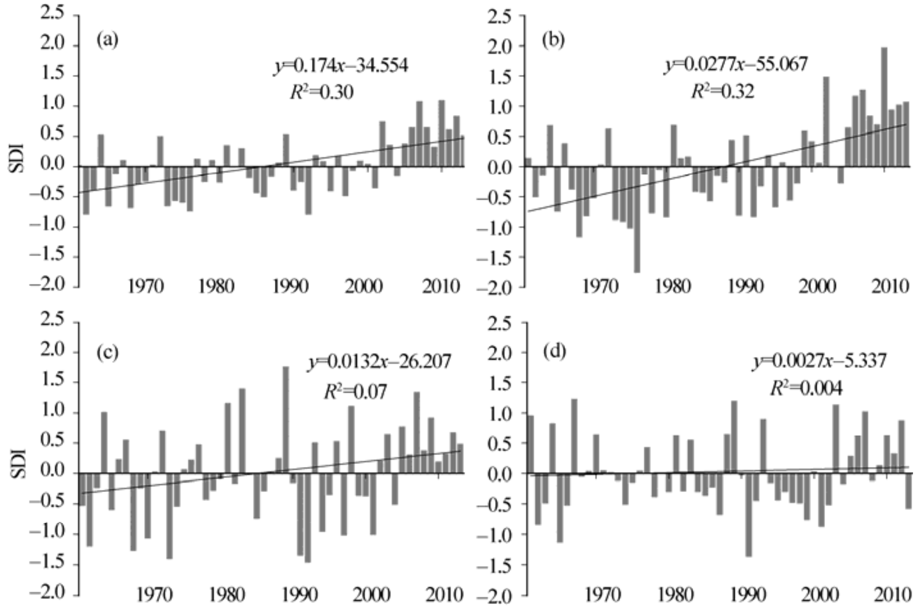

Fig. 2 SDI (streamflow drought index) series for the whole Hexi Corridor (a), Shule River basin (b), Heihe River basin (c) and Shiyang River basin (d)

2.2.2 Wavelet analysis

Figure 3 showed the wavelet transform of the SDI series for the whole Hexi Corridor, Shule, Heihe and Shiyang River basins. In this figure, the red color represented positive SDI values and the blue color represented negative SDI values. There were two cycles in the Hexi area during the study period and the boundary between these cycles happened around 1990. The SDI values were negative before 1978, then positive between 1978 and 1990, negative again between 1990 and 2003 and positive during 2003 and 2013. In the past ten years the SDI values were still positive (Fig. 3). However, the SDI values will be negative in the next few years, as can be discerned from the wavelet transform of the SDI series in Shiyang River basin.

The wavelet variance could reflect the cycles of time series. Figure 4 showed the wavelet variance in the study area. The first major periods for the Heixi Corridor, Shule, Heihe and Shiyang River basins were 22, 20, 23 and 16 years, respectively and the second major periods were 6, 8, 5 and 3 years, respectively. These results indicated a shorter cycle and higher frequency of hydrological drought in the Shiyang River basin.

2.2.3 Probability of drought

Probability of drought was also analyzed in this study. Based on the results of wavelet analysis, we found two cycles (before and after 1990) during the study period. The probabilities before and after 1990 for every hydrological drought category of the three river basins were shown in Fig. 5. In the Shule River basin, the probability of all drought categories showed a decreasing trend, and no extreme drought was found during study period. In the Heihe River basin, mild and severe drought probabilities had decreased after 1990, however, moderate and extreme drought probability showed a slightly increasing tendency. In the Shiyang River basin, except moderate drought, all of the other drought categories had a higher probability after 1990 and the probability of extreme drought had doubled several times. This means that the probability of drought in eastern Hexi Corridor was higher while it is lower in the west during the past 20 years.

2.3 Variability of the SPI12 series in the Hexi Corridor

SPI data for different time scales imply different physical meanings. With shorter timescales, SPI

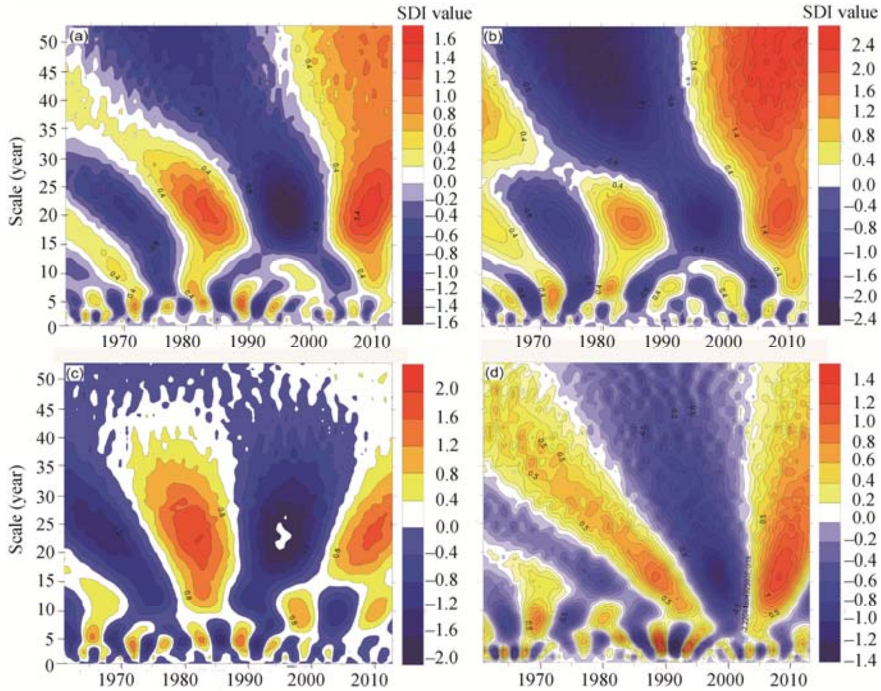

Fig. 3 Wavelet transform of the SDI (streamflow drought index) in the whole Hexi Corridor (a), Shule River basin (b), Heihe River basin (c) and Shiyang River basin (d)

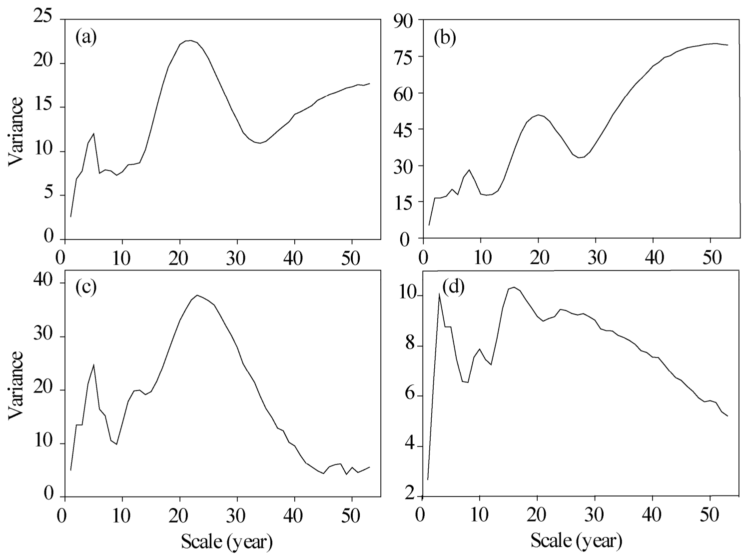

Fig. 4 Wavelet variances of the SDI (streamflow drought index) in the Hexi Corridor (a), Shule River basin (b), Heihe River basin (c) and Shiyang River basin (d)

shows soil moisture changes, which are important for agricultural production. SPI of longer timescales can reflect long-term streamflow variations, which are of practical value for water reservoir management (Bonaccorso et al., 2003; Capra and Scicolone, 2012). In this study, we calculated SPI12 for comparison with hydrological drought values based on the SDI. Figure 6 showed the SDI and the SPI12 series for the Hexi regions. There was good agreement between the SDI and SPI12 series and the correlation coefficient was 0.59. Based on the SPI12 series, we also found a high frequency of drought events before 2001, but no drought was found after 2002 in the whole Hexi Corridor, which was in complete agreement with the SDI results.

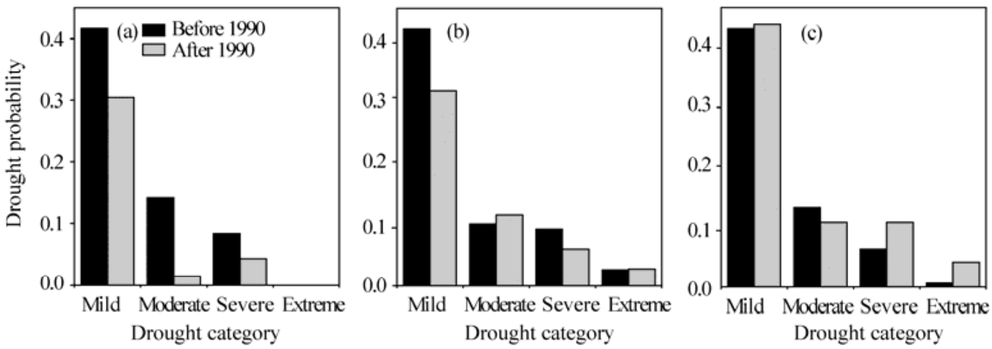

Fig. 5 Drought probabilities in the Shule River basin (a), Heihe River basin (b) and Shiyang River basin (c) before and after 1990

2.4 Spatial and temporal variability of SDI and SPI

For further analyzing the spatial distribution of drought conditions, we calculated the SDI value of each hydrometric station and the SPI12 value of each meteorological station. Then the MK trend test was used to determine the variation trends. Considering that there were two cycles in the Hexi area during the study period and that the boundary happened around 1990. Therefore, we divided the SDI and SPI12 series of each station into two segments: before and after 1990. Figure 7 showed the Z values of the MK trend test of the SDI and the series. Before 1990, the hydrometric and meteorological drought in the Hexi Corridor showed a similar pattern, all of the stations with increased SDI and SPI12 values were in the southern part of the corridor and the stations with decreased values were in the northern part (Figs. 7a and c). After 1990, the number of stations with SDI values showing significant increasing trend had risen from 6 to 11, and these stations were concentrated in the western part of the Hexi area. Stations with the SDI values showing no apparent increase or decrease trend were mainly in the eastern part of the Hexi Corridor, especially in the Shiyang River basin (Fig. 7b). Only two meteorological stations in the corridor showed increased SPI12 values, in which one was located in the western part of the Hexi area and the other was in the middle part. The two stations that showed decreased SPI12 values were located in the Shiyang River basin, which was in accordance with the SDI results (Fig. 7d).

3 Discussion

Based on the long term SDI and SPI12 series in the Hexi Corridor, we found obvious increasing trend during the study period and both of the SDI and SPI12 values were mainly positive in the last ten years. The probability of drought on the whole was also decreasing. That meant the corridor was in a tendency towards wetter conditions. Climate change is the driving factor of drought and wetness variation. In order to find the reason of hydrological drought variation in the Hexi Corridor, we analyzed the climate condition during the study period. Figures 8a and b showed the variation trend of precipitation and temperature from 1960 to 2013 in the Hexi Corridor. Both precipitation and temperature exhibited significant increasing trend. The increased precipitation would make the corridor much wetter. However, the increased temperature would increase the evaporation, and make the corridor much drier. From the results of the above section, a preliminary conclusion can be drawn that precipitation was still the dominated factor of drought and wetness variation in the Hexi Corridor. The Hexi Corridor is mainly in the westerlies and its climate is greatly affected by the strength of the west wind. Ding et al. (2007) investigated the relationship between runoff and WI in Northwest China, and found significant positive correlation between them. In this study, we also analyzed the variation of WI

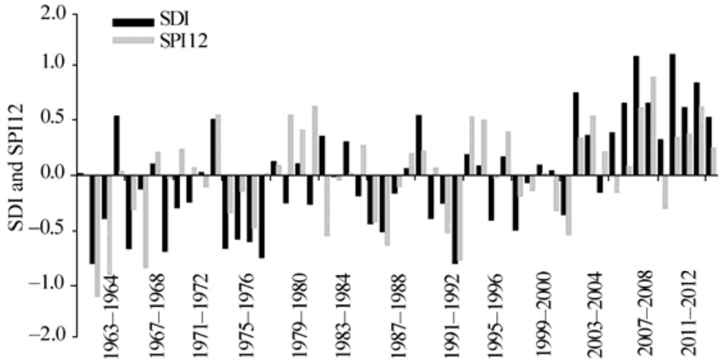

Fig. 6 SDI (streamflow drought index) and SPI12 (standardized precipitation index at 12-month timescale) series during the period 1960–2013 in the Hexi Corridor

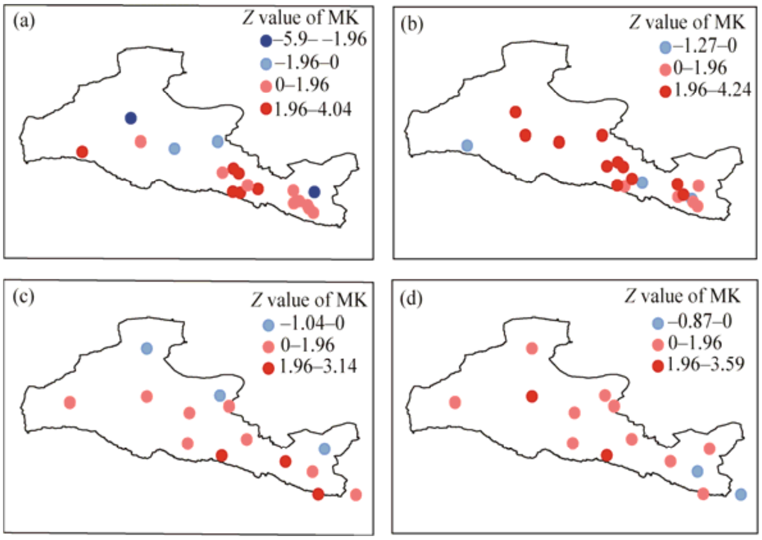

Fig. 7 *Z* values of the MK (Mann–Kendall) trend test of the SDI (streamflow drought index; a, before 1990; b, after 1990) and the SPI12 (standardized precipitation index at 12-month timescale; c, before 1990; d, after 1990) series

and found the WI was also increasing in recent decades (Fig. 8c). Increase of westerly wind strength will bring in more water vapor. Tao et al. (2014) analyzed the variation of water vapor flux at 500 hPa height in the northern hemisphere. They found that the water vapor flux in the Hexi Corridor had increased after 1986. The increased water vapor will also lead the Hexi Corridor to a wetter condition. Furthermore, the effect of glacier runoff should not be ignored. According to the result of glacial catalog of China, there are 2,194 glaciers in the Hexi Corridor and the area is about 1,334.77 km^2 (Gao et al., 2011). Under the background of global climate warming, glaciers in China had retreated since the middle of the 20th century (Ding et al., 2006; Li et al., 2011). Therefore, the effects of glacier degradation on hydrologic drought conditions should not be ignored. Gao et al. (2011) estimated glacier runoff based on a monthly degree-day model in the Hexi inland river basin, and found significant increasing trend of the glacier runoff during the period 1960–2010. The increases of precipitation, water vapor flux and glacier runoff were the main reasons for becoming wetter in the Hexi Corridor.

At the spatial scale, before 1990, drought from the data of hydrological and meteorological stations concentrated in northern part of the Hexi area, however, it moved to the eastern part after 1990. In order to find the reasons, we analyzed the spatial variations of precipitation, temperature and glacier runoff in the Hexi Corridor (Fig. 9). Before 1990, the precipitation in

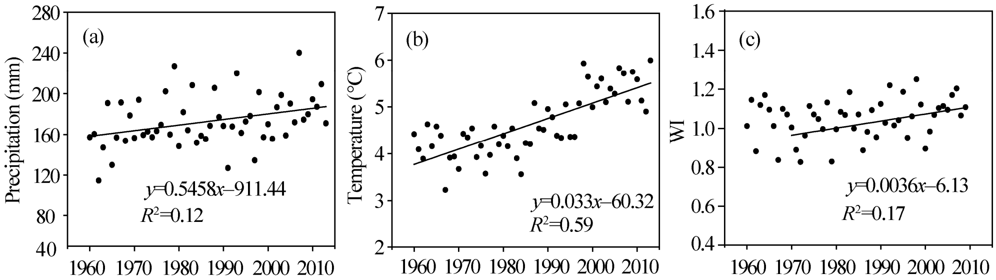

Fig. 8 Long time series of precipitation, temperature and Westerly Index (WI) in the Hexi Corridor

the northern part of the Hexi Corridor was decreasing. Furthermore, the growth rate of glacier runoff was small during the study period. However, the temperature was increasing in the northern part. The decreased precipitation and increased temperature were the reasons that the northern part of the Hexi Corridor had developed toward drought conditions before 1990.

After 1990, drought conditions from the data of hydrological and meteorological stations moved to the eastern part of the Hexi area while wet conditions were concentrated in the central and western parts. It also showed that drought probability had decreased after 1990 in Shule River basin and increased in Shiyang River basin. We analyzed the spatial variation of precipitation and temperature after 1990 (Figs. 9b and d). The temperature had greatly increased in the whole corridor after 1990, which meant the evaporation capacity had also greatly increased during this period. By analyzing the spatial variation of precipitation, we found the increase rate of precipitation was small in the Hexi Corridor; the station with the largest increase rate was in Heihe River basin, the middle part of the corridor. The largest increase rate of precipitation in the upstream of Heihe River basin could be attributed to the wet conditions of this area after 1990. In Shule River basin, the increase rate of precipitation was small after 1990. However, it was also a region prone to getting wet. By analyzing the glacier runoff (Fig. 9e), we found that the glacier runoff in Shule River basin was 600–720 mm before 1990, but reached up to more than 1,000 mm after 1990. The largest increase of glacier runoff could be the reason for the change of drought conditions in Shule River basin.

4 Conclusions

For gaining a better understanding of the hydrological drought characteristics in the Hexi Corridor, we chose two hydrological drought indices (namely SDI and SPI12) during the period 1960–2013. The results showed an increase in the mean annual SDI and SPI12 values in the Hexi Corridor, especially in the last 10 years, both SPI12 and SDI values were positive. This trend was associated with the increases of precipitation, water vapor flux and glacier runoff.

Based on the wavelet analysis, we found two drought cycles in the Hexi Corridor during the period 1960–2013. The first cycle happened before 1990 and the second was after 1990. In comparison with the first cycle, the drought frequency was significantly reduced during the second cycle. This indicated that the incidence of drought in the Hexi Corridor had declined during the past 20 years. However, the wavelet analysis results also showed that during the next few years the Hexi area will enter a period of relative drought and the earliest drought will occur in the Shiyang River basin, the eastern part of the Hexi Corridor.

At the spatial scale, drought was concentrated in the northern part of the Hexi region before 1990, however, it moved to the eastern part after 1990. Wet conditions were concentrated in the central and western parts. The drought probability decreased in Shule River basin while increased in Shiyang River basin. We analyzed the spatial variations of precipitation, temperature and glacier runoff before and after 1990 and found the variations of the three factors were small before 1990 and precipitation was mainly decreasing in the northern part of the corridor.

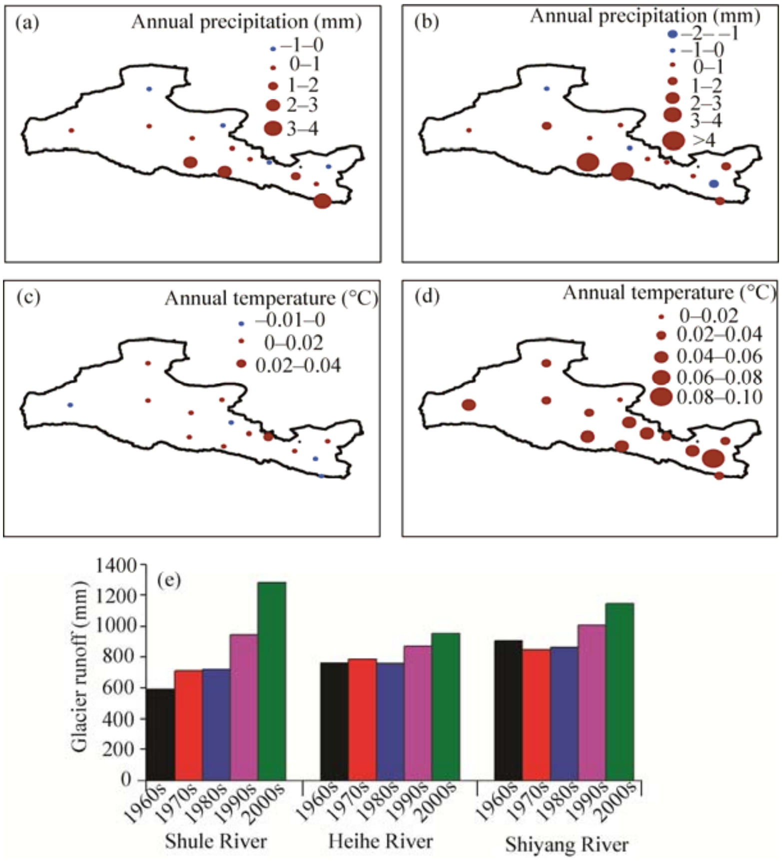

Fig. 9 Spatial variations of precipitation (a, before 1990; b, after 1990), temperature (c, before 1990; d, after 1990) and glacier runoff (e) during the period 1960–2013 in the Hexi Corridor

However, after 1990, precipitation, temperature and glacier runoff had greatly changed. The temperature and glacier runoff had greatly increased and the largest increase rate of precipitation was in the Heihe River basin, central part of the corridor. The increased precipitation in the upstream of Heihe River basin, increased glacier runoff in Shule River basin, and increased temperature in Shiyang River basin were the reasons for spatial difference of the hydrological drought in the Hexi Corridor.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (91125005, 41271083, 41201062), the Incubation Foundation for Special Disciplines of the National Natural Science Foundation of China (J1210003/J0109), and the Open Fund Project of the State Key Laboratory of Frozen Soil Engineering of China (SKLFSE201412).

References

Al-Faraj F A M, Scholz M, Tigkas D. 2014. Sensitivity of surface runoff to drought and climate change: Application for shared river basins. Water, 6(10): 3033–3048.

American Meteorological Society. 2004. Statement on meteorological drought. Bulletin of the American Meteorological Society, 85: 771–773.

Azareh A, Rahdari M R, Sardoii E R, et al. 2014. Investigate the relationship between hydrological and meteorological droughts in Karaj dam basin. European Journal of Experimental Biology, 4(3): 102–107.

Bahramand A. 2014. Hydrological drought analysis using SDI index in Halilrud basin of Iran. International Journal of Environmental Resources Research, 1(3): 279–288.

Bonaccorso B, Bordi I, Cancelliere A, et al. 2003. Spatial variability of drought: an analysis of the SPI in Sicily. Water Resources Management, 17(4): 273–296.

Buttafuoco G, Caloiero T, Coscarelli R. 2015. Analyses of drought events in Calabria (southern Italy) using Standardized Precipitation Index. Water Resources Management, 29(2): 557–573.

Capra A, Scicolone B. 2012. Spatiotemporal variability of drought on a short-medium time scale in the Calabria Region (Southern Italy). Theoretical and Applied Climatology, 110(3): 471–488.

Chen X J, Jiang M J, Han T. 2012. Drought index contrast and climate analysis of five typical stations in Hexi Corridor region. Agricultural Research in the Arid Areas, 30(5): 216–222. (in Chinese)

Chen Y N, Ye Z X, Shen Y J. 2011. Desiccation of the Tarim River, Xinjiang, China, and mitigation strategy. Quaternary International, 244(2): 264–271.

Ding H W, Zhang J. 2004. Relationships between sustainable development and water resources in arid oases area-an example of Hexi corridor. Journal of Arid Land Resources & Environment, 18(6): 50–55. (in Chinese)

Ding Y J, Liu S Y, Li J, et al. 2006. The retreat of glaciers in response to recent climate warming in western China. Annals of Glaciology, 43(1): 97–105.

Ding Y J, Ye B S, Han T D, et al. 2007. Regional difference of annual precipitation and discharge variation over west China during the last 50 years. Science in China Series D: Earth Sciences, 50(6): 936–945.

Falkenmark M, Carl W. 1992. Population and water resources: a delicate balance. In: Population Bulletin. Washington, DC: Population Reference Bureau.

Fang C L, Bao C, Huang J C. 2007. Management implications to water resources constraint force on socio-economic system in rapid urbanization: a case study of the Hexi Corridor, NW China. Water Resources Management, 21(9): 1613–1633.

Gao Q Z, Du H L, Zu R P. 2002. The balance between supply and demand of water resources and the water-saving potential for agriculture in the Hexi Corridor. Chinese Geographical Science, 12(1): 23–29.

Gao X, Zhang S Q, Ye B S, et al. 2011. Recent changes of glacier runoff in the Hexi Inland river basin. Advances in Water Science, 22(3): 344–350. (in Chinese)

Guo X Q, Cao L, Lan X B. 2011. Spatiotemporal changes of precipitation and drought in Hexi Corridor. Journal of Arid Land Resources and Environment, 25(4): 74–78. (in Chinese)

Guttman N B. 1999. Accepting the standardized precipitation index: a calculating algorithm. Journal of the American Water Resources Association, 35(2): 311–322.

He B, Lü A F, Wu J J, et al. 2011. Drought hazard assessment and spatial characteristics analysis in China. Journal of Geographical Sciences, 21(2): 235–249.

Ji X B, Kang E S, Chen R S, et al. 2005. Estimation of ground water budget at the representative irrigated area in the middle stream of Heihe River. Hydrogeology & Engineering Geology, 32(6): 25–29. (in Chinese)

Ji X B, Kang E S, Chen R S, et al. 2006. The impact of the development of water resources on environment in arid inland river basins of Hexi region, Northwestern China. Environmental Geology, 50(6): 793–801.

Kang E S. 2000. Review and prospect of hydrological studies in cold and arid regions of China. Journal of Glaciology and Geocryology, 22(2): 178–188.

Karl T, Knight R W. 1985. Atlas of Monthly Palmer Hydrological Drought Indices (1931–1983) for the Contiguous United States. Asheville, NC: National Climatic Data Center.

Kendall M. 1975. Rank Correlation Methods. London: Griffin.

Labat D. 2005. Recent advances in wavelet analyses: Part 1. A review of concepts. Journal of Hydrology, 314(1–4): 275–288.

Li M S, Li S, Li Y H. 2003. Study on drought in the past 50 years in China. Agricultural Meteorology, 24(1): 7–10. (in Chinese)

Li S M, Cheng G D, Li Y H, et al. 2002. Rational Utilization of Water Resources and Eco-environmental Protection in the Hexi Corridor. Zhengzhou: The Yellow River Water Conservancy, 67. (in Chinese)

Li Z X, He Y Q, An W L, et al. 2011. Climate and glacier change in southwestern China during the past several decades. Environmental Research Letters, 6(4): 045404.

Liu C L, Allan R P. 2013. Observed and simulated precipitation responses in wet and dry regions 1850–2100. Environmental Research Letters, 8(3): 034002.

Livada I, Assimakopoulos V D. 2007. Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI). Theoretical and Applied Climatology, 89(3–4): 143–153.

Lloyd-Huhes B, Saunders M A. 2002. A drought climatology for Europe. International Journal of Climatology, 22(13): 1571–1592.

Ma M W, Ren L L, Yuan F, et al. 2014. A new standardized Palmer drought index for hydro-meteorological use. Hydrological Processes, 28(23): 5645–5661.

Madadgar S, Moradkhani H. 2013. Drought analysis under climate change using copula. Journal of Hydrologic Engineering, 18(7): 746–759.

Manikandan M, Tamilmani D. 2015. Assessing hydrological drought charactertics: a case study in a sub vasin of Tamil Nadu, India. Agricultural Engineering, 1: 71–83.

Mann H B. 1945. Nonparametric tests against trend. Econometrica, 13(3): 245–259.

McKee T B, Doesken N J, Kleist J. 1993. The relationship of drought frequency and duration to time scales. In: Preprints Proceedings of the 8th Conference on Applied Climatology. Anaheim, CA: American Meteorological Society, 179–184.

Mitchell J M, Dzerdzeevskii B, Flohn H, et al. 1966. Climate change, WMO technical note no. 79. In: World Meteorological Organization, 79. Geneva, Switzerland.

Moron V. 1994. Guinean and Sahelian rainfall anomaly indices at annual and monthly scales (1933–1990). International Journal of Climatology, 14(3): 325–341.

Nakken M. 1999. Wavelet analysis of runfall-runoff variability isolating climatic from anthropogenic pattern. Environmental Modeling and Software, 14(4): 283–295.

Nalbantis I, Tsakiris G. 2009. Assessment of hydrological drought revisited. Water Resources Management, 23(5): 881–897.

Palmer W C. 1965. Meteorological drought. In: Research Paper No. 45. Washington, DC: U.S. Weather Bureau.

Shafer B A, Dezman L E. 1982. Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In: Proceedings of the 50th Annual Western Snow Conference. Reno, Nevada: Western Snow Conference, 164–175.

Tabari H, Nikbakht J, Talaee P H. 2013. Hydrological drought assessment in Northwestern Iran based on Streamflow Drought Index (SDI). Water Resources Management, 27(1): 137–151.

Tao H, Borth H, Fraedrich K, et al. 2014. Drought and wetness variability in the Tarim River Basin and connection to large-scale atmospheric circulation. International Journal of Climatology, 34(8): 2678–2684.

Tsakiris G, Pangalou D, Vangelis H. 2007. Regional drought assessment based on the Reconnaissance Drought Index (RDI). Water Resources Management, 21(5): 821–833.

Vicente-Serrano S M, Beguería S, López-Moreno J I. 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate, 23(7): 1696–1718.

Wang A H, Lettenmaier D P, Sheffield J. 2011. Soil moisture drought in China, 1950–2006. Journal of Climate, 24(13): 3257–3271.

Wang G X, Cheng G D. 1999. Water resource development and its influence on the environment in arid areas of China-the case of the Hei River basin. Journal of Arid Environments, 43(2): 121–131.

Wang H J, Chen Y N, Pan Y P, et al. 2015. Spatial and temporal variability of drought in the arid region of China and its relationships to teleconnection indices. Journal of Hydrology, 523: 283–296.

Wang J S, Feng J Y, Yang L F, et al. 2009. Runoff-denoted drought index and its relationship to the yields of spring wheat in the arid area of Hexi corridor, Northwest China. Agricultural Water Management, 96(4): 666–676.

Wang K L, Jiang H, Zhao H Y. 2005. Atmospheric water vapor transport from westerly and monsoon over the Northwest China. Advances in Water Science, 16(3): 432–438. (in Chinese)

Wang Y, Xiao H L, Wang R F. 2009. Water scarcity and water use in economic systems in Zhangye City, Northwestern China. Water Resources Management, 23(13): 2655–2668.

Wilhite D A, Glantz M H. 1985. Understanding: the drought phenomenon: the role of definitions. Water International, 10(3): 111–120.

Xu J H, Chen Y N, Li W H, et al. 2009. Wavelet analysis and nonparametric test for climate change in Tarim River Basin of Xinjiang during 1959–2006. Chinese Geographical Science, 19(4): 306–313.

Yeh C F, Wang J G, Yeh H F, et al. 2015. SDI and Markov Chains for regional drought characteristics. Sustainability, 7(8): 10789–10808.

Zamani R, Tabari H, Willems P. 2015. Extreme streamflow drought in the Karkheh river basin (Iran): Probabilistic and regional analyses. Natural Hazards, 76(1): 327–346.

Zhai J Q, Su B D, Krysanova V, et al. 2010. Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of China. Journal of Climate, 23(3): 649–663.

Zhai L X, Feng Q. 2009. Spatial and temporal pattern of precipitation and drought in Gansu Province, Northwest China. Natural Hazards, 49(1): 1–24.

Zhang J L. 2007. Barriers to water markets in the Heihe River basin in northwest China. Agricultural Water Management, 87(1): 32–40.

Zou X K, Zhai P M, Zhang Q. 2005. Variations in droughts over China: 1951–2003. Geophysical Research Letters, 32(4): L04707.