Chin. Geogra. Sci. 2018 Vol. 28 No. 4 pp. 636–653
https://doi.org/10.1007/s11769-018-0969-z

Springer Science Press
www.springerlink.com/content/1002-0063

Hydrological Processes in the Huaihe River Basin, China: Seasonal Variations, Causes and Implications

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Abstract: Understanding streamflow changes in terms of trends and periodicities and relevant causes is the first step into scientific management of water resources in a changing environment. In this study, monthly streamflow variations were analyzed using Modified Mann-Kendall (MM-K) trend test and Continuous Wavelet Transform (CWT) methods at 9 hydrological stations in the Huaihe River Basin. It was found that: 1) streamflow mainly occurs during May to September, accounting for 70.4% of the annual total streamflowamount with Cv values between 0.16–0.85 and extremum ratio values between 1.70–23.90; 2) decreased streamflow can be observed in the Huaihe River Basin and significant decreased streamflow can be detected during April and May, which should be the results of precipitation change and increased irrigation demand; 3) significant periods of 2–4 yr were detected during the 1960s, the 1980s and the 2000s. Different periods were found at stations concentrated within certain regions implying periods of streamflow were caused by different influencing factors for specific regions; 4) Pacific Decadal Oscillation (PDO) has the most significant impacts on monthly streamflow mainly during June. Besides, Southern Oscillation Index (SOI), North Atlantic Oscillation (NAO) and the Niño3.4 Sea Surface Temperature (Niño3.4) have impacts on monthly streamflow with three months lags, and was less significant in time lag of six months. Identification of critical climatic factors having impacts on streamflow changes can help to predict monthly streamflow changes using climatic factors as explanatory variables. These findings were well corroborated by results concerning impacts of El Nino-Southern Oscillation (ENSO) regimes on precipitation events across the Huaihe River Basin. The results of this study can provide theoretical background for basin-scale management of water resources and agricultural irrigation.

Keywords: streamflow; trend; periodicity; abrupt behavior; climate indices; Huaihe River Basin, China

Citation: SUN Peng, SUN Yuyan, ZHANG Qiang, YAO Rui, 2018. Hydrological Processes in the Huai River Basin, China: Seasonal Variations, Causes and Implications. *Chinese Geographical Science*, 28(4): 636–653. https://doi.org/10.1007/s11769-018-0969-z

1 Introduction

It was well evidenced that warming climate significantly intensifies the hydrological cycle at global and regional scales (Ziegler et al., 2003; Schmidhuber and Tubiello, 2007; Hulme, 2017; Zhang et al., 2017), and has direct

Received date: 2017-09-15; accepted date: 2017-12-23

Foundation item: Under the auspices of National Science Foundation of China (No. 41601023, 41771536), National Science Foundation for Distinguished Young Scholars of China (No. 51425903), State Key Laboratory of Earth Surface Processes and Resource Ecology (No. 2017-KF-04), Creative Research Groups of National Natural Science Foundation of China (No. 41621061), Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research) (No. IWHR-SKL-201720)

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impacts on variability and availability of water resources causing considerable regional-scale consequences for economies and vulnerable ecosystems as well (Bates et al., 2008; Döll and Schmied, 2012). In recent years, impacts of climate change on global and regional hydrological changes have been extensively investigated (Döll et al., 2012; Zhou et al., 2012; Arnell et al., 2013; Kumar et al., 2016; Li et al., 2017; Liu et al., 2017). It should be noted here that, due to intensifying interferences by human activities and climate changes, flow regimes at different regions are subject to different changing properties, which calls for catchment to regional scale studies of streamflow regimes for the sake of the development of the adaptive water resources management schemes because of the different flow regimes at different regions (Ziegler et al., 2010; Schneider et al., 2013).

The Huaihe River Basin (HRB) plays unshakable position in the agricultural development in China. The basin provides 20% of the total agricultural products with 10% of the total crop land of China, feeding 20.4% of the total countryside population. Hence, agricultural development in the Huaihe River Basin is critical for food security of China. However, the basin is located in the transitional zone between humid and semi-humid climates, with frequent droughts and floods. Frequent floods and drought have exerted tremendous influences on agriculture. Thus, massive researches have been done on weather extremes in the Huaihe River Basin. Previous researches have focused on spatiotemporal patterns of precipitation extremes (Zhao et al., 2012; He et al., 2015), mechanism analysis (Ye and Lu, 2011; Shi et al., 2014; Zhang et al., 2017) and so on. However, more researches focused on precipitation changes and related causes behind precipitation variations across the Huaihe River Basin in both space and time. Tang et al. (2013) evaluated seasonal rainfall predictability over the Huaihe River Basin based on 23-year (1981–2003) retrospective forecasts by 10 climate models from the Asia-Pacific Economic Cooperation Climate Center multi-model ensemble prediction system. The results indicated that the summer rainfall variance in this basin is largely internal, which leads to lower rainfall predictability for most individual climate models. Besides, the Multi-Model Ensemble (MME) was corroborated to be effective for increasing the current seasonal forecast skill. Further analysis shows that the MME averaged over predicted SST models has the highest rainfall prediction skill, which is closely related to model's capability in reproducing the observed dominant modes of the summer rainfall anomalies in Huaihe River Basin. Based on the summer precipitation data from the Huaihe River Basin and the middle and lower reaches of the Yangtze River from 1922 to 2007. Wei et al. (2010) analyzed the interannual and interdecadal oscillation and probability distribution characteristics of summer precipitation in the Huaihe River Basin. They found that the intensity change of Quasi-Biennial Oscillation (QBO) of summer precipitation in the Huaihe River Basin is consistent with that of interdecadal oscillation. While, standing researches mainly focused on floods and related management practice of flood. Wang et al. (2016) did summary of the flood management for the Huaihe River Basin in China, which firstly introduced flood and flood disasters of the Huaihe River Basin. In addition, Wang et al. (2016) summarized achievements in flood control and management. Furthermore, this study discussed experiences and enlightenment in flood control and management. Taken together, most of the studies considered only the accuracy of the trend and variation in the precipitation, temperature and streamflow in the Huaihe River Basin. It has been difficult to find exploring causes behind streamflow changes in terms of climate indices.

However, relatively few reports are available adderssing the long-term monotonic trend, abrupt change of streamflow and related periodicity properties of streamflow variations in the Huaihe River Basin. Particularly, no reports are found exploring causes behind streamflow changes in terms of large-scale sea surface temperature variations such as El Nino-Southern Oscillation (ENSO) and so forth. While, these aforementioned scientific issues will be addressed in this current study. Hao et al. (2011) showed that annual streamflow at four hydrological stations across the Huaihe River Basin was in an insignificant decreasing trend, and the change point of streamflow at the Linyi station was detected during 1965 and 1975. Shi et al. (2012) quantified trends in the streamflow series at five hydrological stations and found no significant change in annual streamflow changes across the Huaihe River Basin, while significant decreasing trends can be found in annual streamflow series within some tributaries. However, no confirmative conclusions could be obtained pertaining to whether significant trends can be detectable at basin scale due to poor spatial coverage of the data points. Xia et al. (2012)

detected trends of extreme streamflow regimes using the daily streamflow data from 20 hydrological stations in the upstream to the Bengbu Sluice in the Huaihe River Basin and found decreasing extreme streamflow at 10 stations, while ambiguous increasing trends can be observed at the other stations. Pan et al. (2018) analyzed approximately 50 years of natural and observed streamflow data from 20 hydrological stations. Trends were quantified using the Mann-Kendall test. They obtained some findings such as both the natural and the observed streamflow in the HRB presented downward trends, and the decreasing rate of observed streamflow is generally faster than that of the natural streamflow. The highest decreasing trends for two kinds of streamflow both occurred in spring, and the lowest ones were in autumn and winter. Besides, Pan et al. (2018) found that human activity was the main driving factor in the Xuanwu (80.78%), Zhuangqiao (79.92%), Yongcheng (74.80%), and Mengcheng (64.73%) stations which all belong to the Huaihe River Basin.

However, in recent studies, impacts of different ENSO events on seasonal rainfall in the Huaihe River Basin were thoroughly investigated, especially the comparative analysis of the impacts of canonical ENSO events and ENSO Modoki events on precipitation regimes have been done (Ashok et al., 2007; Zhang et al., 2007; Zhang et al., 2016; Sun et al., 2017). While, precipitation is a critical meteorological variable behind changes of streamflow regimes. Potential relations can be expected between streamflow variations and ENSO regimes, and which constitutes major research motivation of this current study. Streamflow changes of the Huaihe River Basin mean much for basin-scale water resource management and management of agricultural irrigation in particular due to frequency floods and droughts in the Huaihe River Basin. In this study, monthly streamflow at nine stations were collected and statistical properties of streamflow were quantified in terms of periodicity features and trends. In addition, causes behind streamflow changes were explored based on relations between streamflow regimes and ENSO events. Therefore, the objectives of this study are: 1) to quantify statistical properties of streamflow changes in the upper Huaihe River Basin with respect to mean and extreme hydrological processes; 2) to detect trends, periodicity and also abrupt behaviors; and 3) to explore potential causes behind streamflow changes with respect to various ENSO regimes. This study provides theoretical grounds for basin scale water resources management in a changing environment, and particularly the Huaihe River Basin dominated by frequency floods and droughts.

2 Materials and Methods

2.1 Study area

The Huaihe River Basin is located in the humid and semi-humid monsoon climate region of eastern China, between the Yangtze River and the Yellow River (Fig. 1). While the Huaihe River, one of the seven largest rivers in China, is an important energy source and marketable grain base in China, and is utilized as a water resource for domestic, agricultural and industrial use (Zhang et al., 2016; Zhao et al., 2016). It has a vast plain with some mountains and foothills at the western, southern and northern parts, the altitudes of which are normally 1–2 km above the mean sea level. This region has China's highest population density (662 persons per km^2) and 17% of the country's cultivated land, supporting a population of 165 million, and is thus of great socio-economic importance (Jiang et al., 2013; He et al., 2015). Particularly, precipitation in the Huaihe River Basin mainly occurs in the period from mid-May to mid-October, the Meiyu rain season in Chinese, with a history of flooding over many centuries, in turn influenced by the South Asian monsoon, and often causes basin-wide flooding. The unique climate and surface conditions in this region have contributed to the frequent flooding, waterlogging, drought, and storm surge disasters (Cao and Qi, 2014; Zhang et al., 2015).

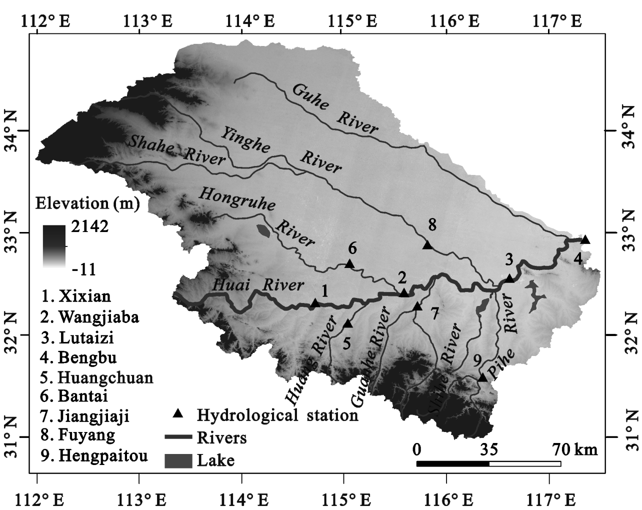

Fig. 1 Locations of study region and distribution of hydrological stations

2.2 Data

Monthly streamflow data were collected from nine stations in the Huaihe River Basin. Locations and related stations names can be found in Fig. 1. Streamflow data collected at the Huangchuan and Hengpaitou stations cover the time interval of 1980–2015, and streamflow data at other stations cover the period of 1956–2015. Few missing data were processed using spline interpolation method. Data related to large-scale climatic signals such as ENSO regimes were collected from National Oceanic and Atmospheric Administration (NOAA) at http://www.noaa.gov/. The Sea Surface Temperature (SST) data were the extended reconstructed SST data covering the regions of Niño1+2 region (0°–10°S, 80°W–90°W), Niño3 region (5°N–5°S, 90°W–150°W), Niño4 region (5°N–5°S, 150°W–160°E), and Niño3.4 region (5°N–5°S, 120°W–170°W) during the period of 1955–2005 (Zhang et al., 2016). These SST data were obtained from the NOAA, USA (Smith et al., 2008). North Atlantic Oscillation (NAO), being centered near the Azores and Iceland, is defined as a meridional dipole in the atmospheric pressure (Moore et al., 2013). A high NAO index is related to stronger than average westerlies in the North Atlantic mid-latitudes, while the opposite is true for negative NAO index (Moore et al., 2013). The NAO index data were extracted from the Climate Prediction Center of NOAA at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml. Pacific. Pacific Decadal Oscillation (PDO) is the SST anomaly in the Pacific to the north of 20°N. The PDO data covering a period of 1960–2013 were extracted from NOAA (http://www.esrl.noaa.gov/psd/data/correlation/pdo.data). The values of the climate indices obtained from http://www.esrl.noaa.gov/psd/data/climateindices/list/ were monthly atmospheric and ocean time series, and then they were aggregated by averaged over the year (Xiao et al., 2015).

Climatic indices analyzed in this study are obtained from NOAA (http://www.noaa.gov/). Relations between monthly streamflow and ENSO were quantified with aim to investigate potential causes behind streamflow variations in the Huaihe River Basin. North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) are formed due to differences in atmospheric pressure from that of North Pole. It is a kind of important climatic factor for arctic meteorology. Multivariate ENSO Index (MEI) is a kind of index which can well reflect development and subduction of ENSO. Niño3.4 is a kind of sea surface temperature anomalies in the area regions circled by 5°N–5°S, 120°W–170°W. South Oscillation Index (SOI) can reflect anti-phase air pressure fluctuation strength between Tahiti and Darwin stations, being a good indicator for strengthening and weakening processes of the atmospheric pressure besides eastern and western side of the Pacific. Pacific Decadal Oscillation (PDO) is an index reflecting annual oscillation index in the high altitude of the Pacific, having direct impacts on inter-annual variations of climate changes in the Pacific and its neighboring regions. These indicators were adopted in this current study to analyzed potential causes behind streamflow changes in the Huaihe River Basin.

2.3 Methods

2.3.1 Modified Mann-Kendall (MM-K) trend test method

Mann-Kendall trend (M-K) detection method is a non-parametric method, being less sensitive to outliers when compared to parametric statistics (Kendall, 1975; Li et al., 2017). However, the results of the M-K test are affected by the serial correlation of time series and the serial effects should be eliminated before analysis (Storch and Navarra, 1995; Gocic and Trajkovic, 2013). Hamed and Rao (1998) proposed a Modified M-K (MM-K) test based on effective or Equivalent Sample Size (ESS) to eliminate the effects of autocorrelation. In the modified version of M-K method, the modified variance of the M-K statistic was used to replace the original one if the lag-i autocorrelation coefficients were significantly different from zero at the 5% level (Hamed and Rao, 1998).

If the lag-1 autocorrelation coefficient, c, is larger than 0.1, pre-whitening is applied. Then, the analyzed time series (x_1, x_2, …, x_n) should be replaced by (x_2–cx_1,…, x_n–cx_{n-1}). However, pre-whitening has been shown with the possibility to underestimate the trend in the time series (Yue et al., 2002). In addition, it is not uncommon to find significant lag-1 autocorrelation even after pre-whitening, probably because only lag-1 autocorrelation is considered by pre-whitening. Suppose a pre-whitened time series still has a lag-1 autocorrelation coefficient over 0.1, denoted as c_1. Then one has $x_{i+1}-cx_i = c_1(x_i - cx_{i-1})$, e.g., $x_{i+1} = (c_1+c)x_i - c_1cx_{i-1}$, which indicates the existence of lag-2 autocorrelation. Actually, MM-K was used in some analyses such as the effect of global warming on small aquatic ecosystems (Daufresne et al., 2009). In this case, MM-K is employed in this study to explore the trends within hydro-meteorological series. The significance level for MM-K was set at 5%. Detailed computation procedure can be referred to Daufresne et al. (2009).

2.3.2 Continuous wavelet transform method

The Continuous Wavelet Transform (CWT) (Torrence and Compo, 1998) was used in this study. x_n is assumed to be a time series with equal time step of δt and n = 0, 1, 2, …, N–1. $\psi_0(\eta)$ is a wavelet function relying on a dimensionless 'time' parameter, η with zero mean and localized in both frequency and time (Farge, 1992; Torrence and Compo, 1998). Morlet wavelet provides a good balance between time and frequency localization, and hence the Morlet wavelet was used in this study:

$$\psi_0(\eta)=\pi^{-1/4}e^{i\omega_0\eta}e^{-\eta^2/2} \tag{1}$$

where ω_0 is the nondimensional frequency and is taken as six to satisfy the admissibility condition (Farge, 1992; Torrence and Compo, 1998). The continuous wavelet transform of a discrete sequence x_n is defined as the convolution of x_n with a scaled and translated version of $\psi_0(\eta)$:

$$W_n(s)=\sum_{n'=0}^{N-1} x_{n'}\psi^*\left[\frac{(n'-n)\delta t}{s}\right] \tag{2}$$

where $W_n(s)$ is the wavelet power spectrum. (*) indicates the complex conjugate. s is the wavelet scale, n is the localized time index. Because the wavelet is not completely localized in time, to ignore the edge effects the Cone of Influence (COI) was introduced. Here COI is the region of the wavelet spectrum in which edge effects become important and is defined here as the e-folding time for the autocorrelation of wavelet power at each scale. This e-folding time is chosen so that the wavelet power for a discontinuity at the edge drops by a factor e^{-2} and ensures that the edge effects are negligible beyond this point (Torrence and Compo, 1998; Grinsted et al., 2004). The statistical significance of wavelet power can be evaluated under the null hypothesis that the signal is generated by a stationary process given the background power spectrum (P_k). It is assumed that the time series has a mean power spectrum, possibly given by Equation (3); if a peak in the wavelet power spectrum is significantly above this background spectrum, then it can be assumed to be a true feature with a certain percent confidence. One multiplies the background spectrum (Equation (3)) by the 95th percentile value for x_2^2 (Torrence and Compo, 1998). Many geophysical series have the red noise characteristics which can be modeled by a first order autoregressive process. The Fourier power spectrum of an autoregressive process with lag-1 autocorrelation α is given by (Grinsted et al., 2004) as:

$$P_k=\frac{1-\alpha^2}{|1-\alpha e^{-2i\pi k}|^2} \tag{3}$$

where k is the Fourier frequency index. Torrence and Compo (1998) used the Monte Carlo method to show that the probability that the wavelet power of a process with a given power spectrum (P_k) is greater than p is:

$$D\left(\frac{|W_n^X(s)|^2}{\sigma_X^2}<p\right)=\frac{1}{2}p_k\chi_v^2(p) \tag{4}$$

where D indicates 'is distributed as'. v is equal to 1 for real and 2 for complex wavelets.

Besides, coefficient of variation (Cv) and extremum ratio were used in this study to analyze relative changing magnitude of the annual steamflow. Large Cv indicates larger inter-annual changes of annual streamflow and hence higher flooding risks and vice versa (Chen et al., 2014). Ratio of the long-term annual maximum streamflow to the long-term annual minimum streamflow is the extremum ratio of the annual streamflow series, showing changing magnitude of annual streamflow.

3 Results

3.1 Monthly streamflow changes at monthly and annual time scales

Streamflow variations are driven mainly by precipitation changes in the Huaihe River Basin. Hence, seasonal variations of precipitation changes result in evident seasonality of streamflow changes. It can be seen from Fig. 2 that streamflow components in the Huaihe River Basin concentrated during May to September, accounting for 70.4% of the annual total streamflow amount. The largest monthly streamflow occurred during July, accounting for 19.4%–28.1%. Meanwhile, the minimum streamflow occurred during January, accounting for

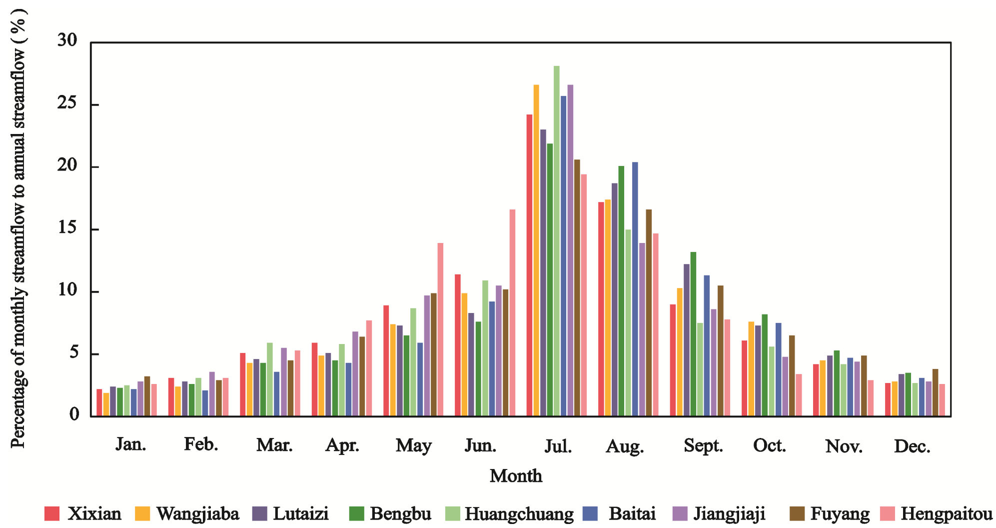

Fig. 2 Percentage of monthly streamflow to annual streamflow in the Huaihe River Basin

1.9%–2.8% of the annual total streamflow amount. Therefore, seasonal clustering of monthly streamflow can be observed in the Huaihe River Basin, which poses serious challenges for basin-scale management of irrigation and water resources.

It can be seen from Fig. 3 that coefficients of variance (*Cv*) of the streamflow series at the stations in the Huaihe River Basin range between 0.16–0.85 and the extremum ratio ranges between 1.70–23.90. Generally, larger coefficients of variance and annual extremum ratio values (the ratio of the maximum monthly streamflow to the minimum monthly streamflow) can be detected for streamflow series at stations in the Huaihe River Basin, indicating larger changing magnitude of hydrological processes. Furthermore, coefficients of variance and extremum ratio of streamflow series at the Huangchuan and Hengpaitou stations follow 'small-large-small' pattern. Coefficients of variance of the stream-

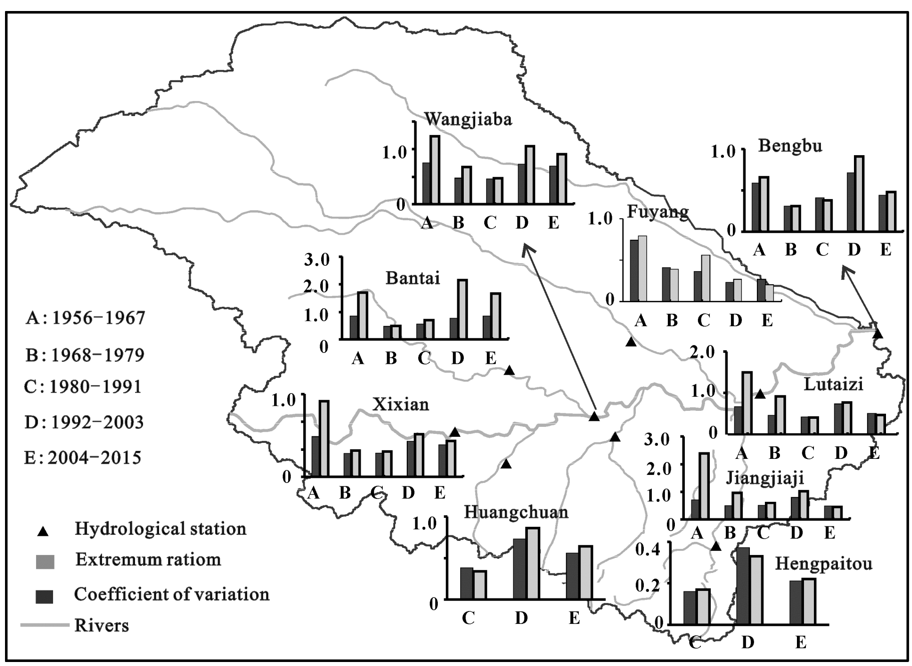

Fig. 3 Coefficient of variation (*Cv*) and extremum ratio (the ratio of the maximum monthly streamflow to the minimum monthly streamflow) of streamflow changes during different time intervals in the Huaihe River Basin. The extremum ratio values in this figure were times by 0.1 for the sake of visual convenience

flow series at the Fuyang station are in persistently decreasing tendency. In addition, coefficients of variance and extremum ratio of streamflow series at other stations follow 'large-small-large' pattern. Particularly, coefficients of variance of streamflow series at the Bantai station are in persistently increasing tendency after 1968 and reach the largest value during 2004–2015.

3.2 Trends, abrupt changes and periodicity properties of streamflow

Fig. 4 illustrates abrupt behaviors of streamflow series at the nine stations in the Huaihe River Basin. It can be seen from Fig. 4 that generally similar trends can be observed for streamflow series at the stations in the Huaihe River Basin. Moderate streamflow changes can be detected at the stations except Huangchuan and Hengpaitou stations. Increasing streamflow can be identified during 1980–1993 and 2003–2015 respectively, while decreasing streamflow during 1993–2003. Specifically, significant decreasing trend can be found during 2003 at the Wangjiaba and Bengbu stations. Moreover, slight decrease of streamflow can be observed at the Wangjiaba station during 1956–2015 and general decrease of streamflow can be observed at other stations. In general, similar changing pattern of streamflow in terms of trends can be discerned for streamflow changes in the Huaihe River Basin, i.e., general decrease of streamflow can be confirmed. MM-K trends of monthly streamflow at nine stations in the Huaihe River Basin (figure not shown here) indicate increase of streamflow at the Xixian and Huangchuan stations during September and December, respectively. While, decreased streamflow at these two stations can be detected during other months. Generally decreasing streamflow can be found at the Lutaizi station and significant decreasing trend can be observed during May. No significant trends of streamflow can be observed at the Bantai and Bengbu stations. From the monthly viewpoint, streamflow during January is increasing, while significant decreasing streamflow during April, May, July, October and November can be detected. Particularly, streamflow during April and May is in decreasing tendency in general and no significant trends can be detected during the rest months. MM-K trends of streamflow during flooding and non-flooding seasons indicate significant decreased streamflow during spring and non-flooding season. Increased streamflow can be found at the Xixian station during autumn. While, increased streamflow at the Wangjiaba and Hengpaitou stations during winter can be identified. General decreased streamflow can be found at other stations. Meanwhile, persistent decrease of streamflow can be found during summer and autumn seasons. In general, decreased streamflow can be confirmed in the Huaihe River Basin.

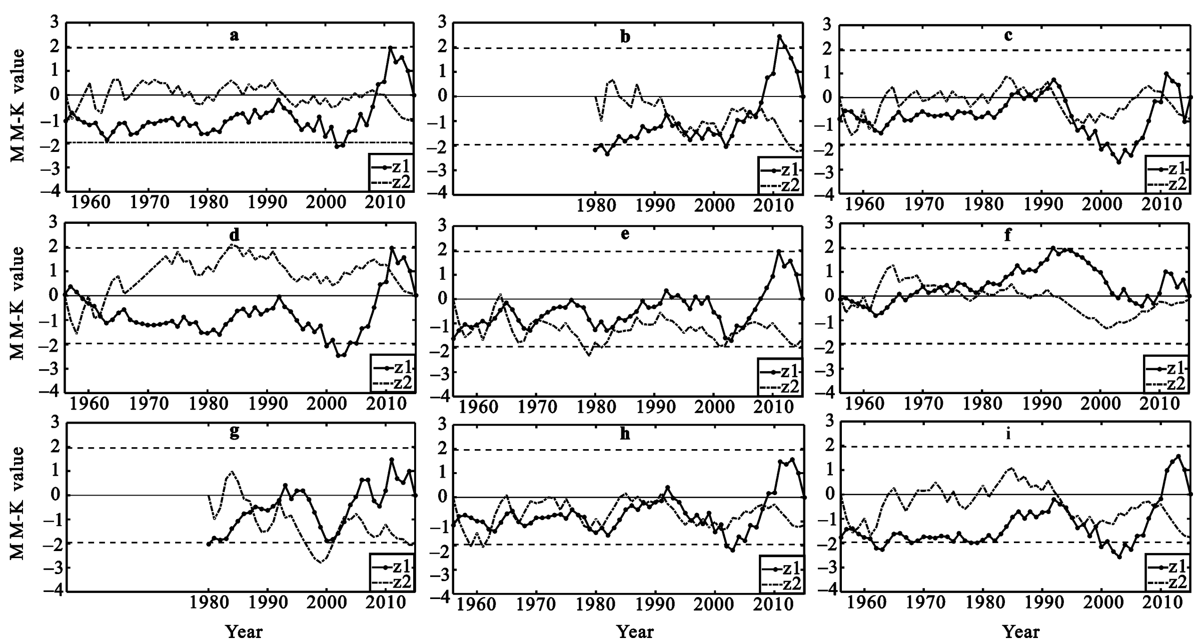

Fig. 4 Modified Mann-Kendall (MM-K) trends of streamflow changes in the Huaihe River Basin. Hydrological stations are: a: Xixian; b: Huangchuan; c: Bantai; d: Wangjiaba; e: Jiangjiaji; f: Fuyang; g: Hengpaitou; h: Lutaizi; i: Bengbu.

3.3 Periodicity property of streamflow changes

Fig. 5 shows periodicity properties of annual streamflow in the Huaihe River Basin. It can be seen that 2–3 yr periods were significant during the late 1990s and early 2000 and these significant periods were detected at the Bantai, Wangjiaba, Lutaizi and Bengbu stations. Fig. 1 demonstrates that these stations are located along the tributaries northern to the mainstream of the Huaihe River Basin and also in the lower Huai River Basin. Besides, significant periodicity of 2–3 yr was found during early 1990s at the Hengpaitou station in the Pihe River Basin, southern to the mainstream of the middle Huaihe River Basin. Periodicity properties of seasonal streamflow changes were illustrated in Figs. 6 and 7. Similar periodicity properties can be observed for spring streamflow changes with significant periods of 48 years during early 1960s. However, different periodicity properties of summer, autumn and winter streamflow changes can be detected. No significant period components can be detected for streamflow changes at the Xixian, Lutaizi and Bengbu stations. Significant periods of eight years and 2–4 yr were found during early 1990s and early 1980s at different stations.

Besides, sporadic distribution of significant periods can be found for streamflow changes during autumn and winter seasons (Fig. 7). These no persistent and discernable changing patterns of periodicity indicate various influencing factors having impacts on periodicity components of the streamflow changes in terms of seasonality. Periodicity properties of seasonal streamflow changes in the Huaihe River Basin during flooding and non-flooding periods were also analyzed (Fig. 8). It can be seen from the flood seasons of Fig. 8 that significant periods of 2, 4 and 8 yr. However, no significant periods were found for streamflow series at the Xixian, Wangjiaba, Lutaizi and Bengbu stations. It can be seen from Fig. 1 that these stations are located along the mainstream of the Huaihe River Basin. Streamflow components in the mainstream Huaihe River Basin were combined results of different streamflow components from different tributaries, which greatly eliminated periodicity components caused by temporal variations of precipitation and other influencing factors. Relatively discernable periods can be detected for streamflow changes during non-flooding seasons, which follows wet and dry periods of climate variations reflected by variability and availability of ground water resources.

3.4 Relationship between the climate indices and streamflow

Climatic indices have significant impacts on streamflow changes at the Huangchuan station (Fig. 9) and relations between streamflow and MEI and PDO are significant at 95% and 99% confidence level respectively. PDO has

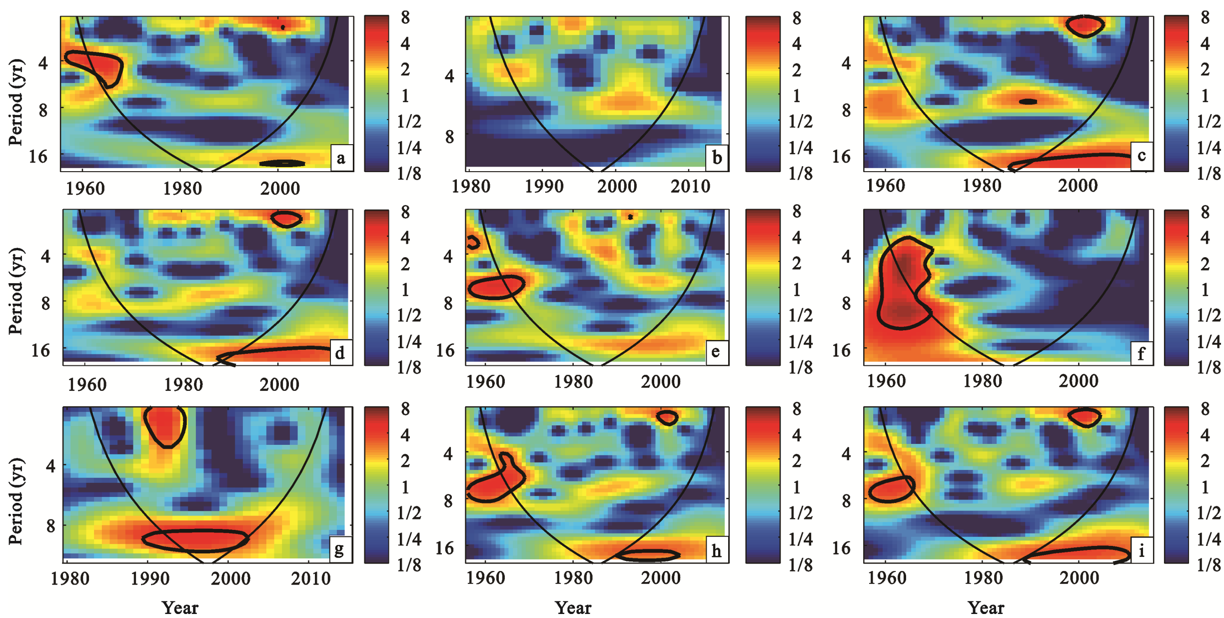

Fig. 5 Periodicity properties of streamflow changes in the Huaihe River Basin. Hydrological stations are: a: Xixian; b: Huangchuan; c: Bantai; d: Wangjiaba; e: Jiangjiaji; f: Fuyang; g: Hengpaitou; h: Lutaizi; i: Bengbu. (Significant periodic changes are only considered within Cone of Influence and high value stand for strongly significant periodic in the bar, similar to Figs. 5–8).

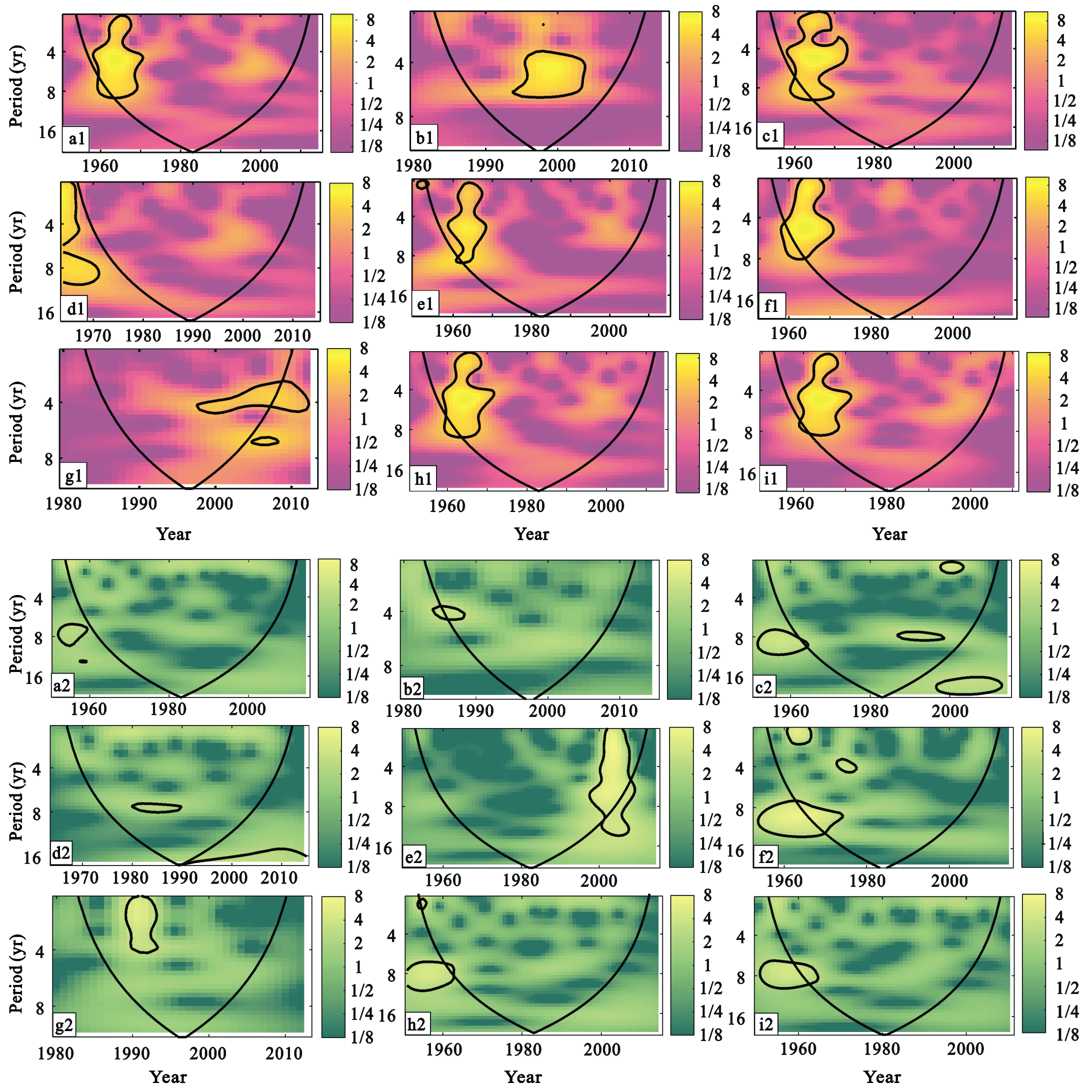

Fig. 6 Periodicity properties of streamflow changes in the Huaihe River Basin during spring (a1–i1), summer (a2–i2). Hydrological stations are: a: Xixian; b: Huangchuan; c: Bantai; d: Wangjiaba; e: Jiangjiaji; f: Fuyang; g: Hengpaitou; h: Lutaizi; i: Bengbu

significant impacts on monthly streamflow changes at all but Fuyang station during June. NAO and AO have general and persistent influences on monthly streamflow changes across the entire Huaihe River Basin. Wherein, AO has significant impacts on monthly streamflow changes at most stations except Bantai station. In addition, MEI and Niño3.4 also have persistent impacts on monthly streamflow changes at almost all hydrological stations. However, these impacts from MEI and Niño3.4 are not statistically significant.

Furthermore, lag time can be quantified between streamflow changes and precipitation as well as climatic indices considered in this study. Fig. 10 indicate relations between climatic indices and monthly streamflow changes during January to December with time lag of three months. It can be easily observed that negative relations can be quantified between monthly streamflow and NAO, and Niño3.4 as well. May witnessed significant relations between NAO and monthly streamflow with time lag of three months. Meanwhile, relations were significant at Lutaizi and Bengbu stations at 99% confidence level. When compared to the time lag of three months between NAO and monthly streamflow variations, relations between NAO and monthly streamflow are relatively weak with time lag of three months. Impacts of Niño3.4 on monthly streamflow in terms of time lag are mainly observed at the Huangchuan and Jiangjiaji stations. Besides, weak relations can be found between AO, PDO and monthly streamflow at almost all hydrological stations across the Huaihe River Basin.

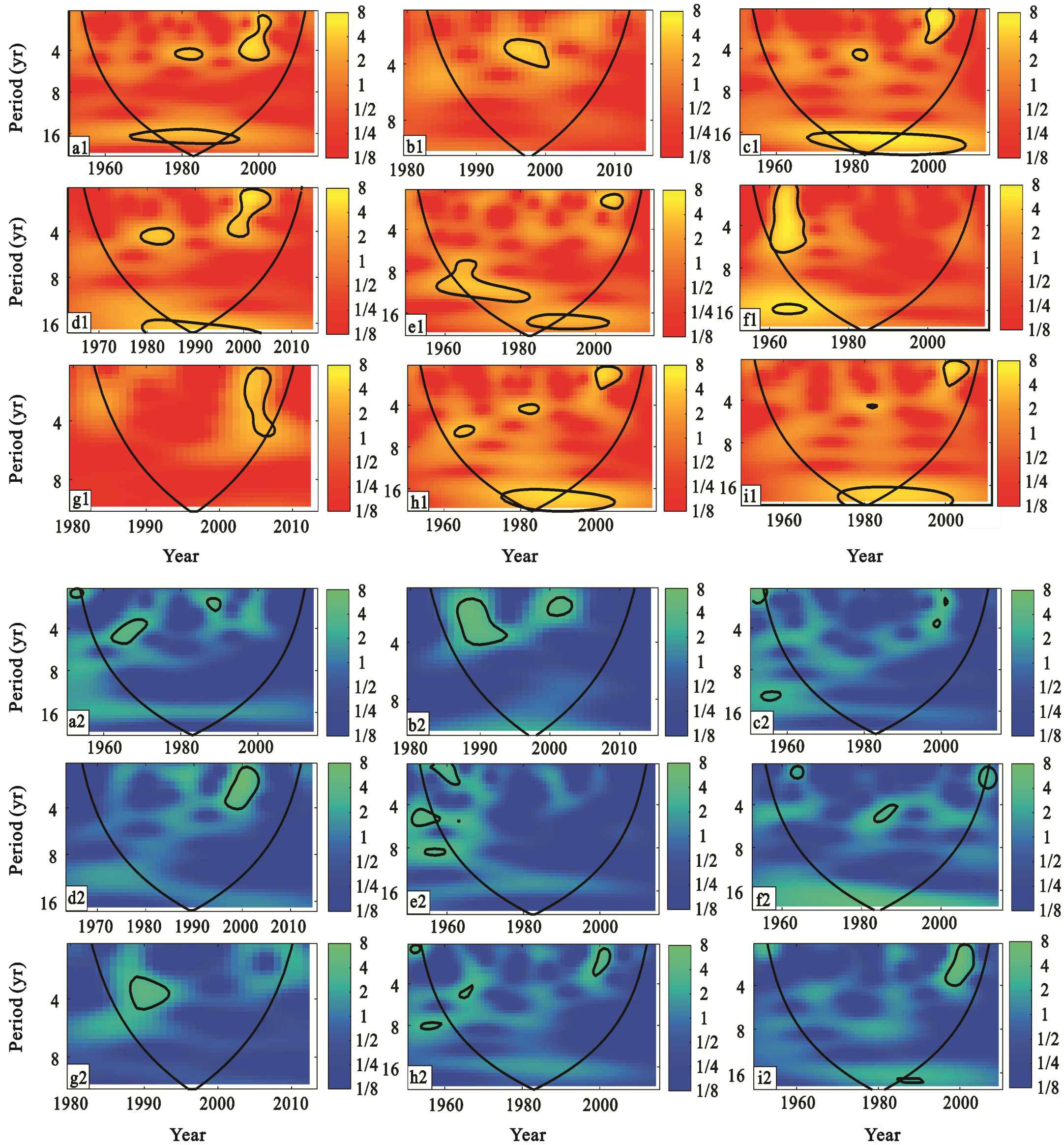

Fig. 7 Periodicity properties of streamflow changes in the Huaihe River Basin during autumn (a1–i1) and winter (a2–i2). Hydrological stations are: a: Xixian; b: Huangchuan; c: Bantai; d: Wangjiaba; e: Jiangjiaji; f: Fuyang; g: Hengpaitou; h: Lutaizi; i: Bengbu

Comparatively, SOI has increasing impacts on monthly streamflow changes in terms of time lag at the Huangchuan, Jiangjiaji and Hengpaitou stations and these impacts were significant at 95% confidence level.

4 Discussion

Larger streamflow amount can be observed during May-September and almost half of the annual total streamflow amount occurs during summer (JJA). Coefficients of variance of the streamflow in the Huaihe River Basin range between 0.16–0.85 and extremum ratio values range between 1.70–23.90 with larger coefficients of variance and extremum ratio values during different time intervals. Research results indicated that larger fluctuations of precipitation can be detected across the Huaihe River Basin in recent 50 years with intensifying precipitation processes (Chen et al., 2005; Zheng et al., 2015). Annual distribution of precipitation is largely uneven with precipitation amount during June to September accounting for 50%–75% of the annual total precipitation amount (Tan et al., 2016). Meanwhile, the Huaihe River Basin is characterized by the highest population density with heavy responsibility of supplier

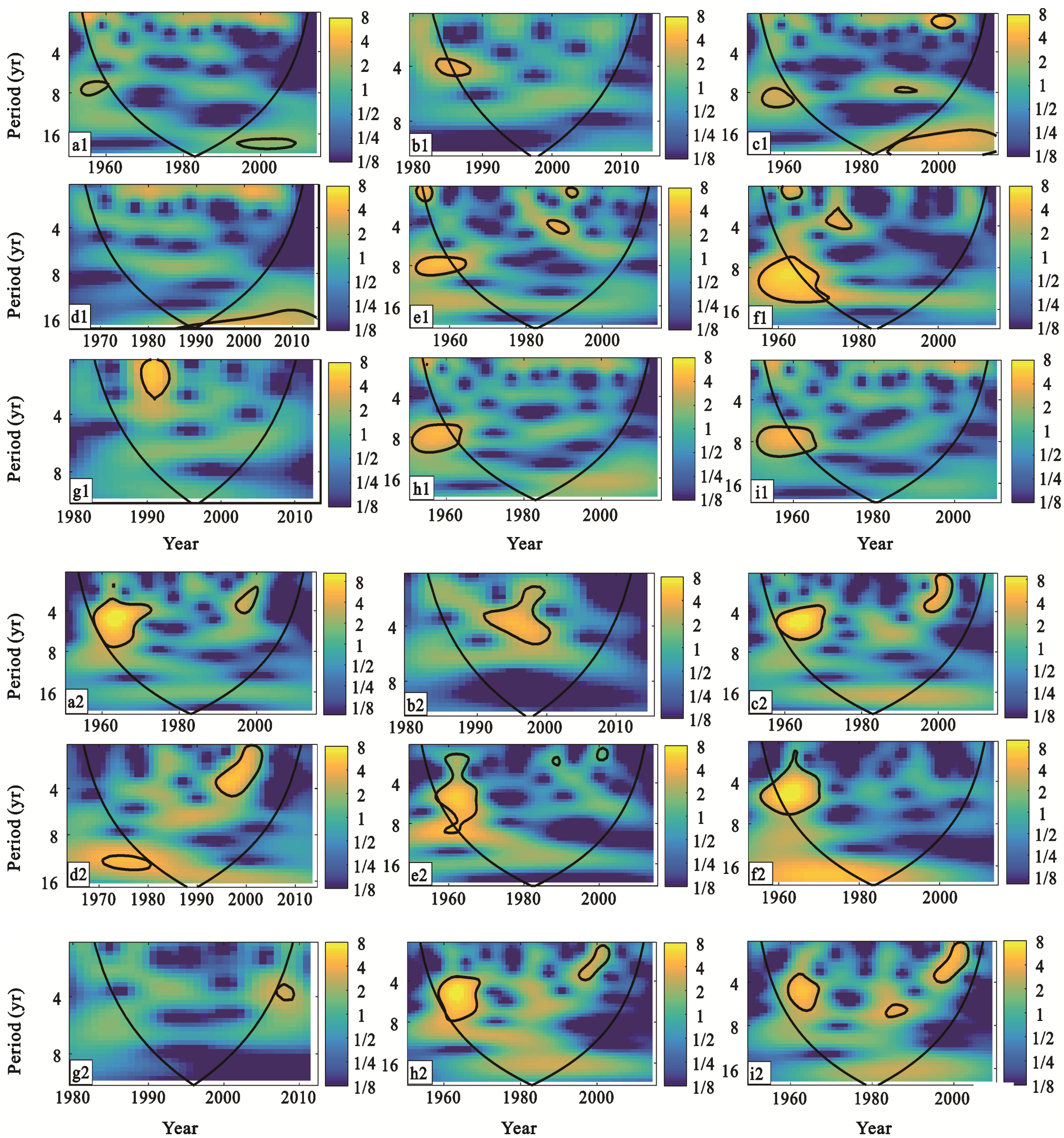

Fig. 8 Periodicity properties of streamflow changes during flooding (a1–i1) and non-flooding (a2–i2) periods in the Huaihe River Basin. Hydrological stations are: a: Xixian; b: Huangchuan; c: Bantai; d: Wangjiaba; e: Jiangjiaji; f: Fuyang; g: Hengpaitou; h: Lutaizi; i: Bengbu

of agricultural products. The crop areas during 1983–2014 increased from 1.64×10^5 to 1.92×10^5 km^2. Besides, there built more than 5700 water reservoirs with total water capacity of 2.72×10^{10} m^3. Besides, there developed 28 flooding mitigation areas with holding capacity of flooding water volume of 8.86×10^9 m^3 (Ning et al., 2003). Human interferences on streamflow changes render hydrological processes larger fluctuations in both space and time.

Generally, moderate streamflow changes can be found during 1956–1980 except those at the Huangchuan and Hengpaitou stations. Coefficients of variance and extremum ratio values are from large to small values. While, more precipitation amounts were observed during early 1960s, middle 1970s. Relatively dry conditions were found during late 1960s, late 1970s (Wang and Yan, 2014). Floods and droughts occur two times per three years in the Huaihe River Basin (Ning et al., 2003). In this sense, frequent floods and droughts can be found across the Huaihe River Basin. Floods occurred during 1957, 1963, 1968, 1974 and 1975 before 1980s. While, water reservoirs were built across the Huaihe

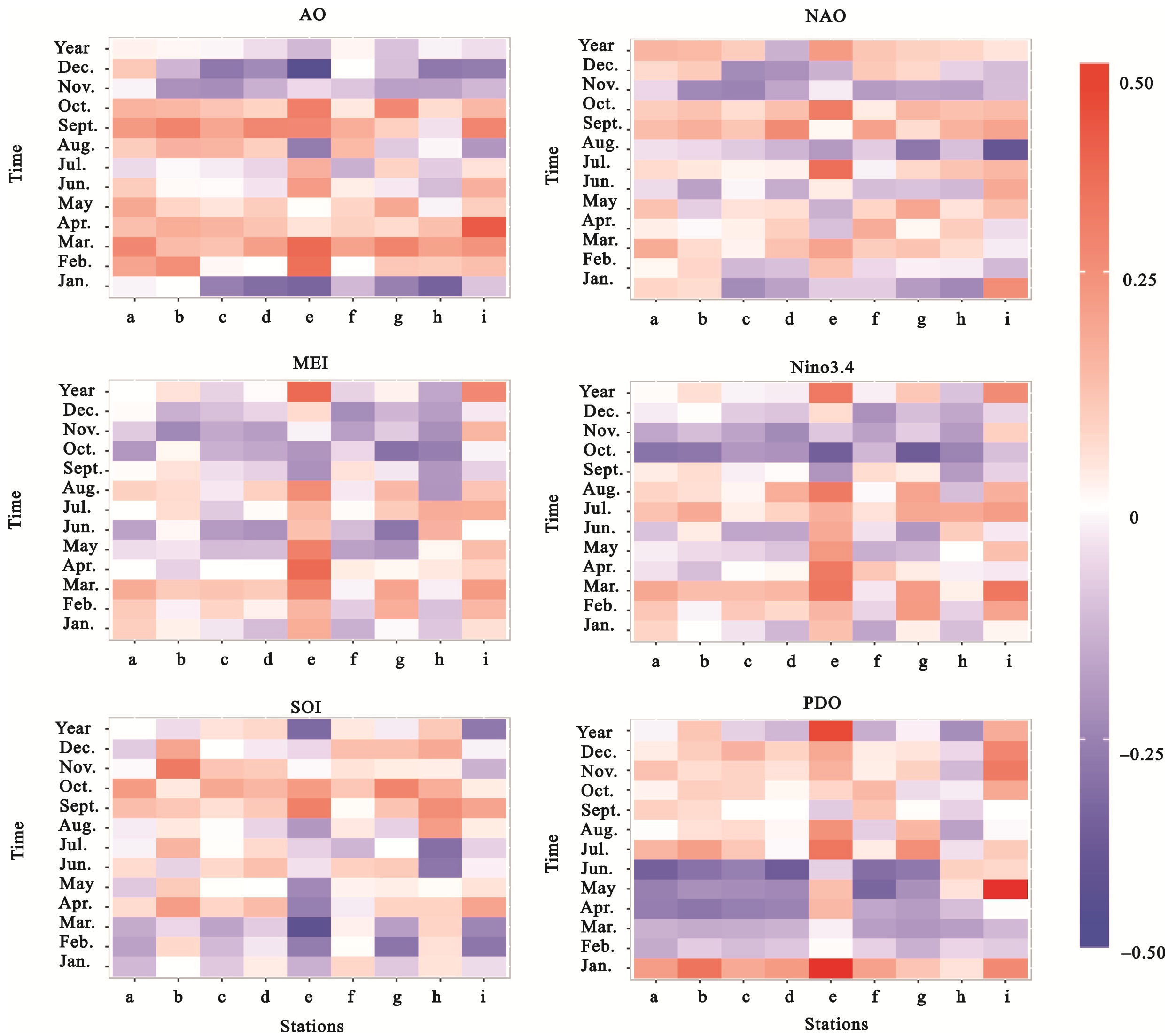

Fig. 9 Correlation coefficients between climatic indices and monthly streamflow changes during January to December in the Huaihe River Basin. Hydrological stations are: a: Xixian; b: Huangchuan; c: Bantai; d: Wangjiaba; e: Jiangjiaji; f: Fuyang; g: Hengpaitou; h: Lutaizi; i: Bengbu. Climatic indices: Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Multivariate ENSO index (MEI), Niño3.4 Sea Surface Temperature (Niño3.4), South Oscillation Index (SOI), Pacific Decadal Oscillation (PDO)

River Basin during the late 1950s and early 1960s, Xianghongdian, Mozitan and Shishan water reservoirs were built during 1958, 1958 and 1962 respectively. These water reservoirs can help to decrease peak flood flow and increase low flow. Hence, moderate streamflow changes can be found after the building of these water reservoirs. Increased streamflow can be observed during 1981–1993. For the sake of development of socio-economy of China, ecological conservation was done to reduce loss of soil and water. The protected land area can reach 20 000 km^2 and enhancement of water reservoirs for the sake of flood mitigation was completed. Water supply can be expected to be increased to 170 × 10^8 m^3 to 210 × 10^8 m^3 and the total water supply of the entire Huaihe River Basin reaches 560 × 10^8 m^3 to 660 × 10^8 m^3. Besides, two floods occurred during 1991. Flood magnitude in the Dabieshan regions along the Huaihe River Basin and southern Huaihe River Basin, Lixia River Basin reached the flood magnitude during 1954. Therefore, increased streamflow can be expected across the Huaihe River Basin (Ning et al., 2003). Evident decrease of streamflow can be found during 1994–2003. In recent years, significant warming was observed across the Huaihe River Basin with warming rate of 0.203℃ per ten years. More significant warming processes can be found after 1990 and it is particularly

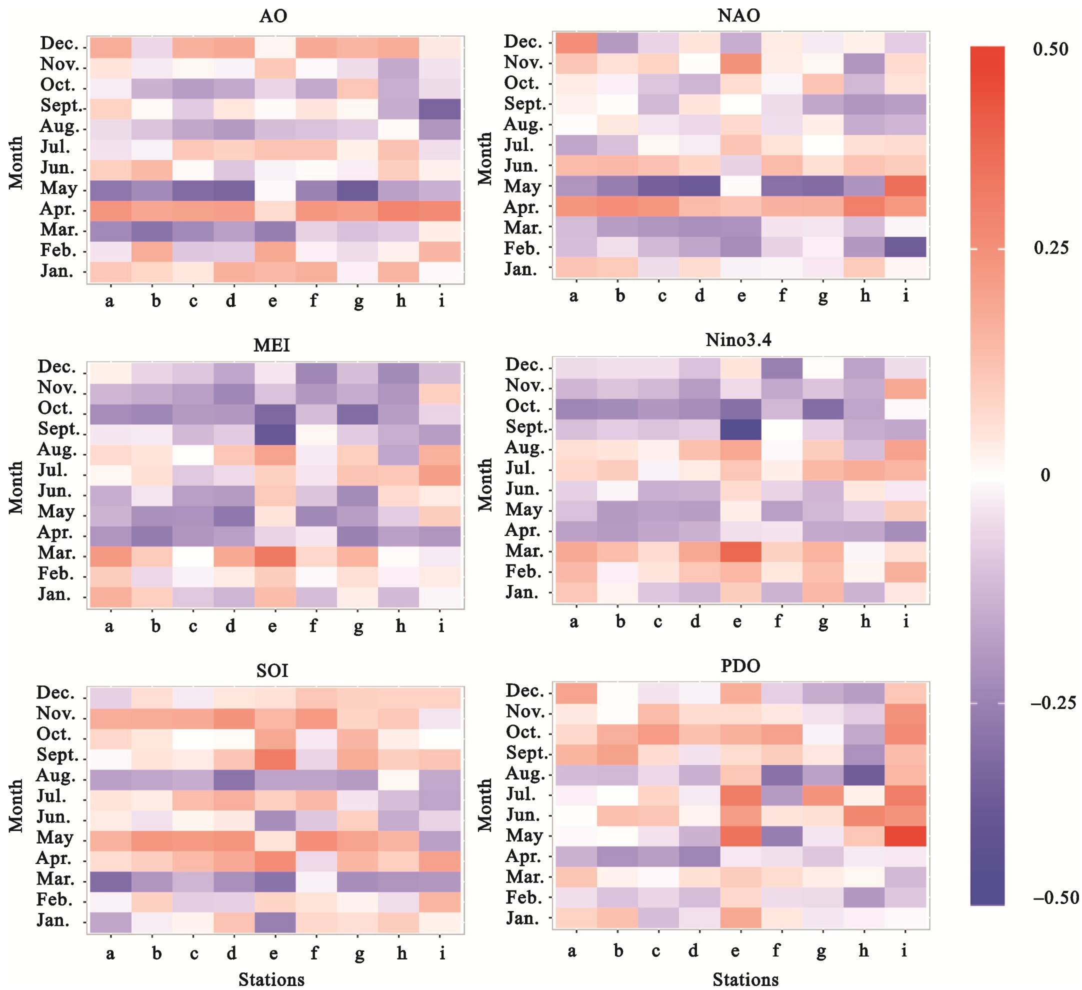

Fig. 10 Correlation coefficients between climatic indices and monthly streamflow changes during January to December with time lag of 3 months in the Huaihe River Basin. Hydrological stations are: a: Xixian; b: Huangchuan; c: Bantai; d: Wangjiaba; e: Jiangjiaji; f: Fuyang; g: Hengpaitou; h: Lutaizi; i: Bengbu. Climatic indices: Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Multivariate ENSO index (MEI), Niño3.4 Sea Surface Temperature (Niño3.4), South Oscillation Index (SOI), Pacific Decadal Oscillation (PDO)

the case after 1997 (Ye et al., 2016), which greatly modified streamflow processes of the Huaihe River Basin with larger streamflow fluctuations. Less precipitation during late 1980s and early 21st century resulted in three serious droughts during 1994, 1999 and 2001 respectively (Lu et al., 2011).

Especially in 2001, there was a continuous drought in spring, summer, autumn and winter, and no streamflow events occurred at the Wangjiaba Station for 9 days. The annual total streamflow amount at the Bengbu station reached 7.4 × 10^8 m^3, being only 25% of streamflow amount for the same period of the previous year, and water volume during flooding season is only 4.2 × 10^8 m^3 (Ning et al., 2003). Therefore, a significant decrease trend of streamflow at 95% confidence intervals can be found at the Baitai, Wangjiaba and Bengbu stations in 2003. The general increase of streamflow can be found during 2004–2015 across the Huaihe River Basin. In particular, significant upward trend of streamflow at the Huangchuan station can be detected during 2010 at 95% confidence level, which should be attributed to excessive precipitation after 2003 (Wang and Yan, 2014). After floods across the entire Huaihe River Basin after 2003, another major floods across the entire Huaihe River Basin occurred during 2007 and 2010 respectively. Overall, streamflow in the Huaihe River Basin showed a generally decreasing trend, especially during April-May when is the critical time for development of winter wheat and decreased streamflow is a greater threat for the growth of winter wheat. The increase in grain acreage has led to an ever-increasing demand of water resources by agricultural irrigation. Since the

1990s, cultivated land area and population have also been increasing. From 1994 to 2003, an increase of 5.8×10^6 ha of arable land made it the major cause behind decreased streamflow across the Huaihe River Basin. In addition, from the periodicity viewpoint, there are significant periods in both time and frequency domain can be detected for streamflow changes at the Bantai, Wangjiaba, Lutaizi and Bengbu stations, and a certain degree of similarities in time-frequency structure can also be identified in periodicity properties of streamflow. The periods are within 2.0–3.4 yr during 2000. In addition, periodicity of streamflow series at the Xixian, Huangchuan and Jiangjiaji is not significant at 95% confidence interval between the early 1990s and the early 21st century, but they are still in high-energy zones at this scale. While, the continuous wavelet spectrum of streamflow during the flood and non-flood seasons at all stations considered in this study shows that the significant periods are concentrated in 1960s, 1980s and 2000s, with major periods of 2–8 and 2–4 yr. While, streamflow change is mainly influenced by climate change and human activities. Among them, the contribution of precipitation to the upstream streamflow in the Huaihe River Basin is 24% and is 21% in the middle Huaihe River Basin (Tang et al., 2015). The precipitation in the Huaihe River Basin is subject to the strongest fluctuation with periods of 6 years and followed by the main oscillation with period of about 14 years (Cao et al., 2015). The stations are distributed in different areas of the Huaihe River Basin. Periodic variations of the streamflow changes are basically the same except for the strength of the cycles although the topography and climatic conditions are different, indicating that the periodic features of streamflow in the Huaihe River Basin are strongly influenced by human activities (water conservancy projects) (Ma et al., 2014). Therefore, human activities are the main reasons for the shortening of the streamflow period.

The spatio-temporal characteristics of the streamflow process in the Huaihe River Basin are the results of combined impacts from more than one driving factor. Research showed that there is a significant correlation between El Niño anomalies and precipitation anomalies across the Huaihe River Basin. During development periods of the El Niño regime, precipitation in the Huaihe River Basin increased, and vice versa. The warm events in the central Pacific and the warm events in the eastern Pacific have a significant impact on heavy rainfall and torrential rains in the Huaihe River Basin. Floods often occur in the central Huaihe River Basin during the warm events in the central Pacific and the warm events in the eastern Pacific (Wang et al., 2016a; 2016b; Zhang et al., 2016). Abnormal atmospheric circulation leads to abnormal precipitation, and the change of streamflow is closely related to the change of precipitation. According to the analysis of the relationship between climatic index, the annual streamflow and monthly streamflow in the Huaihe River Basin, we can find that the annual streamflow at the Huangchuan station has the most obvious response to the climatic factors, and the response to MEI and PDO index respectively is significant at 95% and 99% confidence level. This is mainly because the Huangchuan catchment area is the smallest, only 2050 km^2, and is sensitive to climate factors. In addition, the most significant direct impact of PDO can be observed on the monthly streamflow across the Huaihe River Basin during June. Especially, impacts of PDO on streamflow changes at the Bantai station during January, April and June are significant at the 95% confidence level. Relevant studies showed that ENSO influences the precipitation across major regions of China via its impacts on the East Asian monsoon. Apart from impacts of ENSO on precipitation across the Huaihe River Basin, precipitation across the Huaihe River Basin is affected by many climatic factors such as PDO and NAO (Xiao et al., 2015). While, PDO is a key factor affecting summer precipitation in the Huaihe River Basin, and has a significant negative correlation with summer precipitation (Wang et al., 2016a). Both NAO and AO tended to have similar impacts on monthly streamflow changes in the study area, both of these two climatic factors can reflect the intensity of the westerly winds in the mid-latitudes. However, AO has more pronounced impacts on streamflow changes at stations across the Huaihe River Basin. With the exception of the Bantai stations, impacts of NAO and AO on monthly streamflow changes are significant at 95% confidence level with positive correlation. Similarly, MEI and Niño3.4 also showed similar impacts on monthly streamflow at each site, but the impacts of these two factors on monthly streamflow changes in the study area are not significant statistically. The natural inertia of climate change and the time scale of atmospheric circulation determine the intensity of the impact of climate change on streamflow. The greater the impact of climatic factors on streamflow, the more significant the lag time is. Precipitation anomalies in the Huaihe River Basin and the anomalies in the equatorial eastern Pacific are not synchronous. The influence of the equatorial Pacific SST anomaly on the precipitation in the Huaihe River Basin is a kind of process and the impacts are the strongest with time lag of three months. Then, for the time lag of six months, the response was almost the same as that of the same period. The ENSO event is an anomalous warming of the SST in the equatorial eastern Pacific Ocean. The anomalous precipitation regimes in the Huaihe River Basin has obvious response to ENSO events from March to June (Xin and Xie, 2005). The response of the monthly streamflow in the Huaihe River Basin to most climatic factors also shows obvious time lag. Figs. 9–10 show that the impact of climatic factors on the streamflow in the Huaihe River Basin is the most significant with three months in time lag, and impacts are weakening with time lag of six months.

In general, climate changes and human activities caused violent fluctuations in streamflow in the Huaihe River Basin, which further contributed to the non-uniform distribution and concentration of streamflow during the year. This distribution of inhomogeneities and overall dispersion of hydrological processes also reflects the cross-superimposition of the north-south transitional climates across eastern China (wang et al., 2015), and is also the major reason behind highly concentrated occurrences of floods and waterlogging events.

5 Conclusions

Understanding streamflow changes in terms of trends and periodicities and relevant causes is the first step into scientific management of water resources in a changing environment. Actually, there are a range of researches addressing precipitation changes and streamflow variations. However, few and even no reports can be found handling scientific issues pertaining to trends, variability, change points and periodicity of streamflow changes. Particularly, causes behind streamflow changes in terms of ENSO etc. have not been investigated so far. Thus, in this study, monthly streamflow variations were analyzed using MM-K trend test and CWT methods at nine hydrological stations in the Huaihe River Basin. These analysis results can well answer the aforementioned scientific issues to be addressed in the introduction section of this study. It was found that streamflow amount mainly occurs from May to September and the monthly streamflow in summer exceeds half of the annual total. Streamflow processes of the Huaihe River Basin are subject to larger variability, e.g., the coefficient of variation of streamflow ranges from 0.16 to 0.85, and annual extremum ratio of the streamflow between 1.70–23.90 in the Huaihe River Basin. Increased cropland areas and precipitation of large variability result in higher coefficient of variation from 1992 to 2015. However, the highest coefficient of variation before 1964 should be attributed to be free of hydrological regulations of water reservoirs. These above-mentioned results indicated highly concentrated streamflow changes during May to September with larger streamflow variability. Higher monthly concentration of streamflow and larger streamflow variability can be attributed to high irrigation requirements and larger variability of precipitation processes in the Huaihe River Basin.

Three time intervals can be differentiated being characterized by different trends and periodicities in the streamflow series. Causes behind different trends and periodicities of streamflow variations within these three time intervals were discussed with more details. Specifically, in terms of trends in streamflow components, a period of 1956–2015 witnessed persistent downward trends. Streamflow amount in the Huaihe River Basin is increasing during 1980–1993 and 2003–2015 because of increased precipitation. While the period 1993–2003 witnessed decreased streamflow amount due to decreased precipitation and increased irrigation requirements as a result of increased cropland area. Therefore, it can be tentatively concluded that precipitation change is the critical factor behind streamflow changes. Agricultural irrigation can reduce the streamflow amount and it is particularly true during April and May when the water resource demand peaks for agriculture irrigation and hence low flow during April and May. Periodicity of streamflow series is the result of precipitation changes. While human activities such as agricultural irrigation can potentially introduce noise into the periodicity by climate changes. Periodicities of 2.0–8.0 yr or 2.0–4.0 yr of streamflow series can be detected across the Huaihe River Basin during periods of 1960s, 1980s and 2000s. However, periodicities of streamflow series are slightly different at specific stations. For example, periodicities of 2.0–3.4 yr of streamflow changes were detected at the Bantai, Wangjiaba, Lutaizi and Bengbu stations around 2000. While, no significant periodicities can be identified the Xixian, Huangchuan and Jiangjiaji stations during early 1990s to early 21st century.

Different impacts of PDO, AO on streamflow changes were identified. Besides, our results also indicated seasonality of impacts of PDO, AO on streamflow variations across the Huaihe River Basin. Specifically, causes behind streamflow changes were identified based on relations between monthly streamflow components and climatic factors. Most significant impacts can be found for PDO and during June in particular. PDO is in negative relations with streamflow changes and specifically, PDO is in significant relations with streamflow at the Bantai station during January, April and June. Meanwhile, AO has the most significant impacts on streamflow changes across the entire Huaihe River Basin, except the Bantai station. The influence of climatic factors on streamflow in the Huaihe River Basin was the most significant in time lag of three months, and was less significant in time lag of six months. Identification of critical climatic factors having impacts on streamflow changes can help to predict monthly streamflow changes using climatic factors as explanatory variables.

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