Theor Appl Climatol
DOI 10.1007/s00704-013-0888-y

ORIGINAL PAPER

The impact of changing environments on the runoff regimes of the arid Heihe River basin, China

Yan-Fang Sang · Zhonggen Wang · Changming Liu · Jingjie Yu

Received: 21 September 2012 / Accepted: 21 March 2013

Abstract This study analyzed the inter- and inner-annual variations of discharge regimes in the upper and mid reaches of the Heihe River basin. These variations then correlated with temperature and precipitation variations in the area. The differences between the runoff regimes at the upper and mid reaches were compared, and the human impacts on discharge variations in the Heihe River were discussed. The results indicate that in the upper reaches, the long-term trends and periods of discharge and precipitation correlate well. In the mid reaches, the discharge and temperature trends correlate well, and the short discharge and precipitation periods correlate well. Precipitation increases would generate more runoff in both the upper and mid reaches, but the effects of temperature increases on discharge are different in the upper and mid reaches. Temperature increases would enhance the glacial ablation processes and increase runoff in the upper reaches. However, temperature increases would increase the evaporation and decrease runoff in the mid reaches. After the 1980s, higher temperature enhanced snow and glacial melt, and increasing precipitation increased the discharge in the upper reaches. Although increasing precipitation increased some discharge, great human activities caused a notable discharge decrease in the 1990s in the mid reaches, especially during the spring to autumn when large amounts of water resources were used for irrigation. In summary, both precipitation and temperature impact the availability of water resources in the study area, and active and effective adaptation strategies should be developed to improve the efficiency of water resource exploration and to prevent the desertification processes in the arid Heihe River basin.

Y.-F. Sang · Z. Wang (✉) · C. Liu · J. Yu
Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
e-mail: wangzg@igsnrr.ac.cn

1 Introduction

Climate change and human impact are two main factors impacting the runoff regimes in various basins and regions, and these factors have exacerbated the shortage of available water resources in many basins worldwide (Vorosmarty et al. 2000; Kalnay and Cai 2003; Labat et al. 2004). Therefore, to address water resources utilization and management, increased attention has been given to the effect of climate change and human activities on runoff variations. Due to their geographical differences, basins vary in their sensitivity to climate change and human activities (Zhang et al. 2006a; Sang et al. 2012b). Arid and high-latitude regions are among the most sensitive and susceptible regions (Chen et al. 2005; Tanaka et al. 2006; Huo et al. 2008). In arid basins, low precipitation and limited water resources are the key limiting factors for agricultural and economic developments and urbanization (Wen and Jin 2012). Even small precipitation decreases and temperature increases can cause large, sometimes even irreversible, eco-environmental deterioration, especially when compounded by human activities impacts (Feng et al. 2000; Chen et al. 2006).

Northwest China is one of the most sensitive regions in the world with regard to climate change (Wang et al. 2012). Due to its special topography and geographical conditions, the Heihe River basin (the second largest arid interior basin in Northwest China) is noticeably influenced by climate change and human activities (Ma et al. 2008; Wu et al. 2010; Dang et al. 2011). The Heihe River basin is located at 98.0–101.5° E longitude and 38.0–42.5° N latitude, with a drainage area of 142,900 km^2. The upper reaches are mountainous, with an elevation of 2,000–5,000 m; the mid reaches are an oasis, with an elevation of 1,300–3,200 m; and the low reaches belong to the arid Gobi desert, with an elevation of 910–1,450 m. The Heihe River basin is characterized by a topography leading from mountains to plains, with the mountains encircling the large plains. Because mountains can intercept a great deal of

Published online: 11 April 2013

water vapor and form convective precipitation, the runoff is mainly generated in the mountain areas (i.e., the upper reaches). Precipitation is rarely generated over the extremely arid plains, i.e., the mid and low reaches. Overall, runoff in the upper reaches of the Heihe River basin generates almost all of the water resources necessary to support the social and economic developments and maintain the ecosystem for the entire basin (Guo et al. 2009; Zhang et al. 2011).

The upper reaches of the Heihe River basin is comprised of sparsely populated regions, but more than 90 % population settled in the mid reaches, which is also one of the primary grain-producing areas in Northwest China (Huo et al. 2008). Since the 1950s, the Heihe River basin has experienced the exploitation of its land and water resources as well as serious eco-environmental problems in the lower and mid reaches, including the enhanced evaporation of rivers and lakes, groundwater depletion and desertification (Zhu et al. 2004; Zhang et al. 2006b; Jin et al. 2008). Furthermore, temperature increases seriously impact the processes of glacial ablation, water and soil conservation, marsh shrink, and grassland desertification (Li et al. 2006; Wang et al. 2011). We expect climate change to be the largest factor in the upper reaches, as human use is neglectable. However, the mid reaches are greatly impacted by both human activities and climate change. Observing the impacts of climate change and human activities on hydrological processes can help the development and implementation of adaptation strategies by public policy makers.

Despite efforts to study spatial–temporal climate variability and the runoff regimes in the Heihe River basin (Feng et al. 2000; Li et al. 2006; Ma et al. 2008; Wu et al. 2010; etc.), there remains a lack of in-depth analyses of the runoff's non-stationary characteristics and their correlations with the non-stationary climate variability as well as human activities. The objective of this paper is to use the monthly and annual temperature, precipitation, and discharge data to investigate variations of the runoff regimes in the Heihe River due to climate change and human activities. The inter-annual periodic characteristics of temperature, precipitation, and discharge were examined, and the results were compared to establish relation about how temperature and precipitation variations affect the discharge variations in the Heihe River. Furthermore, the inner-annual runoff distributions were analyzed by examining the exploitation of water resources in the basin, and the impact of human activities was investigated. Conclusions were made finally.

2 Dataset and methods

2.1 Dataset

Annual and monthly temperature and precipitation data from six stations were selected for this study: the Tuole, Yeniugou, Qilian, Shandan, Zhangye, and Gaotai as shown in Fig. 1b. The climatic data were obtained from the National Climate Center of the China Meteorological Administration. All of the series covered the same period (1960–2000), with no missing segments.

The Yingluoxia hydrological station is located at the outlet of the upper reaches, and the Zhengyixia hydrological station is located at the outlet of the mid reaches in the Heihe River basin. Discharge data of the two stations were obtained from the Water Yearbook of China. Any variations of the runoff measured at the Yingluoxia station reflect the impact of climate change in the upper reaches. Variations of the runoff measured at the Zhengyixia station reflect the impacts of climate change and human activities in the upper and mid reaches. The arithmetical average temperature and precipitation measured at the Tuole, Yeniugou, and Qilian stations were compared with the discharge at the Yingluoxia hydrological station. The arithmetical average temperature and precipitation measured from all six stations were compared with the discharge at the Zhengyixia hydrological station.

2.2 Wavelet analysis

We used the wavelet transform method to examine the variations of temperature, precipitation, and discharge under multi-temporal scales. Compared to conventional transform techniques such as the Fourier transform, which cannot depict the time-varying characteristics, the wavelet transform method is capable of simultaneously revealing the series' non-stationary characteristics under multi-temporal scales (Percival and Walden 2000; Sang et al. 2012a). This makes it suitable for hydrological series analysis (Sang 2013). A series $f(t)$ can be decomposed into a series of periodic functions known as continuous wavelet transform, which is operated via the translation and dilation (or contraction) of a mother wavelet $\psi(t)$ across series $f(t)$ as a function of time t (Labat 2005):

$$W_f(a,b) = \int_{-\infty}^{+\infty} f(t)\psi_{a,b}{}^{*}(t)dt \text{ with } \psi_{a,b}(t) = |a|^{-1/2}\psi\left(\frac{t-b}{a}\right) a,b \in R, a \neq 0 \quad (1)$$

where parameter a is the temporal scale (i.e., period) and parameter b is the time translation in the whole time domain concerned; $\psi^{*}(t)$ is the complex conjugate, and $W_f\ (a,b)$ is the continuous wavelet coefficient. We used the Morlet mother wavelet, which is used widely for hydrological series analysis (Torrence and Compo 1998). By changing the values of parameters a and b, the computation results of wavelet coefficients $W_f\ (a,b)$

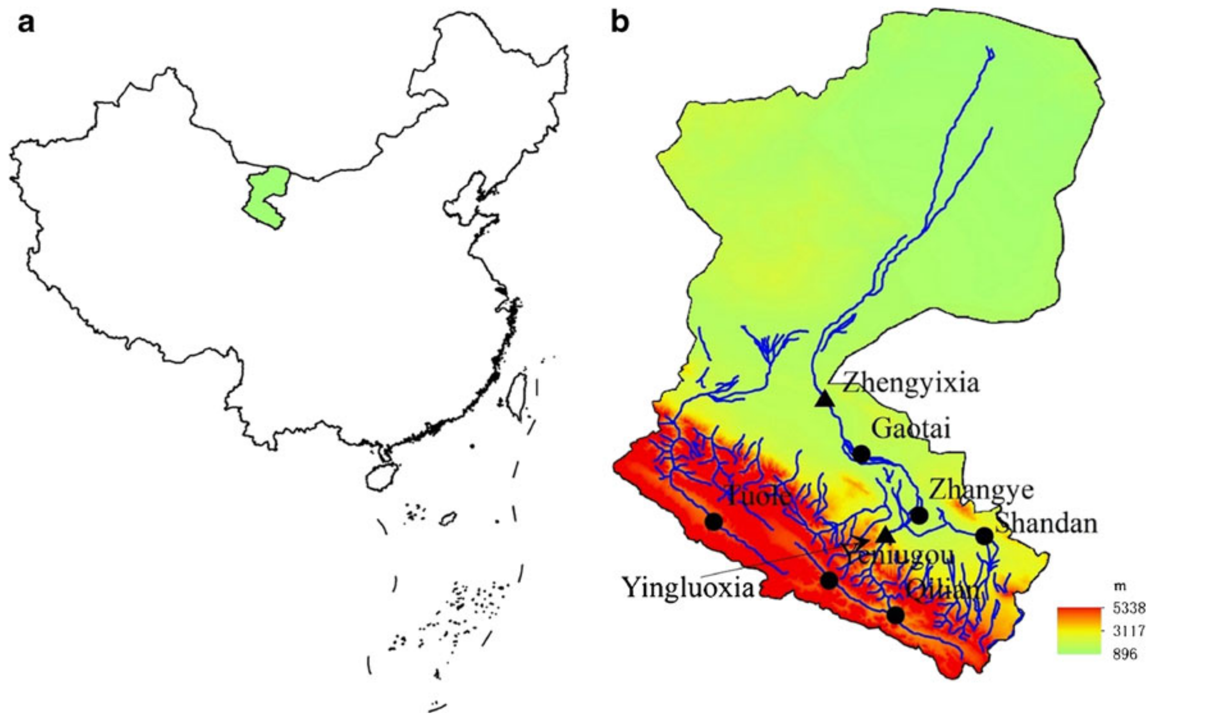

Fig. 1 The location of the Heihe River Basin in China (**a**), and the six weather stations and two hydrological stations in the Heihe River Basin used in this study (**b**). The *blue lines* in **b** are rivers in the study area

can cover the entire frequency and time domain. As wavelet analysis decomposes a signal into a series of wavelet functions of varying periods, it illustrates how amplitudes of varying periodicity change through time: (1) variations of the curve W_f $(a,b)\sim a$ reflect series' characteristics at certain time position b but different temporal scales; (2) variations of the curve W_f $(a,b)\sim b$ reflect series' characteristics at certain temporal scale a but different time positions; (3) wavelet coefficients under different scales reflect different characteristics of series: plus coefficients values correspond to wet seasons, minus values correspond to dry seasons, and zero point corresponds to the turnover point from wet to dry seasons, or from dry to wet seasons; and (4) absolute values of wavelet coefficients show the significance of characteristics: bigger absolute values of wavelet coefficients reflect more statistical significance of the characteristics, vice versa. Furthermore, the methods in Torrence and Compo (1998) were used to quantitatively evaluate the statistical significance of the continuous wavelet results.

The discharge, temperature, and precipitation series can be decomposed into a set of functions with varying periods and amplitudes by the wavelet transform method. Correlating the periods and amplitudes of the discharge series to the temperature and precipitation series sheds light on how the basin's discharge regime may be linked to climatic variables. Comparing the periods and amplitudes of the two discharge series also sheds light on how the discharge may be linked to human activities.

3 Results and discussion

3.1 Inter-annual discharge variations

The inter-annual variations of discharge and precipitation show similarity in the upper reaches, but the periodic variations of temperature differ (Fig. 2). Overall, the inter-annual trend of discharge in the upper reaches correlates better with precipitation rather than temperature. The 5-year periodic discharge variations correlate well with both the 7-year periodic temperature variations and 4-year periodic precipitation variations.

Variations of the three variables are more complex in the mid reaches as opposed to the upper reaches. Overall, the inter-annual variations of discharge and temperature in the mid reaches show similarity, but they differ from the variations of precipitation (Fig. 3). We concluded that inter-annual trend of discharge in the mid reaches correlates well with temperature rather than precipitation, while the 16-year periodic discharge variation correlates well with the 18-year periodic temperature variation; the 5-year periodic discharge variation correlates well with both the 7-year periodic temperature variation and the 4-year periodic precipitation variation.

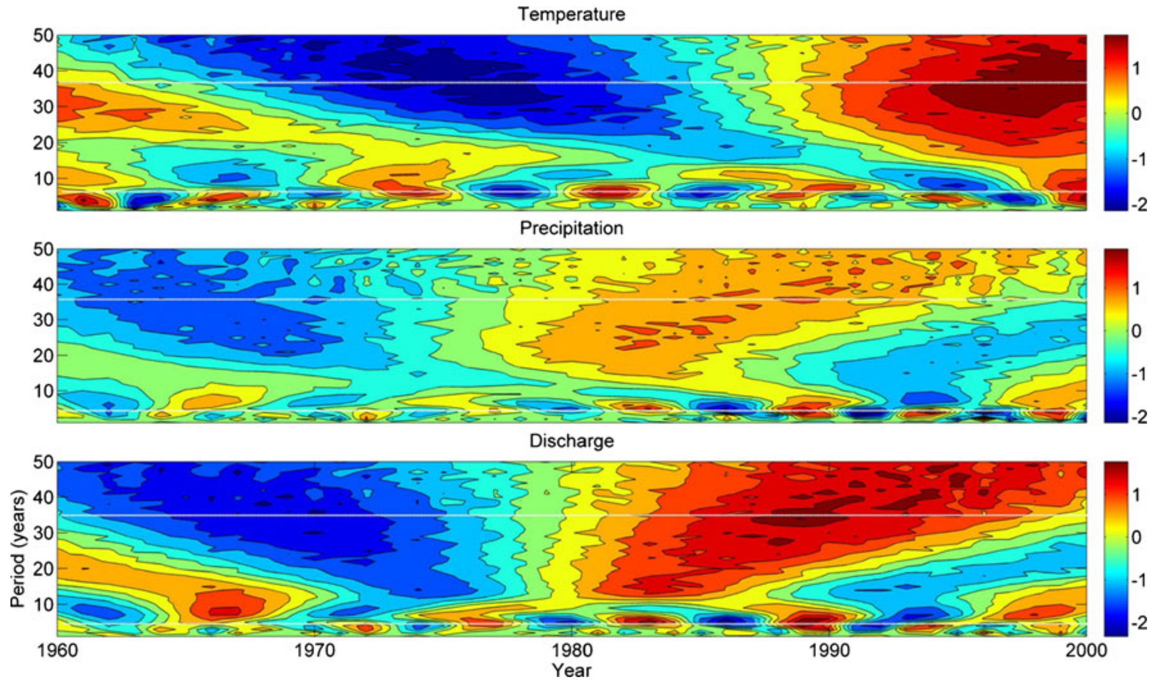

Fig. 2 Wavelet coefficients contours of the discharge, spatial average temperature, and precipitation in the upper reaches of the Heihe River Basin

According to the geographical conditions, it is known that precipitation increases would generate more runoff in both the upper and mid reaches, but the impacts of temperature increases on discharge are different in the upper and mid reaches. Temperature increases would enhance the glacial ablation processes and increase runoff in the upper reaches. However, temperature increases would increase the evaporation and decrease runoff in the mid reaches where the potential evapotranspiration is approximately 1,700 mm per year. Because temperature and precipitation have increased over the past decades, discharge in the upper reaches has increased as well. In the mid reaches, although precipitation has increase over the past decades, discharge has shown the downward trend, and it is mainly due to the

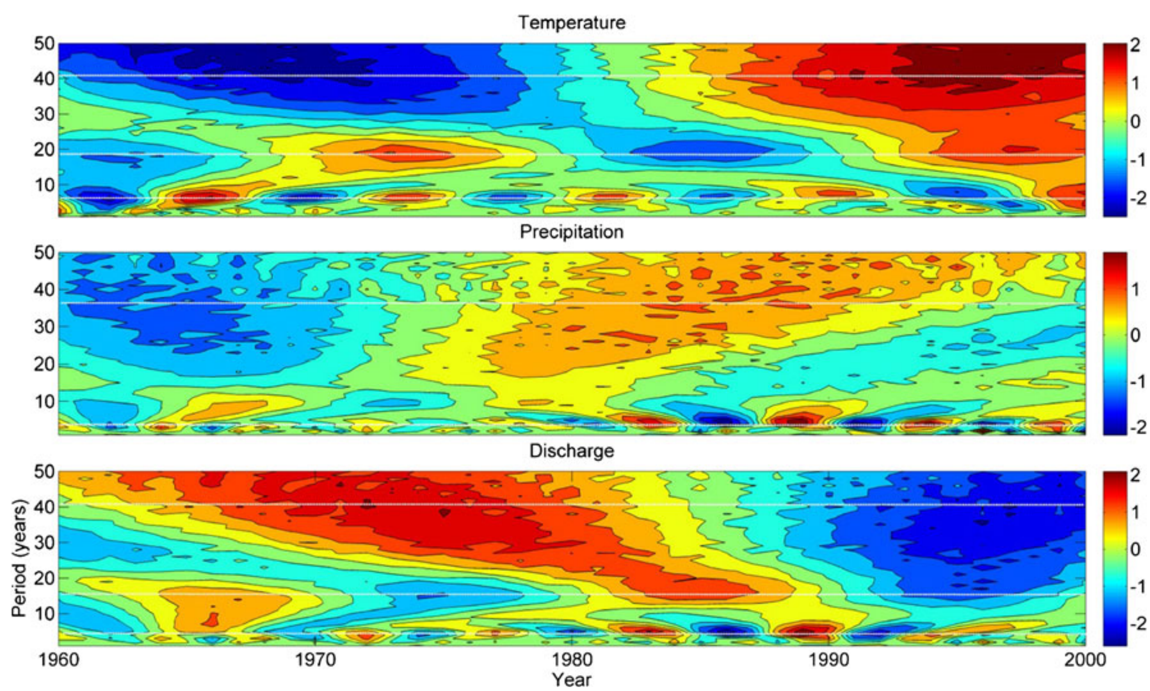

Fig. 3 Wavelet coefficients contours of the discharge, spatial average temperature, and precipitation in the mid reaches of the Heihe River Basin

more obvious evapotranspiration increases caused by temperature increase. To confirm this fact, we further used wavelet coefficients to demonstrate how discharge varies in amplitude and periodicity over time and how discharge is linked to temperature and precipitation.

In the upper reaches, the trend variations of wavelet coefficients of discharge correlate better with precipitation rather than temperature under the temporal scale of 41 year (Fig. 4), and the discharge has the biggest amplitude (Table 1). For the smaller periodic variations, temperature has the biggest amplitudes compared with precipitation and discharge. Therefore, it is thought that the 5-year periodic discharge variation is determined by both the 7-year periodic temperature variations and 4-year periodic precipitation variations. These comparisons confirm the positive effects that higher temperature and increased precipitation have on the discharge increase in the upper reaches.

In the mid reaches, the wavelet coefficients curves of discharge and temperature show inverse variations (Fig. 5). The periodic variations of precipitation are not as obvious as the two variables (Table 1). The trend variations of discharge in the mid reaches correlate better with temperature rather than precipitation. The trend amplitudes of discharge are lower than temperature, which is probably due to the compensating effect of precipitation. For the smaller 5-year periodic variations, temperature has the largest amplitudes compared to the precipitation and discharge. Therefore, it is thought that the 5-year periodic discharge variation is determined by both the 7-year periodic temperature variations and 4-year periodic precipitation variations. The above comparisons of wavelet coefficients also confirm the negative effects that higher temperature and decreased precipitation have on the discharge increase in the mid reaches.

Table 1 The wavelet coefficient values of discharge (*D*), temperature (*T*), and precipitation (*P*) in the upper and mid reaches of the Heihe River basin

Reaches	Temporal scales, years	Wavelet coefficient values
The upper reaches	41	−3~3 (*D*), −1~1 (*T*), −2~2 (*P*)
	4–7	−1~1 (*D*), −2~2 (*T*), −1~1 (*P*)
The mid reaches	41	−2~2 (*D*), −3~3 (*T*), −1~1 (*P*)
	18	−2~2 (*D*), −1~1 (*T*), −0.5~0.5 (*P*)
	5	−1~1 (*D*), −3~3 (*T*), −1~1 (*P*)

As a result, both temperature and precipitation variations impact the discharge variations in the Heihe River basin. Compared to precipitation, which has positive impacts on discharge variations in both the upper and mid reaches, temperature variability has different impacts on the discharge in the upper and mid reaches.

3.2 Inner-annual variation of discharge

The above results indicate that human activities have little impact on the inter-annual periodic variation of discharge in the Heihe River basin because periodic variations of temperature, precipitation, and discharge correlate closely. To investigate the impact of human activities on the inner-annual distribution of discharge, we analyzed the average inner-annual distribution of discharge over a 41-year period (i.e., the length of these series analyzed) (Fig. 6).

Both temperature and precipitation are at their highest levels in the summer (from June to September), and temperature is the lowest in the winter (from November to

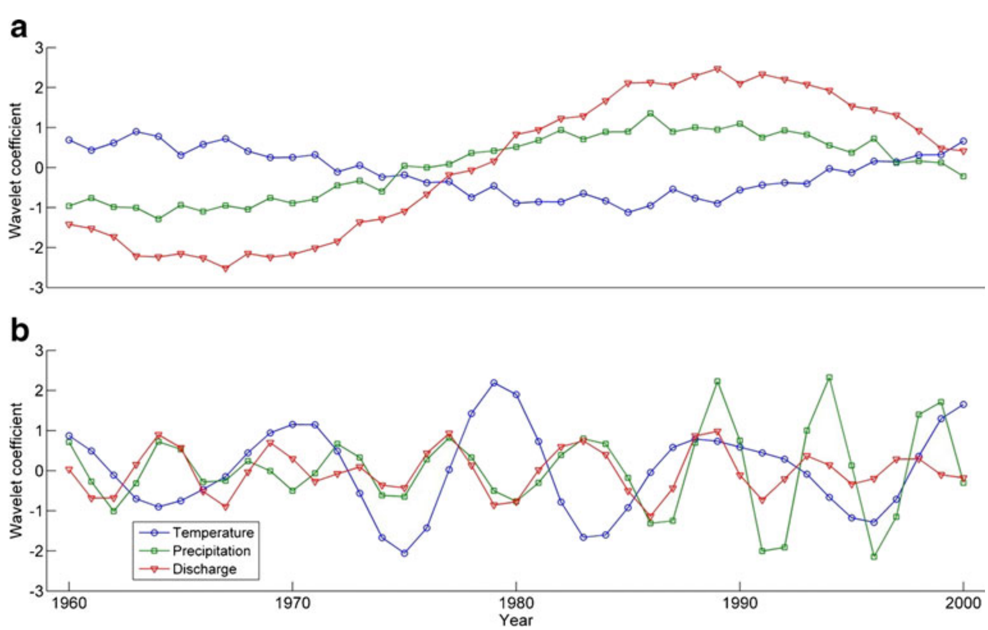

Fig. 4 Wavelet coefficients of trends (*a*) and dominant periods (*b*) of the discharge, spatial average temperature, and precipitation series in the upper reaches of the Heihe River Basin

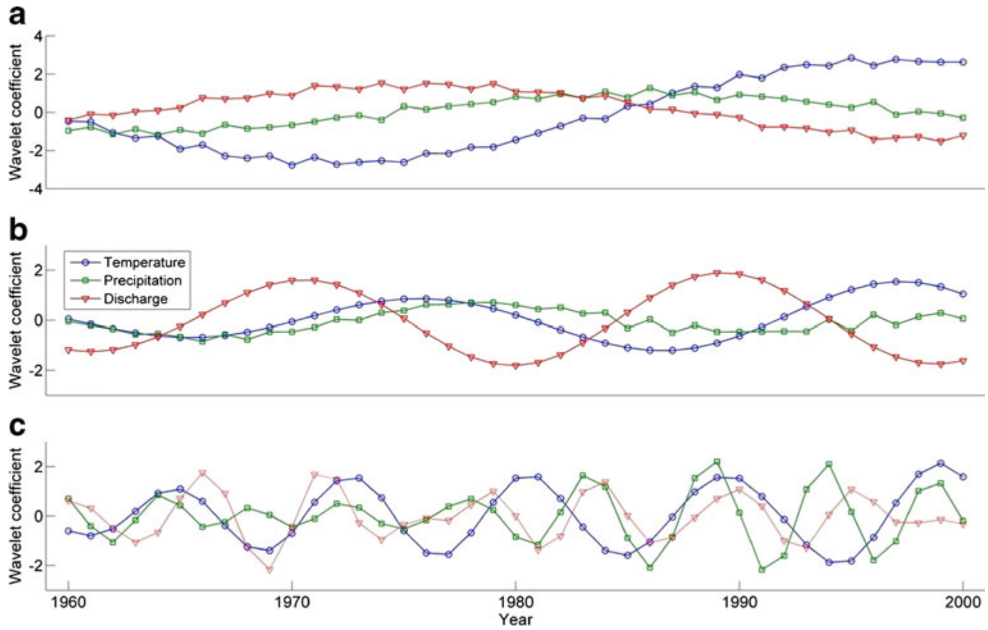

Fig. 5 Wavelet coefficients of trends (*a*) and two dominant periods (*b* and *c*) of the discharge, spatial average temperature, and precipitation series in the mid reaches of the Heihe River Basin

February), with little precipitation occurring in the upper and mid reaches. The mid reaches have a higher spatially averaged temperature but lower spatial precipitation compared to the upper reaches. Under the control of temperature and precipitation variations as well as human activities, inner-annual distributions of discharge at two hydrological stations show obvious differences. Discharge at the Yingluoxia hydrological station (upper reaches) shows similarly inner-annual variation as temperature and precipitation, with the biggest discharge occurring in July but the smallest discharge happening in winter, and the amount of runoff in summer (from June to September) account for more than 75 % of the total annual runoff. However, inner-annual variations of discharge at the Zhengyixia hydrological station are obviously different from the inner-annual variations of temperature and precipitation in the mid reaches.

Winter discharge (December to March) is higher at the Zhengyixia station than at the Yingluoxia station, as groundwater recharges river and almost no water is extracted in the mid reaches in winter. Spring discharge (April to June) is very small at the Zhengyixia station due to the exploration of river water for spring ploughing. Along with increasing precipitation, discharge at the Zhengyixia station increases more than the human water withdrawal in summer (July to September). Discharge decreases again in fall (October to November) due to the exploration of water resources for autumn irrigation.

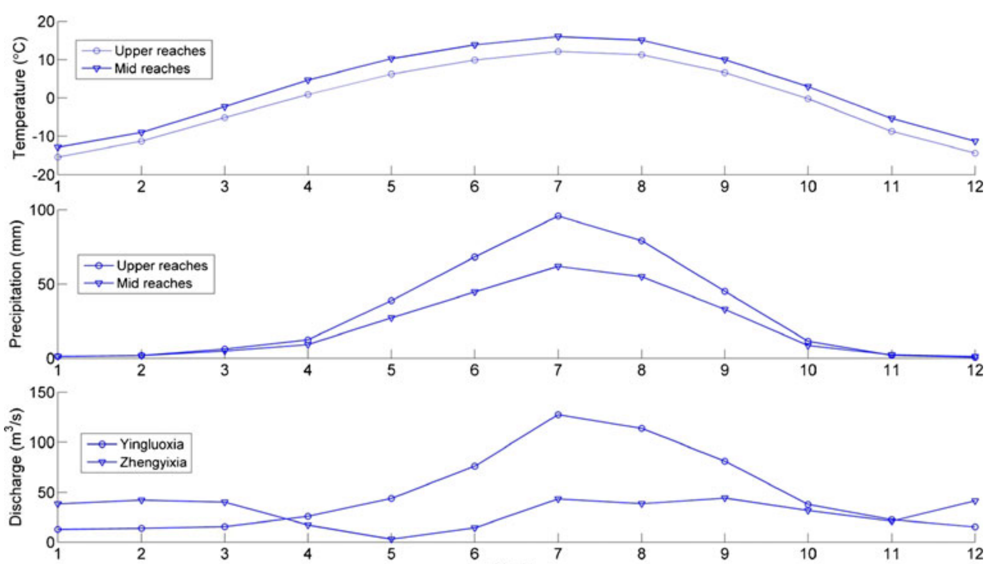

Fig. 6 Inner-annual variations of the discharge, spatial average temperature, and precipitation series in the Heihe River Basin over the entire 41-year period concerned

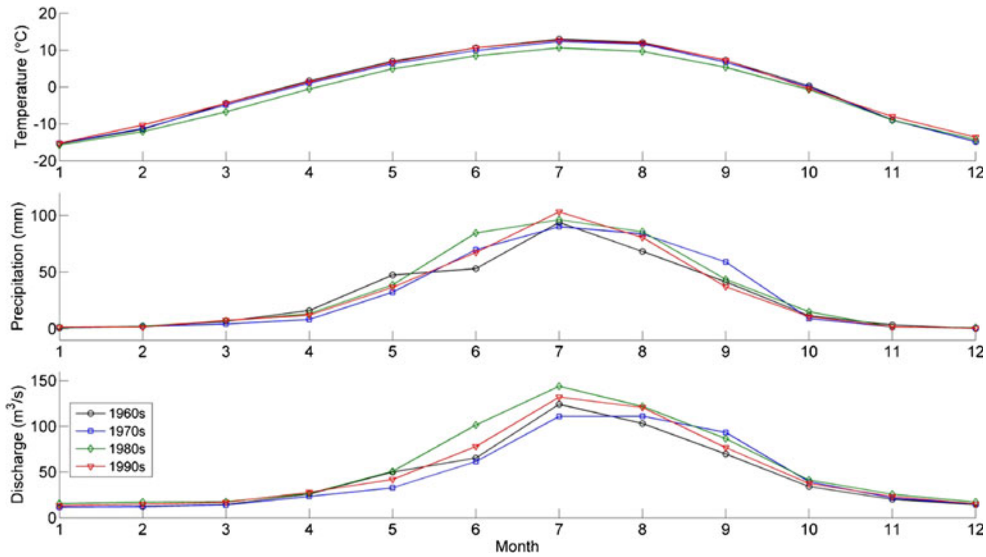

Fig. 7 Inner-annual variations of the discharge, spatial average temperature, and precipitation series in the upper reaches of the Heihe River Basin in each of the last four decades

To further analyze the impacts of climate change and human activities, the inner-annual distribution of discharge in four decades (1960–1970, 1971–1980, 1981–1990, and 1991–2000) were compared (Fig. 7). It is apparent that over the years, precipitation in the upper reaches is increasingly concentrated to summer (July) and decreases in other months. Under the control of both temperature and precipitation variations, discharge is also concentrated to summer (July), especially in the 1990s, which would be unfavorable for the finite water resources exploration in winter in the Heihe River basin. In winter, little changes of precipitation in four decades lead to little changes of discharge; increasing winter temperatures in the 1990s had little impact on the discharge variations because very much below zero degree of temperatures have no influences on the snowmelt processes.

In the mid reaches, precipitation is becoming more concentrated to the summer (July) but lower in other months over years (Fig. 8). However, discharge did not show the concentrated tendency to summer, obviously differing from the discharge variations in the upper reaches. In summer (from June to September), increasing precipitation in the 1970s and 1980s cause large amount of runoff, but in the 1990s, summer discharge decreased despite having the unchanged precipitation. Even though there are little changes of precipitation in four decades and temperature has very much below 0 °C, discharge also obviously decreases in winter in the 1990s. Here it is thought that the obvious decrease of discharge in the 1990s is mainly caused by water withdrawal in the mid reaches, especially in April, May, and June when water interception frequently occurred. Overall, the discharge regime in the mid reaches is greatly

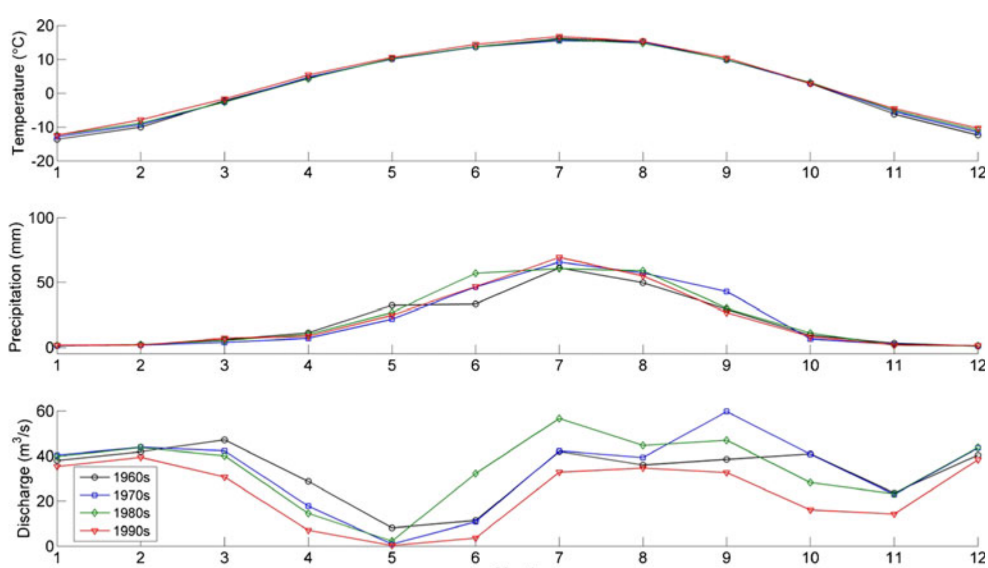

Fig. 8 Inner-annual variations of the discharge, spatial average temperature, and precipitation series in the mid reaches of the Heihe River Basin in each of the last four decades

impacted by human activities after the 1990s, and along with the concentrated tendency of precipitation in summer, the situation of water shortage would become severer.

4 Conclusion

We analyzed the inter- and inner-annual discharge variations in the upper and mid reaches of the arid Heihe River basin, and further investigated their correlation with temperature and precipitation variations. The runoff regime differences between the mid and upper reaches were compared, and the impacts of human activities on the discharge variation in the mid reaches were discussed.

Differing from previous studies which mainly analyzed precipitation and runoff trends (Feng et al. 2000; Ma et al. 2008; Wu et al. 2010; etc.), we found from the results that long-term trends and periods of discharge and precipitation correlate well in the upper reaches. In the mid reaches, long-term trends of discharge and temperature correlate well, and short periods of discharge and precipitation also correlate well. After the 1980s, temperature and precipitation increases caused the discharge increases in the upper reaches. This increase also occurred in the 1980s in the mid reaches. However, in the 1990s the high impact of human activities caused notable discharge decreases in the mid reaches.

In conclusion, both precipitation and temperature impact the availability of water resources in the arid Heihe River basin. Although recent precipitation increases are favorable for solving the water shortage in the mid reaches, recent temperature increases may intensify evapotranspiration. Together with the rapidly increasing water consumption in the mid reaches, these factors have contributed to streamflow reduction and even the enhanced evaporation of the Heihe River in the low reaches and depletion of groundwater table, latter seriously influenced the oasis maintenance, accelerated the desertification process, and further destroyed the weakened ecological system, as similarly mentioned in previous studies (Zhu et al. 2004; Zhang et al. 2006b; Wang et al. 2011). Therefore, the impacts of environment change on runoff regimes in the study area should be carefully considered. In the future, active and effective adaptation strategies should be developed and implemented by public policy makers from local government and planning departments. The efficiency of water resource exploration should also be improved, mainly to prevent the process of desertification in the Heihe River basin.

Acknowledgments The authors gratefully acknowledged the helpful comments and suggestions on the manuscript given by the editor, Jianping Li, and the anonymous reviewers. The authors also thanked Ms. Feifei Liu for her assistance in the preparation of the manuscript. This project was financially supported by the National Key Basic Research Development Program of China (no. 2009CB421305), and the National Natural Science Foundation of China (nos. 41201036 and 41271048).

References

Chen M, Pollard D, Barron EJ (2005) Hydrologic processes in China and their association with summer precipitation anomalies. J Hydrol 301:14–28

Chen YN, Takeuchi K, Xu CC, Chen YP, Xu ZX (2006) Regional climate change and its effects on river runoff in the Tarim Basin China. Hydrol Process 20:2207–2216

Dang S, Wang Z, Liu C (2011) Baseflow separation and Its characteristics analysis in the upstream of Heihe River Basin (in chinese with english abstract). Resour Sci 33:2232–2237

Feng Q, Cheng GD, Masao MK (2000) Trends of water resource development and utilization in arid north-west China. Environ Geol 39:831–838

Guo QL, Feng Q, Li JL (2009) Environmental changes after ecological water conveyance in the lower reaches of Heihe River, northwest China. Environ Geol 58:1387–1396

Huo Z, Feng S, Kang S, Li W, Chen S (2008) Effect of climate changes and water-related human activities on annual stream flows of the Shiyang river basin in north-west China. Hydrol Process 22:3155–3167

Jin XM, Hu GC, Li WM (2008) Hysteresis effect of runoff of the Heihe River on vegetation cover in the Ejian Oasis in northwestern China. Earth Sci Front 15:198–203

Kalnay E, Cai M (2003) Impact of urbanization and land-use change on climate. Nature 423:528–531

Labat D (2005) Recent advances in wavelet analyses: part 1. A review of concepts. J Hydrol 314:275–288

Labat D, Godderis Y, Probst JL, Guyot JL (2004) Evidence for global runoff increase related to climate warming. Adv in Water Resour 27:631–642

Li L, Wang ZY, Wang QC (2006) Influence of climate change on flow over the upper reaches of Heihe River. J Geogr Sci 26:40–46

Ma Z, Kang S, Zhang L, Tong L, Su X (2008) Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China. J Hydrol 352:239–249

Percival DB, Walden AT (2000) Wavelet methods for time series analysis. Cambridge University Press, Cambridge

Sang YF (2013) A review on the applications of wavelet transform in hydrologic time series analysis. Atmos Res 122:8–15

Sang YF, Wang ZG, Liu CM (2012a) Period identification in hydrologic time series using empirical mode decomposition and maximum entropy spectral analysis. J Hydrol 424:154–164

Sang YF, Wang ZG, Li ZL, Liu CM, Liu XJ (2012b) Investigation into the daily precipitation variability in the Yangtze River Delta. China. Hydrol Process. doi:10.1002/hyp.9202

Tanaka S, Zhu T, Lund J, Howitt R, Jenkins M, Pulido M, Tauber M, Ritzema R, Ferreira I (2006) Climate warming and water management adaptation for California. Clim Chang 76:361–387

Torrence C, Compo GP (1998) A practical guide to wavelet analysis. B Am Meteorol Soc 79(1):61–78

Vorosmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change acid population growth. Science 289:284–288

Wang P, Yu JJ, Zhang YC, Fu GB, Min LL, Ao F (2011) Impacts of environmental flow controls on the water table and groundwater chemistry in the Ejina Delta, northwestern China. Environ Earth Sci 64:15–24

Wang ZG, Ficklin D, Zhang YY, Zhang MH (2012) Impact of climate change on streamflow in the arid Shiyang River Basin of Northwest China. Hydrol Process. doi:10.1002/hyp.8378

Wen L, Jin J (2012) Modelling and analysis of the impact of irrigation on local arid climate over northwest China. Hydrol Process 26:445–453

Wu J, Ding Y, Ye B, Yang Q, Zhang X, Wang J (2010) Spatial-temporal variation of stable isotopes in precipitation in the Heihe River Basin, Northwestern China. Environ Earth Sci 61:1123–1134

Zhang Q, Liu CL, Xu CY, Xu YP, Jiang T (2006a) Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River basin, China. J Hydrol 324:255–265

Zhang J, Zhang Q, Yang LH, Li DL (2006b) Seasonal characters of regional vegetation activity in response to climate change in west China in recent 20 years. J Geogr Sci 16:78–86

Zhang Y, Yu J, Wang P, Fu G (2011) Vegetation responses to integrated water management in the Ejina basin, northwest China. Hydrol Process 25:3448–3461

Zhu YH, Wu YQ, Drake S (2004) A survey: obstacles and strategies for the development of ground-water resources in arid inland river basins of Western China. J Arid Environ 59:351–367