

Trend, abrupt change, and periodicity of streamflow in the mainstream of Yellow River

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Abstract The Yellow River is the second largest river in China. The annual runoff of which is only about 2 % of China's total, but contributes to 9 % of China's GDP and directly supports 12 % of the population. Today, the water shortage in the Yellow River basin has been aggravated due to rapid population growth and global warming. In order to best maximize water resources management, the natural and observed streamflow series from six hydrologic gauging stations (Guide, Lanzhou, Hekou, Sanmenxia, Huayuankou, and Lijin) are obtained, and the linear regression, Mann–Kendall test, and wavelet transform methods were used to detect the characteristic of streamflow variation from 1956 to 2007. The results show that: (1) both the natural streamflow and observed streamflow present a downward trend over the past 52 years, and the trends are intensified downstream; the decreasing rate of observed

streamflow is more rapid than that of the natural streamflow; (2) most of the abrupt changes in natural streamflow and observed streamflow appear in the late 1980s to early 1990s through the result of the Mann–Kendall test; and (3) other than the Guide station, the streamflows at the rest of the stations appear to have strongest periodicity of 19–21 years with a 52-year scale. The results of this study imply that less precipitation and warmer climate in the basin are the primary factors that cause this decreasing trend of natural streamflow. Additionally, the rapid ascent of water consumption by human being results in the reduction of observed streamflow further. Furthermore, human activities like reservoir construction, soil and water conservation measures, etc. influence the streamflow as well. It is recommended that the society takes some effective countermeasures to cope with the water shortage.

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Introduction

All organisms in the world, including human, require water for their survival. The available water resources throughout the world are becoming depleted and this water scarcity problem is aggravated in developing countries, through increased population growth, developing industry, expanding agriculture, and urban construction (Gao et al. 2012b; Miao et al. 2012b).

Currently, some 30 countries are considered to be water stressed; 20 of which are absolutely water scarce. It is predicted that by 2020, the number of water scarce countries will likely approach to 35 (Rosegrant et al. 2002). An even more worrying estimate is that developing countries face the greatest crisis and it has been estimated that by 2025, one third of the population of the developing world will face severe water shortages (Seckler et al. 1998).

Hydrology plays a central role in the development and management of water resources, and the streamflow constitutes a major phase in the hydrologic cycle. So, in order to mitigate water stress, limited water resources should be managed more effectively. The streamflow change in the world needs to receive more and more attention. On the global and continental scale, Currie (1996) and Probst and Tardy (1987) studied mean annual discharge fluctuation of 50 major rivers distributed around the world, and their studies showed that North American and European runoffs fluctuate in opposition while South American and African runoffs present synchronous fluctuation. Betts et al. (2007) found that the physiological effect of doubled carbon dioxide concentrations on plant transpiration increases simulated global mean runoff by 6 % relative to preindustrial levels.

On the country scale, Lettenmaier et al. (1994) showed that an increasing trend of streamflow exists for most parts of the USA, except for a small number of catchments in the Northwest, Florida, and coastal Georgia regions where a downward trend has been detected. Zhang et al. (2001a) analyzed the monthly mean streamflow in Canada and stated that there are almost no basins exhibiting an upward trend. Kahya and Kalayci (2004) computed the streamflow trend during the last 31 years in Turkey and found that the streamflows in western and southern Turkey exhibit downward trends and no significant trend in eastern Turkey. Birsan et al. (2005) identified the main streamflow in Switzerland and found there is an increase in annual runoff due to increases in the winter, spring, and autumn season runoff. Barnett et al. (2008) detected that the river flow in the western USA experiences relative increases in the spring and relative decreases in the summer months during the period of 1950 to 1999.

China is the largest developing country and the most populous. Its central government, local agencies, and scholars have already realized the importance of

streamflow dynamics. A lot of significant studies had been conducted, and most of the researches focused on the Yangtze River (Yin and Li 2001; Zhang et al. 2006a, b; Jiang et al. 2007; Xu et al. 2008; Gao et al. 2012a) and the Yellow River (Hu and Feng 2001; Xu et al. 2002; Fu et al. 2004; Xu 2005; Wang et al. 2006; Zheng et al. 2007; Wu et al. 2008), due to their vital domestic status.

The Yellow River is the second largest river in China, with a total length of 5,464 km. It originates in the northeast of the Tibetan Plateau, runs across the Loess Plateau of North China and the Ordos Plateau, and flows eastwards to the Bohai Sea. The Yellow River basin ($7.52 \times 10^5 \text{ km}^2$) is one of the most important basins in China. The annual runoff of which is only about 2 % of the China's total, but it directly supports 12 % of the national population (mostly farmers and rural people), feeds 15 % of the irrigation area, and contributes to 9 % of China's GDP (Miao et al. 2011). In addition, water resources in the basin are characterized by large spatial and temporal changes. Over thousands of years in the Chinese history, catastrophic floods and droughts appeared frequently in the Yellow River basin, which resulted in tremendous losses of life and property (Hu et al. 1998). In a recent study, it was found that the runoff changes over an interannual and decadal scale (Hu and Feng 2001). Analyzed further in headwater catchments of the Yellow River basin, no significant trend of the streamflow was detected from 1956 to 2001 (Zheng et al. 2007), while river flow in the middle Yellow River (Xu 2005), the lower Yellow River (Wu et al. 2008), and the water fluxes to the sea (Wang et al. 2006) have declined significantly since the 1970s. The decline trend results in a progressive intensification of water stress in the downstream direction (Vörösmarty et al. 2000; Xu et al. 2008; Miao et al. 2010).

There have been many publications that discuss the river runoff change in the Yellow River over the last half century, especially in Chinese literature. However, there are some deficiencies for the past studies: (1) most of preexisting research only focused on the whole linear trend. Other than the linear trend, the other variation characteristics such as periodicity analysis, abrupt change, etc. are seldom involved; (2) the hydrologic datasets used in the previous studies was mainly the observed streamflow, not the natural streamflow. Indeed, the natural streamflow manifests the condition of water resources more objectively; (3)

the streamflow series data are not updated. Most of research concentrates on the streamflow in the last century, but we still do not know how the streamflow changes after entering the new century.

Therefore, the natural and observed river runoff recorded by six streamflow gauging stations were obtained in this study to: (1) detect the variation characteristics of observed and natural streamflow in the whole Yellow River basin during 1956–2007, which include linear change trends, change periods, and abrupt change and (2) discuss the factors that influence streamflow change. This study will be helpful for policy-maker to manage water resources more effectively.

Data and methods

Data

Considering the influences of human activities such as water withdrawal from the river channel for irrigation, industry, and domestic usage and the role of dams in controlling the streamflow, the Yellow River Conservancy Commission (YRCC) conducted a great deal of complex work to collect data and build the real, or so-called natural streamflow, series (Xu and Ma 2009). The natural streamflow at a given station can be calculated as (Xu 2005):

$$Q_{w,n} = Q_{w,m} + Q_{w,div} \tag{1}$$

where $Q_{w,m}$ is the streamflow observed at this station and $Q_{w,div}$ is the “net” water quantity diverted from the river above the station. $Q_{w,div}$ can be calculated as water quantity actually diverted from the river minus the water quantity finally returning to the river after use. Therefore, $Q_{w,div}$ reflects the importance of man-made lateral branch of the water cycle (Xu and Ma 2009). Although some hydrologists question the accuracy of natural runoff, the natural runoff published by the YRCC is widely used in water resource management and planning and hydrological engineering projects (Fu et al. 2004). In this study, in order to eliminate the effect of serial correlation, the method of free pre-whitening (TFPW) was applied to the streamflow series with significant autocorrelation. The analysis method was presented in Yue et al. (2002) in detail.

In terms of the different physical–geographical settings, the Yellow River basin has been divided into three

water source areas: upper (above the Hekou station), middle (from the Hekou station to the Taohuayu station), and lower (below the Taohuayu station) reaches (Fig. 1). The observed and natural streamflow data from six main gauging stations in the Yellow River (Guide, Lanzhou, Hekou, Sanmenxia, Huayuankou, and Lijin) were selected to analyze the streamflow characteristic, which represent the upper, middle, and lower reaches of Yellow River, respectively. More detailed information concerning hydrologic records of these six gauging stations is shown in Table 1.

The annual streamflow series (observed and natural) were provided by the YRCC. The annual regional precipitation and temperature series were interpolated from data from 175 meteorological stations provided by the National Meteorological Information Center, China Meteorological Administration. And the normalized difference vegetation index (NDVI) in the Yellow River basin from 1982 to 2006 was derived from Global Inventory Monitoring and Modeling Studies dataset.

Methodology

1. Linear regression

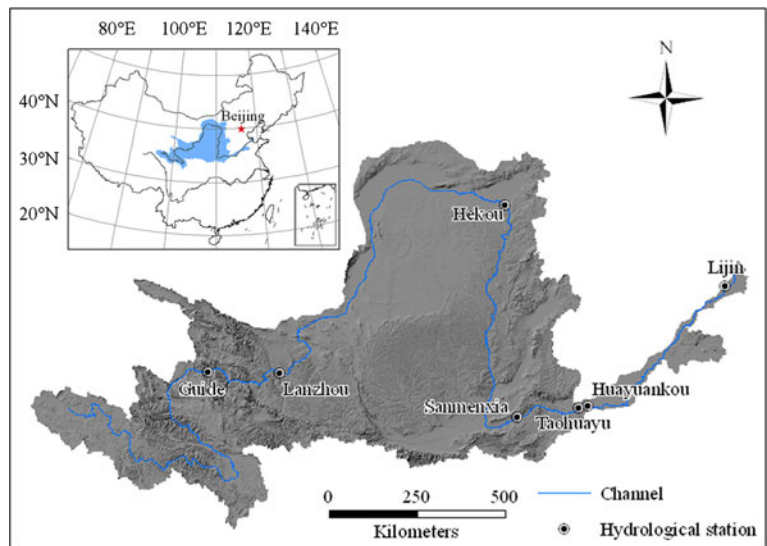
The linear regression attempts to explore the trend of streamflow series. The slope of the regressive line reflects the trend direction—positive slope means increasing trend and vice versa. The absolute value of slope presents the variation rate.

2. Mann–Kendall test

The nonparametric Mann–Kendall test (*MK*) originated from Mann (1945) and rephrased by Kendall (1948). In this study, the Mann–Kendall test procedure follows Gerstengarbe and Werner (1999) who used the method to test an assumption about the beginning of the development of trend within a sample (x_1, x_2, \dots, x_n) of the random variable x , based on the rank series r of the progressive and retrograde rows of this sample. The assumption (null hypothesis) is formulated as follows: the sample under investigation shows no beginning of a developing trend. The following test is performed to prove or to disprove the assumption, and a *MK* test statistic, d_k , is calculated firstly:

$$d_k = \sum_{i=1}^k r_i (2 \leq k \leq n) \tag{2}$$

Fig. 1 Location of the study region and hydrological gauging stations. The shaded area represents the drainage of the Yellow River basin



where

$$r_i = \begin{cases} +1 & \text{if } x_i > x_j \ (j = 1, 2, \dots, i). \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Presuming that the series is random and independent, the statistic d_k is distributed as a normal distribution with the expected value of $E[d_k]$ and the variance $\text{Var}[d_k]$ as follows:

$$E[d_k] = \frac{n(n-1)}{4} \quad (4)$$

$$\text{Var}[d_k] = \frac{n(n-1)(2n+5)}{72}. \quad (5)$$

Under the above assumption, the definition of the statistic index Z_k is calculated as:

$$Z_k = \frac{d_k - E[d_k]}{\sqrt{\text{Var}[d_k]}} \ (k = 1, 2, 3, \dots, n). \quad (6)$$

Z_k follows the standard normal distribution. A positive Z value denotes an upward trend and a negative Z value denotes a downward trend, and if Z exceeds the confidence line, it means there is a significant trend. In contrast to the traditional MK test which calculates above statistic variables only once for the whole sample, the corresponding rank series for so-called retrograde rows are similarly obtained for the inverse series (x_n, x_{n-1}, \dots, x_1). Following the same procedure as shown in Eqs. (2)–(6), the statistic variables, d_k , $E[d_k]$, $\text{Var}[d_k]$, and Z_k , will be calculated for the inverse series. The Z values calculated with progressive and retrograde series are named Z_1 and Z_2 , respectively, in this paper. In a two-sided test for trend, the null hypothesis of no trend will be rejected at the confidence level of α if $|Z| > Z_{(1-\alpha/2)}$, where $Z_{(1-\alpha/2)}$ is the critical value of the standard normal distribution with a probability exceeding $\alpha/2$. In this paper, a typical confidence level of 95 % was used. In the case of observed streamflow series at the Guide station, the two

Table 1 Detailed hydrological record in the Yellow River basin

Station name	Drainage area (km ²)	Time interval		Location
		Observed streamflow	Natural streamflow	
Guide	133,650	1956–2007	1956–2007	Upper drainage basin
Lanzhou	222,551	1956–2007	1956–2007	Upper drainage basin
Hekou	367,898	1956–2007	1956–2007	Middle drainage basin
Sanmenxia	688,421	1956–2007	1956–2007	Middle drainage basin
Huayuankou	730,036	1956–2007	1956–2007	Lower drainage basin
Lijin	751,869	1956–2007	1956–2000; 2003–2007	Lower drainage basin

lines intersected at the time of 1995, and the intersection point of the two lines, Z_1 and Z_2 , is between the two confidence lines; we consider that abrupt change took place at 1995 (Fig. 2).

3. Wavelet analysis

The basic objective of the wavelet transform is to achieve a complete time scale (or shift scale) representation of localized and transient phenomena occurring at different time scales. Based on the results of time scale distribution, it is easy to analyze the periodicity of streamflow series. For time series $f(t) \in L^2(R)$, the continuous wavelet transform (CWT) is defined as the sum over all time of the real signal $f(t)$ multiplied by the scaled (Nakken 1999), shifted versions of the wavelet function Ψ , i.e.,

$$W_f(a, b) = |a|^{-\frac{1}{2}} \int_{-\infty}^{+\infty} f(t) \left(\frac{t-b}{a} \right) dt \tag{7}$$

where the wavelet coefficients $W_f(a, b)$ are the result of the CWT of signal $f(t)$. The scale or dilation parameter, a , scales a function by compressing or stretching it, while b is the translation of the wavelet function along the time axis.

The key point of wavelet transform lies in the selection of wavelet function. The real part and imaginary part of complex wavelet have a phase difference of $\frac{\pi}{2}$, which can eliminate the modular vibration of wavelet transform coefficient of real form, so in this study, complex Morlet wavelet was adopted to analyze the variation characteristics of natural streamflow in relation to time. Complex Morlet wavelet is a single-frequency complex sinusoidal function tapered with a Gaussian window and is expressed as:

$$\psi(t) = e^{ict} e^{-\frac{t^2}{2}} \tag{8}$$

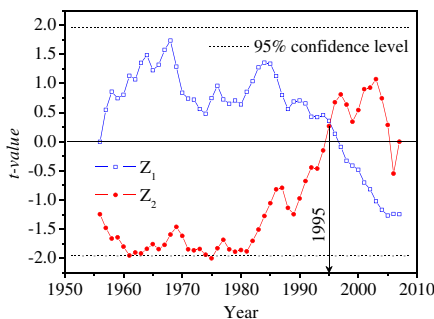


Fig. 2 A case study of MK test at the Guide-observed streamflow series

where c is a constant; i represents imaginary part. The main period of on time series is obtained by wavelet variance (Li et al. 2009), which is expressed as follows:

$$\text{Var}(a) = \sum (W_f)^2(a, b) \tag{9}$$

where $\text{Var}(a)$ is the wavelet variance. In the case of observed streamflow series at Lanzhou station (Fig. 3a), the solid line in the contour map of real part wavelet coefficient represents the coefficient >0 , and the dash line represents the coefficient <0 . It is easy to detect the periodicity of the streamflow series that is present, <5 , $8-10$, $20-25$, and >50 years, according to the position of the concentric circle in the contour map (dashed rectangle in Fig. 3a). Since wavelet variance denotes the distribution of wavelet energy by scale (period), the domain predominant periods of one time series can be obtained from its extreme values. According to the extreme variance value, the most obvious periodicity is ~ 20 -year for the observed streamflow series at the Lanzhou station (Fig. 3b).

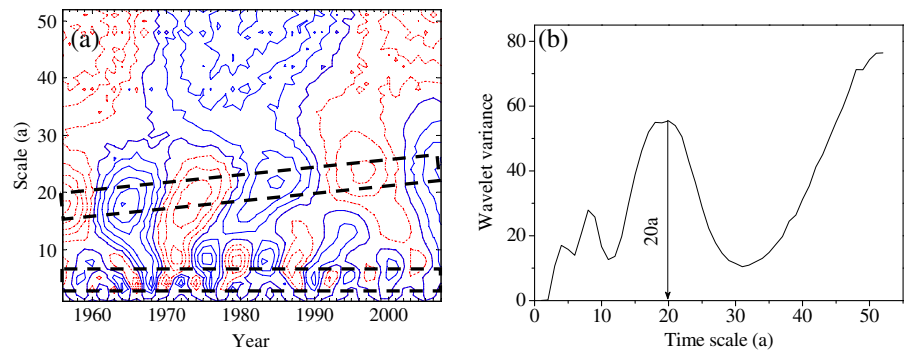
Results

Upper drainage basin

The linear regression exhibits the whole streamflow series (observed streamflow and natural streamflow) with a downward trend during 1956–2007, and the downward trend of the observed streamflow is significant at the 95 % confidence level ($p < 0.05$). The decreasing rate of the observed streamflow (the slope of the linear regression is -0.99) is higher than that of the natural streamflow (the slope of linear regression is -0.77) (Table 2). Analyzing further in virtue of the MK test, the observed streamflow and natural streamflow show an increasing trend during 1956–1996 ($Z_1 > 0$), and a decreasing trend after 1996 ($Z_1 < 0$); however, all the trends are not significant at the 95 % confidence level. The intersection points of Z_1 and Z_2 curves of the observed streamflow and natural streamflow at the Guide station appeared in the same time at 1996 (Table 2). Because of the obvious correlation, the fluctuation characteristics and change trends of the observed streamflow and natural streamflow are similar.

By using the Morlet wavelet transformation, the streamflow periodicity at the Guide station within a 52-year scale is detected. From the real part wavelet

Fig. 3 A case study of Wavelet analysis at the Lanzhou streamflow series. **a** Contour map of real part wavelet coefficient for streamflow series. **b** Wavelet variance of Morlet wavelet transform coefficients for observed streamflow



coefficient, there are circa 8- and 17-year periodicity for the observed streamflow, and circa 7-, 15-, and 22-year periodicity for the natural streamflow (Table 2 and Fig. 4). Due to the length limitation of streamflow series, it is difficult to find out the >50-year period definitely. Moreover, the positive coefficient reflects the abundant streamflow and vice versa. Although the whole trend of streamflow is downtrend, the observed streamflow and natural runoff during the 1968–1993 are abundant at the 52-year scale (the wavelet coefficients >0), and the streamflow shortage has begun from 1993 to a certain year in the future.

The linear regression exhibits the whole streamflow series (observed and natural) with a downward trend during 1956–2007, and the downward trend of the observed streamflow is significant at the 99 % confidence level ($p < 0.01$). The decreasing rate of the observed streamflow (the slope of the linear regression is -1.74) is greater than that of the natural streamflow (the slope of linear regression is -1.05) (Table 2). Moreover, the decreasing rates of streamflow (observed and natural) at the Lanzhou station are faster than that at the Guide station. It is seen from the MK

test that the observed streamflow shows an upward trend during 1956–1991 ($Z_1 > 0$) and a downward trend after 1991 ($Z_1 < 0$); however, both trends are not significant at the 95 % confidence level. The MK test results of the natural streamflow are similar to those of the observed streamflow except the ending time of upward trend is extended into 1994. The intersection point of Z_1 and Z_2 curves of the observed streamflow at the Lanzhou station appeared in 1990, and for the natural streamflow, besides 1990, the intersection point appeared again in the next year.

The streamflow series (observed and natural) at the Lanzhou station present the periods of <5, 8–10, 20–25, and > 50 years, and the periodicity is prolonged with the passage of time when facing the period of 20–25 years. Both the center periodicity of the observed streamflow and natural streamflow is focused into 4, 8, and 20 years through the results of wavelet variance, and the 20-year periodicity is significantly obvious (Table 2 and Fig. 4). In addition, the wavelet coefficient value demonstrates that the observed streamflow and natural streamflow during the 1968–1993 are abundant at the 52-year scale and is in low

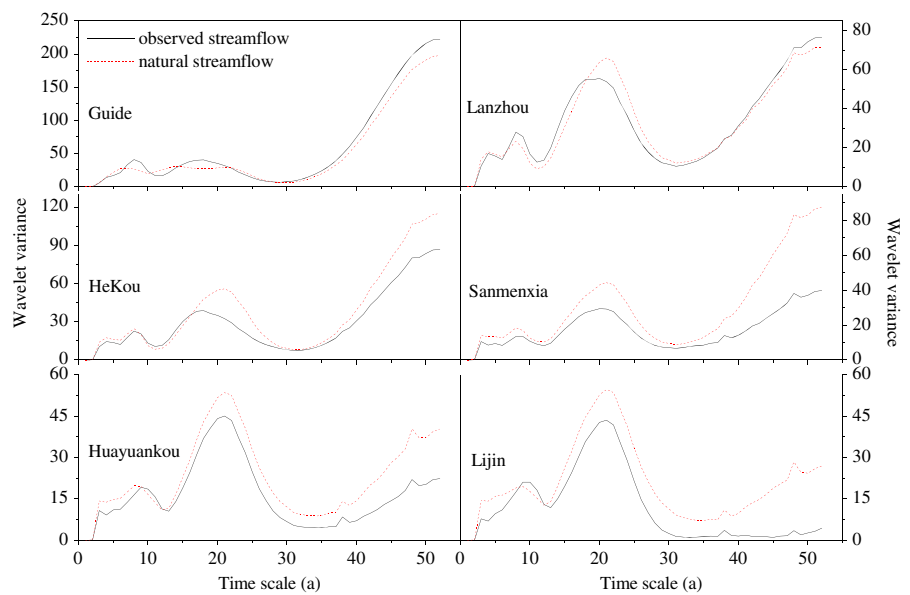
Table 2 Summary of the hydrological results at the six stations

Station	Slope of regression		Intersected time		Main periodicity	
	Observed	Natural	Observed	Natural	Observed	Natural
Guide	-0.99^a	-0.77	1996	1996	8, 17	7, 15, 22
Lanzhou	-1.74^b	-1.05	1990	1990	4, 8, 20	4, 8, 20
Hekou	-2.55^b	-1.23	1991	1994	4, 8, 18	4, 8, 21
Sanmenxia	-5.68^b	-3.01^b	1991	1994	4, 8, 20	3, 8, 21
Huayuankou	-6.03^b	-3.28^b	1987~1989	1991~1992	3, 9, 21	3, 9, 21
Lijin	-8.38^b	-3.14^{**}	1982	1993	3, 9, 21	3, 9, 21

^a Correlation is significant at the 0.05 level (two-tailed)

^b Correlation is significant at the 0.01 level (two-tailed)

Fig. 4 Wavelet variance of Morlet wavelet transform coefficients for observed and natural streamflow series among six hydrological stations



streamflow status after 1993, which is the same as the characteristics which appeared at the Guide station, reflecting the close correlation of streamflow between the Guide and Lanzhou stations.

Middle drainage basin

Similar to the upper reaches, the streamflow series (observed and natural) present the downward trend during 1956–2007, and the trend of the observed streamflow is significant at the 99 % confidence level ($p < 0.01$). The peak values of the observed and natural streamflow series appeared in 1967. As similarly observed in the upper reaches, the decreasing rate of the observed streamflow (the slope of the linear regression is -2.55) is higher than that of the natural streamflow (the slope of linear regression is -1.23) (Table 2). The MK test shows that the observed streamflow at the Hekou station is in upward trend during 1956–1990, it becomes downward since 1991, and the downward trend is significant at the 95 % confidence level after 2001. The results of MK test for the natural streamflow are similar to those of the observed streamflow, except that the ending time of upward trend is extended into 1994, but both upward and downward trends are not significant at the 95 % confidence level almost. The intersection points of Z_1 and Z_2 curves of the observed streamflow and natural streamflow at the Hekou station appeared in 1991 and 1994, respectively (Table 2).

The streamflow series (observed and natural) at the Hekou station present the periods with < 5 , 7–10, 18–22, and > 50 years. Based on the calculation of wavelet variance, the quantitative periodicity of the observed streamflow is located into circa 4, 8, and 18 years, and the 18-year cycle is the strongest within the 52-year scale; while the periodicity of the natural streamflow was located into circa 4, 8, and 21 years, and the 21-year cycle is the most obvious (Table 2 and Fig. 4). Moreover, through contour maps of wavelet coefficients, the observed streamflow and natural streamflow were abundant during 1969–1994 at the 52-year scale and is in low streamflow condition after 1994.

Both the observed streamflow and natural streamflow at the Sanmenxia station present the significant downward trend ($p < 0.01$) during 1956–2007. Similar to the above-mentioned streamflow series, the decreasing rate of the observed streamflow at the Sanmenxia station (the slope of the linear regression is -5.68) is faster than that of the natural streamflow (the slope of linear regression is -3.01), and for either the observed or natural streamflow, their decreasing rate is accelerated further (Table 2). The peak values of observed and natural streamflow appeared in the same time with 1967. Excluding 1985, the downward trend of the observed streamflow was observed during 1972–2007, and the trend is significant at the 95 % confidence level after 1998. The natural streamflow at the Sanmenxia station presents downward trend since

1993, and the trend is significant at the 95 % confidence after 2004. The intersection points of Z_1 and Z_2 curves appeared in 1991 and 1994 for the observed streamflow and natural streamflow, respectively.

The streamflow series (observed and natural) at the Sanmenxia station present the periods of <5, 7–10, 19–23, and >50 years. Identified by using wavelet variance, there are circa 4-, 8-, and 20-year periodicity for the observed streamflow within the 52-year scale, and the 20-year periodicity is the strongest (Table 2 and Fig. 4). For the natural streamflow, the main periodicity of 3, 8, and 21 years is obtained, and the 21-year cycle is the most obvious. Similar to the streamflow at the Hekou station, the streamflows (observed and natural) were plentiful during 1969–1994 at the 52-year scale and have been in the low streamflow from 1995 to a certain year in the future.

Lower drainage basin

During 1956–2007, for either the observed streamflow or the natural streamflow at the Huayuankou station, the downward trend is significant at the 99 % confidence level ($p < 0.01$) (Table 2). Similar to the upper and middle reaches, the decreasing rate of the observed streamflow is higher than that of the natural streamflow. The peak streamflow (observed and natural) appeared in 1964. From the MK test results of the observed streamflow, it is seen that the downward trend begins after 1970, with significance at the 95 % confidence level since 1997. Compared with the observed streamflow, the natural streamflow at the Huayuankou station delays the downward process until 1991 and almost no significant level all through. The intersection points of Z_1 and Z_2 curves occurred during 1987–1989 and 1991–1992 for the observed streamflow and natural streamflow, respectively (Table 2).

The streamflows (observed and natural) at the Huayuankou station present the periods of <5, 9–10, 19–22, and >50 years. More accurate information from the wavelet variance demonstrates that the observed streamflow and natural streamflow have the same main periodicity, which is circa 3-, 9-, and 21-year periods within the 52-year scale, and the 21-year periodicity is the strongest. Similar to the streamflows in the upper and middle reaches, the streamflows (observed and natural) in Huayuankou are relatively plentiful during 1969–1994 at the 52-year scale (Table 2 and Fig. 4).

The whole streamflow series at the Lijin station present significant decreasing trend ($p < 0.01$) for the observed streamflow and natural streamflow, and the decreasing rate of the observed streamflow (the slope of linear regression is -8.38) is faster than that of the natural streamflow (the slope of linear regression is -3.14) (Table 2). In the Lijin station, the decreasing rate of streamflow is the highest when compared with the above-mentioned streamflow series. As occurring in the Huayuankou station, the peak streamflows (observed and natural) at the Lijin station appeared in 1964. The MK test shows a decreasing trend during 1971–2007 for the observed streamflow, and the trend is significant at the 95 % confidence level after 1995. The time beginning to show the downward trend in the natural streamflow delayed into 1989 with the significance at the 95 % confidence level after 2000. The intersection points of Z_1 and Z_2 curves occurred in 1982 and 1993 for the observed streamflow and natural streamflow, respectively (Table 2).

The streamflows (observed and natural) at the Lijin station present the periods of <5, 8–10, and 20–23 years, and the streamflow period is prolonged from 20 to 23 years along with the time. The same main periodicity of 3, 9, and 21 years for the observed and natural streamflow is obtained from the wavelet variance, and the 21-year period is the strongest within the 52-year scale (Table 2 and Fig. 4).

Discussion

The linear regression results of the natural streamflows show the downward trend in the whole Yellow River basin: the decreasing rate is intensified downstream, and the decreasing rate is more obvious for the observed streamflow compared with the natural series (Table 2). During hydrologic processes, precipitation offers water for runoff, but runoff will not be generated until excess infiltration or excess storage occurs. The precipitation in the Yellow River basin decreased during 1956–2007 (Fig. 5), less precipitation cuts down the infiltrated rate of runoff and delays the full-storage time of soil layer. Lijin is the last hydrologic gauging station downstream in the Yellow River basin; thus, the discharge at the Lijin station reflects the water fluxes from the Yellow River into the Bohai Sea. A significant correlation ($r = 0.80$, $p < 0.01$) between annual precipitation in the Yellow River basin and the natural streamflow at the Lijin station

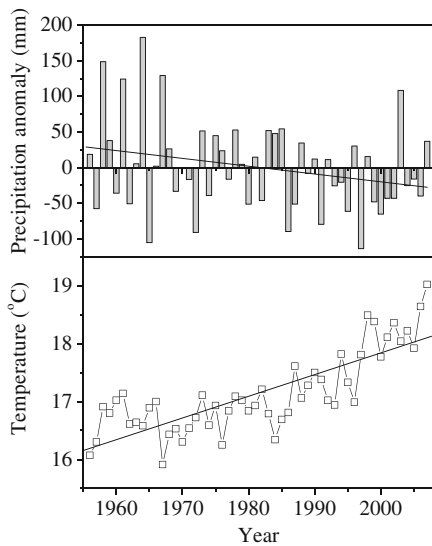


Fig. 5 Precipitation and temperature change in the whole Yellow River basin during 1956–2007

implies that the precipitation is the direct influence factor on the natural streamflow. In contrast, the increasing trend of temperature is detected in the Yellow River basin (Fig. 5), and the increasing rate is intensified further in recent 20 years. The warmer surroundings accelerate evaporation (includes evaporation from open channels of the river, soil, shallow groundwater, and water stored in vegetation) and extend the thickness and area of the dried soil layer. Part of the runoff will return directly to the atmosphere because of evaporation, plant transpiration, dried soil layer, etc. The land surface with depleted water storage can become a larger “stomach” to absorb precipitation. The negative correlation is found between annual temperature in the Yellow River basin and the natural streamflow at the Lijin station (not significant at the 95 % confidence level, $r=-0.212$), which interprets the temperature’s complex effect on the natural streamflow. The influence is indirect but important. The effects of the coexistence of less precipitation and warmer climate in the study area result in the decreasing trend of the natural streamflow.

In addition, the humans have already realized the serious eco-environmental problem and have begun to develop some measures to conserve soil and water since the 1970s, such as the “Grain for Green” program in 1999 (Miao et al. 2012c). The objective of this program was to increase the vegetation coverage on steep slopes in the landscape by planting trees or sowing grass on former cropland. By calculating the NDVI, Sun et al.

(2001) and Yang et al. (2002) found that the vegetation cover in the Yellow River basin was improved from 1982 to 1999, and the vegetation cover has been increased further since 1999 (Fig. 6). Three main effects of vegetation cover on runoff can be identified: absorptency, interception, and infiltration. Firstly, plants need to absorb water during the growth; secondly, the precipitation can be intercepted by crown surfaces and trunks, part of the interception is evaporated later and the rest is delayed into ground. Interception loss is a primary water loss as it represents water that never enters the soil, although the amount depends on the vegetation density, height and height of canopy, etc. An experimental study in Dayton, Ohio demonstrated that 22 % canopy cover reduced runoff by 7 % (Guevara-Escobar et al. 2007). Finally, the roots of vegetation meliorate soil structure and consequently increase the water-holding power of soil. In short, the improving vegetation cover reduces the probability of runoff generation.

In hydrology, the Yellow River basin is characterized by the fact that the dominating sediment and streamflow come from different sources. The sediment generates mainly in the middle reaches, while most streamflow comes from the upper reaches (Xu 2003); the discharge above the Lanzhou station accounts for 56.4 % amount of whole basin (Ye 1994). The double decreases (precipitation decreases in the middle-lower reaches and discharge decreases in the upper reaches) induce the reducing rate of the natural streamflow and is intensified downstream (Table 2).

Compared with the natural streamflow, the linear trend of the observed streamflow is more obvious. All downward trends of these streamflow series from the six gauging stations are significant at the 95 % confidence level (Table 2). The net water division is the gap between the natural streamflow and observed streamflow, mainly

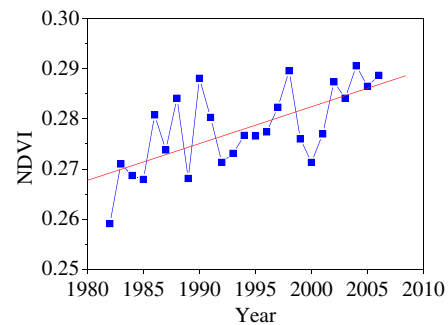


Fig. 6 Interannual variation of annual average NDVI in the Yellow River basin (1982–2006)

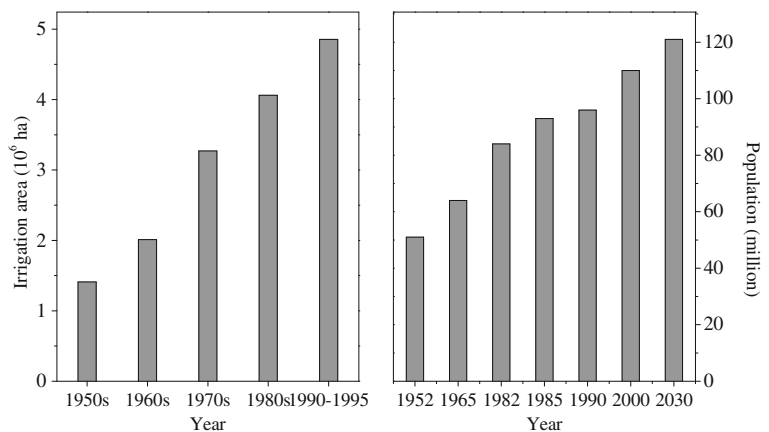
includes agricultural water, industrial water, domestic water, etc. In China, the Yellow River basin contains 15 % arable land and is developed as a production base for wheat, soybean, corn, and cotton. However, most of the drainage area of the Yellow River is located in a semiarid climate; agricultural water supply is mainly met by extensive irrigation. Agricultural irrigation accounts for the 85 % of whole water consumption (Xu and Ma 2009). On one hand, the Yellow River basin is undergoing rapid population growth in the past 50 years (Fig. 7), and the population in the basin is projected to reach 1.21 billion in 2030 (YRCC 2002). In order to meet the food demand accompanied with sharp population growth, cultivated land area (especially irrigation area) has expanded remarkably (Fig. 7). It is calculated that the amount of irrigated land increased at a rate of up to 61,600 ha/year between 1959 and 1969, and this grew to 134,000 ha/year during the period 1969–1979 (Xu and Ma 2009); moreover, Chen et al. (2001) found that the total area of irrigated land increased from 0.80×10^6 ha in 1950 to 7.35×10^6 ha in 1999. On the other hand, the agricultural cultivation with low efficiency (no more than 40 %) of water utilization is ignored chronically. As a result, the gap between natural streamflow and observed streamflow (net water diversion) increased gradually. Xu (2006) found that the total quantity of water diversion represented 50–60 % of the total annual natural runoff of the whole Yellow River in the 1990s. The water consumption increases with decreasing natural streamflow from 1956 to 2007, and as a result, the observed streamflow exhibits the downward trend with higher reducing rate (Table 2). Liu and Zhang (2004) quantitatively calculated the contribution to the reduction of observed streamflow

from 1956 to 2000 and showed the climate change and human activity, respectively, occupied the 75 and 25 % in the upper drainage basin, and the proportion changed into 43 % (climate change) and 57 % (human activity) in the middle reaches.

Aside from the above-mentioned human activity, construction of reservoirs in the basin is another unneglectable aspect affecting the runoff. In order to generate electricity, store water, trap sediments, mitigate flood, and sluice sediment, more than 3,1470 reservoirs in the Yellow River basin have been built, with a combined storage capacity of 57.4 km^3 (Zhang et al. 2001a, b). Twenty-four large dams and reservoirs with individual storage capacities exceeding 0.1 km^3 are distributed widely through the river basin. These reservoirs not only redistribute the seasonal water discharge and sediment load within any given year, but also adjust their inter-annual distribution. Surface water evaporation from the upper and middle mainstream reaches of the Yellow River increased by approximately 68 % due to the construction of the cascade of reservoirs, resulting in a corresponding 2.3 % decrease in water discharge (Liu and Zhang 2004).

The wavelet transform shows the close periodicity of the streamflow, which reflects the similar oscillation characteristic of 12 streamflow series (including observed and natural). Correlation analysis shows the significant correlation ($p < 0.01$) among the streamflows series at the six streamflow gauging stations (Table 3). Other than the streamflow at Guide station, the river runoff series (observed and natural) at the rest stations appear the strongest periodicity of 19–21 years. The distinguishing periodicity of streamflow at Guide station

Fig. 7 The development of population and irrigation area in the Yellow River basin



is pertinent with the special geomorphic features and unique climatic conditions above the Guide area. It is the source area of the Yellow River with an average altitude over 3,000 m above the mean sea level; There is typical continental climate with cold and dry characteristic, the annual average temperature is $-5\sim-4.1$ °C, and the annual average frozen period is over 160 days (Miao et al. 2012a). In addition, the results of wavelet transform reveal the potential water resource crisis in the Yellow River basin: the natural streamflow will continue in the low levels from the 1990s (the contour map of real part wavelet coefficient is negative).

When facing the potential crisis of water shortage, some positive countermeasures can be considered. (1) Harmonizing the water resources with a unified plan in the whole basin: The runoff in the basin is highly uneven in the temporal and spatial scale. Furthermore, the water consumption among agriculture, industry, domesticity, etc. is out of proportion. Establishing the mode of unified management according to the reasonable and scientific scheme is the premise to solve water shortage in so large area. (2) Expanding public awareness of water saving: Water saving should not be the concern of only policy-makers and scientists. Indeed, it is everyone’s duty to save water. So, it is necessary to promote the public participation through bringing up everyone the consciousness of water saving, and only in this way can we achieve the success of water saving finally. (3) Popularizing new

irrigation techniques: The overwhelming proportion of agricultural water in the Yellow River basin cannot be changed in a short period. Traditional irrigation techniques with large consumption but low efficiency need to be replaced by new techniques of water-saving irrigation. Moreover, farmer participation is very important for the implementation and success of water-saving irrigation scheduling. The success of any measure adopted to conserve irrigation water depends on it being understood and acceptable to the farmers. (4) Developing techniques to refresh and reuse the polluted water. Polluted water is generated from agriculture, industry, and households: Recycling of the polluted water is one of the main approaches when looking for new sources of water in water scarce regions, such as the Yellow River basin.

Conclusions

In this study, we used linear regression, Mann–Kendall test, and wavelet transform to reveal the variation characteristic of observed streamflow and natural streamflow in the Yellow River basin. Some conclusions can be achieved:

1. The natural streamflow presents a downward trend over 1956–2007 in the whole basin, and this trend is more obvious from the upper Yellow River to

Table 3 The correlation among streamflow series at different stations

	Station	Observed streamflow						Natural streamflow					
		G	La	He	S	Hu	Li	G	La	He	S	Hu	Li
Observed streamflow	G	1	0.92 ^a	0.89 ^a	0.75 ^a	0.72 ^a	0.60 ^a	0.86 ^a	0.79 ^a	0.80 ^a	0.74 ^a	0.70 ^a	0.67 ^a
	La		1	0.98 ^a	0.87 ^a	0.84 ^a	0.75 ^a	0.85 ^a	0.91 ^a	0.91 ^a	0.87 ^a	0.84 ^a	0.81 ^a
	He			1	0.93 ^a	0.89 ^a	0.80 ^a	0.81 ^a	0.87 ^a	0.89 ^a	0.89 ^a	0.85 ^a	0.82 ^a
	S				1	0.98 ^a	0.92 ^a	0.69 ^a	0.77 ^a	0.80 ^a	0.92 ^a	0.90 ^a	0.88 ^a
	Hu					1	0.96 ^a	0.66 ^a	0.74 ^a	0.76 ^a	0.90 ^a	0.92 ^a	0.91 ^a
	Li						1	0.53 ^a	0.63 ^a	0.64 ^a	0.80 ^a	0.84 ^a	0.85 ^a
Natural streamflow	G							1	0.94 ^a	0.94 ^a	0.83 ^a	0.78 ^a	0.75 ^a
	La								1	0.99 ^a	0.91 ^a	0.87 ^a	0.84 ^a
	He									1	0.93 ^a	0.89 ^a	0.86 ^a
	S										1	0.98 ^a	0.96 ^a
	Hu											1	0.99 ^a
	Li												1

G Guide station, La Lanzhou station, He Hekou station, S Sanmenxia station, Hu Huayuankou station, Li Lijin station

^aCorrelation is significant at the 0.01 level (two-tailed)

the lower Yellow River. Decreasing precipitation and warmer surroundings are the main reasons that cause this downward trend. In addition, the measure of soil and water conservation is indirect factor for natural streamflow.

2. Similar to natural streamflow, the decreasing trend is found for observed streamflow, and all the trends of observed streamflow at the six hydrologic gauging stations are significant at the 95 % confidence level. The decreasing rate is intensified downstream. Besides the decreasing precipitation and increasing temperature, water consumption by humans is another unneglectable aspect, which directly causes rapid reduction of the observed streamflow.
3. All the 12 streamflow series show the significant correlation; some close periods are found by using wavelet transform, other than the streamflow at the Guide station (the main periods of observed streamflow at the Guide station are 8 and 17 years, and the main periods of natural streamflow are 7, 15, and 22 years), and streamflow series at the rest stations appear in the main periods with 3–4, 8–9, and 19–21 years, and the periodicity of 19–21 years is the strongest.
4. The results of wavelet transform reveal that the streamflows have been in the shortage status from the 1990s to a certain year in the future, so some effective measures should be put into practice, such as harmonizing the water resources with a unified plan, expanding public awareness of water saving, popularizing new techniques of water-saving irrigation, and developing techniques to reuse the polluted water.

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