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Spatio-temporal variability of streamflow in the Yellow River: possible causes and implications

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Spatio-temporal variability of streamflow in the Yellow River: possible causes and implications

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Abstract The water shortage in the Yellow River, China, has been aggravated by rapid population growth and global climate changes. To identify the characteristics of streamflow change in the Yellow River, approximately 50 years of natural and observed streamflow data from 23 hydrological stations were examined. The Mann-Kendall and Pettitt tests were used to detect trends and abrupt change points. The results show that both the natural and the observed streamflow in the Yellow River basin present downward trends from 1956 to 2008, and the decreasing rate of observed streamflow is generally faster than that of the natural streamflow. Larger drainage areas have higher declining rates, and the declining trends are intensified downstream within the mainstream. The possibility of abrupt changes in observed streamflow is higher than in natural streamflow, and streamflow series in the mainstream are more likely to change abruptly than those in the tributaries. In the mainstream, all the significant abrupt changes appear in the middle and latter half of the 1980s, but the abrupt changes occur somewhat earlier for observed streamflow than for natural streamflow. The significant abrupt change for the observed streamflow in the tributaries is almost isochronous with the natural streamflow and occurs from the 1970s to 1990s. It is implied that the slight reduction in precipitation is not the only direct reason for the streamflow variation. Other than the effects of climate change, land-use and land-cover changes are the main reasons for the natural streamflow change. Therefore, the increasing net water diversion by humans is responsible for the observed streamflow change. It is estimated that the influence of human activity on the declining streamflow is enhanced over time.

Key words streamflow; trend; abrupt change; Yellow River, China

Causes éventuelles et implications de la variabilité spatio-temporelle des débits du fleuve Jaune

Résumé La pénurie d'eau dans le fleuve Jaune, en Chine, a été aggravée par la croissance rapide de la population et les changements climatiques. Pour identifier les caractéristiques du changement des débits dans le fleuve Jaune, près de 50 ans de données sur les débits naturels et observés à partir de 23 stations hydrologiques ont été examinés. Les tests de Mann-Kendall et de Pettitt ont été utilisés pour détecter les tendances et les points de changement brusques. Les résultats montrent que tant l'écoulement naturel que l'écoulement observé dans le bassin du fleuve Jaune présentent des tendances à la baisse de 1956 à 2008, et que le taux de diminution du débit observé est généralement plus rapide que celui du débit naturel. Les grandes surfaces de drainage présentent des taux de diminution plus élevés, et les tendances à la baisse sont intensifiés en aval dans le bief principal. La probabilité de changements abrupts dans le débit observé est supérieure à celle de l'écoulement naturel, et la série des débits dans le bief principal est plus susceptible de changer brusquement que celles des affluents. Dans le bief principal, tous les changements brusques significatifs apparaissent au milieu et vers la fin des années 1980, mais les changements brusques se produisent un peu plus tôt pour les débits observés que pour l'écoulement naturel. Le brusque changement significatif du débit observé dans les affluents est presque simultané avec celui du débit naturel et se

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produit à partir des années 1970 à 1990. Il est implicite que la légére diminution des précipitations n'est pas la seule raison directe du changement de débit. A part les effets du changement climatique, les changements de la couverture et de l'usage des sols sont les principales raisons du changement d'écoulement naturel. Par conséquent, l'augmentation des prélèvements nets d'eau par l'homme est responsable du changement des débits observés. On estime que l'influence de l'activité humaine sur la baisse des débits s'est renforcée au fil du temps.

Mots clefs débit; tendance; changement brusque; fleuve Jaune, Chine

1 INTRODUCTION

The usable water resources throughout the world are becoming depleted. Currently, this water scarcity problem is aggravated due to climate change, population growth, industry development, expanding agriculture and urban construction (Xu *et al*. 2002). Hydrology plays a central role in the development and management of water resources, and streamflow constitutes a major phase in the hydrological cycle. To mitigate the stress on water depletion and manage limited water resources more effectively, the streamflow change of watersheds in the world needs to be studied extensively (Lettenmaier *et al*. 1994, Kahya and Kalayci 2004, Zhang *et al*. 2010).

The Yellow River is the second largest river in China and is called the Mother River because it nurtured Chinese civilization. The annual runoff from the Yellow River is approximately 2% of China's total river discharge, but it directly supports 12% of the national population (mostly farmers and rural people), feeds 15% of the irrigated land, and contributes to 9% of China's gross domestic product (GDP). Over thousands of years in Chinese history, catastrophic floods and droughts appeared frequently in the Yellow River basin, resulting in tremendous losses of life and property (Liu 1989, Hu *et al*. 1998). Under the influence of global climate change and intensified human activities, coupled with harsh natural conditions and a fragile ecosystem, great changes have taken place in the eco-environment of the Yellow River basin over the last several decades (Wang and Cheng 2000). It has become a seasonal river; drying up of the main river along its lower reaches started in 1972 and has increased rapidly since (Cong *et al*. 2009). The most serious situation occurred in 1997; the main river closest to the sea dried up for 226 days, and the no-flow distance reached 704 km away from the river mouth (Yang *et al*. 2004).

Due to its important role in sustaining life and its drastic seasonal flow variation, many studies about the streamflow variation of the Yellow River have been published. Streamflow in the entire Yellow River basin has changed over inter-annual and decadal scales (Hu and Feng 2001, Yang *et al*. 2010). The water discharge from 1950 to 2000 significantly decreased in the range of −28 mm per 50 years to −61.5 mm per 50 years from the upper to the lower reaches (Yang *et al*. 2004). The reduction in the 1990s was the most serious, with values of −17% to −58% compared with the average value for 1956–2000 (Liu and Zhang 2004). In the headwater catchments of the Yellow River basin, which contribute nearly 35% of the streamflow in the basin (Zheng *et al*. 2009), no significant trend of streamflow was detected from 1956 to 2000, but change-point analysis showed that a significant change in annual streamflow occurred around 1990 (Zheng *et al*. 2007). The streamflow in the Upper Yellow River (Yang *et al*. 2004), the Middle Yellow River (Xu 2005a, Miao *et al*. 2010), the Lower Yellow River (Liu and Zheng 2004, Fu *et al*. 2004, Wu *et al*. 2008) and the water fluxes to the sea (Xu 2005b, Wang *et al*. 2006) have declined significantly in the last several decades. The declining trend results in a progressive intensification of water stress in the downstream direction (Vörösmarty *et al*. 2000, Xu *et al*. 2008). Reduction in streamflow from the Yellow River can be attributed to decreasing precipitation and intensified human activity (Yang *et al*. 2004). Zheng *et al*. (2009) reported that land-use change is responsible for more than 70% of the decreasing streamflow in the 1990s in the headwater catchments of the Yellow River basin. Liu and Zhang (2004) found that the reduced precipitation in 1990s was directly responsible for 75% and 43% of the reduction in river discharge in the upper and middle drainage basins, respectively. The changes in natural runoff and the groundwater in the Yellow River basin have also been studied. Cong *et al*. (2009) employed a distributed hydrological model (GBHM) to simulate the natural runoff without considering artificial water intake and found that the simulated natural runoff decreases significantly. Liu and Zheng (2004) found that the natural streamflow and groundwater at the Huayuankou station (in the Lower Yellow River) have significant decreasing trends from 1952 to 1997, and Fu *et al*. (2004) calculated the rate of decrease to be approximately 0.49% per year.

Many publications have discussed the river runoff change in the Yellow River over the last half-century. However, most previous studies only used three to six hydrological series located in the mainstream to represent the temporal variability of streamflow (e.g. Liu and Zhang 2004, Zheng *et al*. 2007, Zhang *et al*. 2009a). The spatial geographical characteristics in the Yellow River differ significantly throughout the basin. In order to systemically and convincingly explore the temporal change of streamflow in such a large basin, it is essential to have richer hydrological monitoring data. Questions about streamflow change in the tributaries are not well answered in existing research. At the same time, analysis of the difference in spatial variability of the streamflow dynamics is necessary to manage the distribution of the water resource. Moreover, most previous studies focused on the observed streamflow (e.g. Liu and Zhang 2004, Yang *et al*. 2004, Zheng *et al*. 2007, 2009) and insufficient study has been made of the natural streamflow in the Yellow River. The difference between observed and natural streamflow change can effectively explain some real phenomena of streamflow change. Additionally, the streamflow series are not up-to-date; most of the previous research concentrated on the second half of the 20th century. We still do not know how the streamflow has changed in the 21st century.

In this study, data of the natural and observed river runoff were collected at 23 hydrological gauging stations to help us detect streamflow variations over the entire Yellow River basin, and discuss the factors that influence streamflow change. This study can provide helpful information for policy makers to manage water resources more effectively.

2 DATA AND METHODS

2.1 Data

A dense network of hydrometric stations was established in the Yellow River basin in the 1950s, and complete data sets for streamflow have been recorded since. Simultaneously, considering the influence of human activities, such as water withdrawal from the river channel for irrigation, industrial and domestic usage, and the role of dams in controlling the streamflow, the Yellow River Water 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 difference between the natural and the measured streamflow is the water abstracted from the river and consumed in agricultural, domestic and industrial uses (Liu and Zheng 2004). The natural streamflow at a given station can be calculated as (Xu 2005a):

$$Q_{\mathrm{w,n}} = Q_{\mathrm{w,m}} + Q_{\mathrm{w,div}} \qquad (1)$$

where $Q_{\mathrm{w,n}}$ is the calculated natural streamflow, $Q_{\mathrm{w,m}}$ is the observed streamflow and $Q_{\mathrm{w,div}}$ is the net water quantity diverted from the river above the station. The formula for estimating natural runoff requires detailed information that is extremely difficult to collect. The difference between observed runoff and natural runoff is generally due to three factors: (a) the amount of water directly collected from the river channel for irrigation, industry and domestic usage, and the amount returning to the downstream river channel after use; (b) the amount of water controlled by dams, including extra water losses through evaporation and seepage; and (c) the amount of water transported into and out of the watershed. Although some hydrologists question the accuracy of natural runoff, it is generally believed that the natural runoff data published by the YRCC is the most authoritative and most accurate information. Hence, the data are widely used in water resource management and planning, and in hydrological engineering projects (Fu *et al*. 2004).

The Yellow River basin has been divided into the following three water source areas: Upper, above the Hekou station; Middle, between the Hekou and Huayuankou stations; and Lower, below the Huayuankou station. The observed and natural streamflow data from 23 gauging stations (nine stations situated along the mainstream, 14 on the major tributaries) in the Yellow River were selected for analysis of streamflow characteristics of the three reaches (Fig. 1). Detailed information concerning the hydrological records of these 23 gauging stations is shown in Table 1. Annual natural and observed streamflow series were provided by the YRCC. Climate data from 175 meteorological stations (Fig. 1), provided by the National Meteorological Information Centre, China Meteorological Administration, were used to interpolate the annual regional climatic series from 1956 to 2008 by the method of inverse distance weighting (IDW).

2.2 Methodology

Two statistical methods were used in this study to analyse the streamflow variation: the Mann-Kendall (MK) test and the Pettitt test. The MK test is used for detecting monotonic trends, while the Pettitt test is used to detect the abrupt changes in the mean level (Zhang *et al*. 2009b). The two non-parametric methods are briefly described in the following sections.

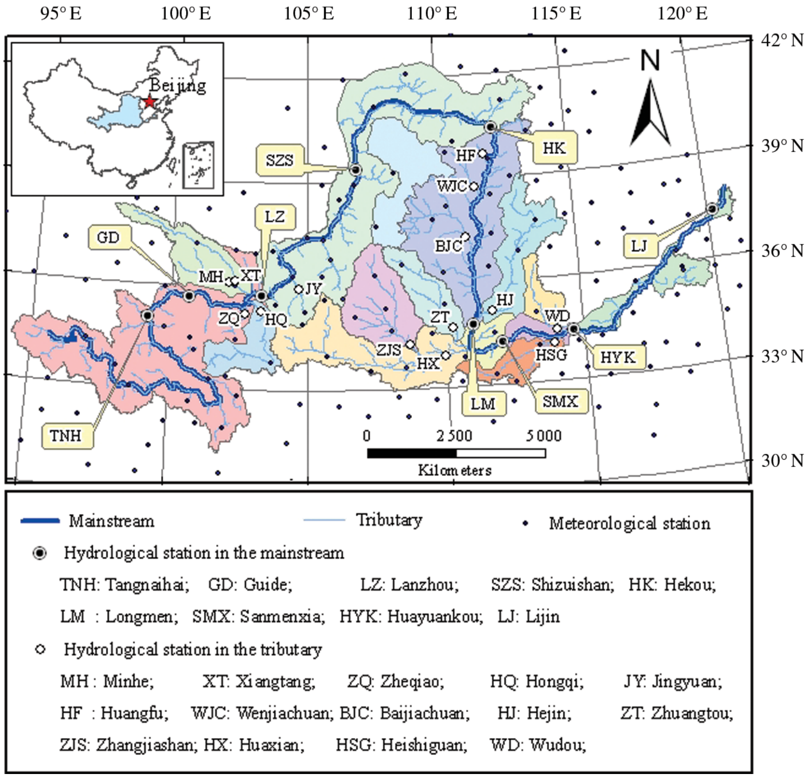

Fig. 1 Yellow River basin: locations of hydrological and meteorological stations.

Table 1 Detailed hydrological record for the Yellow River basin.

No.	Station	Location	Basin area ($10^4 \times$ km^2)	Time interval	
				Observed streamflow	Natural streamflow
Mainstream					
1	Tangnaihai		12.20	1956–2008	1956–2008
2	Guide		13.37	1956–2008	1956–2008
3	Lanzhou		22.26	1956–2008	1956–2008
4	Shizuishan		30.91	1956–2008	1956–2008
5	Hekou		36.79	1956–2008	1956–2008
6	Longmen		49.76	1956–2008	1956–2008
7	Sanmenxia		68.84	1956–2008	1956–2008
8	Huayuankou		73.00	1956–2008	1956–2008
9	Lijin		75.19	1956–2008	1956–2008
Tributary					
10	Minhe	Huangshui River	1.53	1956–2008	1956–2000
11	Xiangtang	Datong River	1.51	1956–2008	1956–2000
12	Zheqiao	Daxia River	0.68	1956–2008	1956–2000
13	Hongqi	Tao River	2.50	1956–2008	1956–2000
14	Jingyuan	Zuli River	1.07	1956–2002	–
15	Huangfu	Huangfuchuan River	0.32	1956–2007	–
16	Wenjiachuan	Kuye River	0.87	1956–2007	1956–2000
17	Baijiachuan	Wuding River	2.97	1956–2007	1956–2000
18	Hejin	Fen River	3.87	1956–2008	1956–2000
19	Zhuangtou	Beiluo River	2.56	1956–2008	1956–2000
20	Zhangjiashan	Jing River	4.32	1956–2008	1956–2000
21	Huaxian	Wei River	10.65	1956–2008	1956–2000
22	Heishiguan	Yiluo River	1.86	1956–2008	1956–2000
23	Wudou	Qin River	1.29	1956–2008	1956–2000

The non-parametric Mann-Kendall test was originally proposed by Mann (1945) and revised by Kendall (1948). This test has the advantage of not assuming any distribution form for the data and has similar power to its parametric competitors (Serrano *et al*. 1999). Thus, it is highly recommended by the World Meteorological Organization for general use (Mitchell *et al*. 1966). The Mann-Kendall test is given as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}} & S < 0 \end{cases} \tag{2}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{3}$$

$$\mathrm{sgn}(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \quad \text{if} & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{4}$$

$$\mathrm{var}(S) = \left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \Big/ 18 \tag{5}$$

in which x_j and x_i are the sequential data values at times j and i, respectively, $j > i$; n is the length of the time series; q is the number of tied groups; t_p is the pth group; and $\sum$ denotes the summation over all ties (Gilbert 1987, Xu *et al*. 2007). The positive (or negative) value of Z indicates an upward (or downward) trend. The magnitude of the trend slope can also be calculated as:

$$\mathrm{Slope} = \mathrm{Median}\left(\frac{x_j - x_i}{j = i} \right) \tag{6}$$

where a positive (negative) value of Slope indicates an upward (downward) trend, i.e. increasing (decreasing) values with time. The null hypothesis (H_0) is no trend (Slope = 0). The H_0 is accepted if $-Z_{1-\alpha/2} \le Z \le Z_{1-\alpha/2}$, where α is the significance level of the test. A typical significance level of 5% was used.

The non-parametric scheme developed by Pettitt (1979) can be used to determine the point of significant change in the time series (Kiely *et al*. 1998, 1999). This method detects one unknown change point by considering a sequence of random variables $X_1, X_2, \ldots, X_T$ that may have a change point at N if X_t for $t = 1, 2, \ldots, N$ has a common distribution function $F_1(x)$ and X_t for $t = N + 1, \ldots, T$ has a common distribution function $F_2(x)$, and $F_1(x) \neq F_2(x)$ (Pettitt 1979, Dou *et al*. 2009). The null hypothesis (H_0, no change, or $N = T$) is tested against the alternative hypothesis (H_a, change, or $1 < N < T$) using the non-parametric statistic:

$$K_t = max_{1 \le t \le T} \left| U_{t,T} \right| \tag{7}$$

$$U_{t,T} = U_{t-1,T} + \sum_{j=1}^{T} \mathrm{sgn}(X_t - X_j) \quad \text{for } t = 2, \ldots, T \tag{8}$$

where

$$\mathrm{sgn}(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \quad \text{if} & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{9}$$

and

$$p = 2\exp\left\{ -6K_T^2 / - 6K_T^2 (T^3 + T^2) \right\} \tag{10}$$

When p is smaller than the specific significance level, e.g. 0.05 in this study, the null hypothesis is rejected. The time, t, when K_t occurs is the change point time. If a significant change point exists, the time series is divided into two parts at the location of the change point, and the approximate significance probability for the change point is $1 - p$.

Both the Mann-Kendall and Pettitt tests assume that sample data are serially independent and not robust against autocorrelation. However, hydrological time series are frequently autocorrelated due to the coherent and inertial effects from influencing factors (e.g. precipitation and human activities) during hydrological circulation. A series with a positive serial correlation inflates the variance of the estimated mean and, therefore, the effective sample size contains less information about the mean than a random series (Matalas and Langbein 1962). The autocorrelation coefficient, r_k, between the hydrological time series and the same series lagged by k time steps is given by:

$$r_k = \frac{\sum_{i=1}^{n-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{11}$$

where k is the lag time steps, n is the length of hydrological series, x_i is the ith value in the series, and $\bar{x}$ is the average value overall. The critical value of r_k for a given significance level (e.g. 95%) is calculated as (Salas *et al*. 1980):

$$r_k(95\%) = \frac{-1 \pm \sqrt{n-k-1}}{n-k} \tag{12}$$

The autocorrelation of hydrological series will increase the possibility to reject the null hypothesis (Type I error) (Yue *et al*. 2002, Yue and Wang 2004). To eliminate the effect of serial correlation on the Mann-Kendall and Pettitt tests, the method of trend-free pre-whitening (TFPW) developed by Yue *et al*. (2002) was applied to the streamflow series with significant autocorrelation. The detailed procedure for TFPW can be found in Yue *et al*. (2002).

3 RESULTS

3.1 Monotonic trends of streamflow series

The results of the MK test show that both the observed and natural streamflow have decreasing trends in the whole Yellow River basin from 1956 to 2008 (Table 2). In the mainstream, except for the Tangnaihai station, the decreasing trend of the observed streamflow is significant at the 5% confidence level. However, the significant trend of natural streamflow only appears in the Guide, Longmen, Sanmenxia, Huayuankou and Linjin stations. In the tributaries, except for the Xiangtang station, the downward trend of the observed streamflow passes the 5% significance test, but half of the natural streamflow series fails. The absolute value of Slope during the MK test reflects the change rate being analysed. The decreasing rate of the observed streamflow is greater than that of the natural streamflow, and the trend in the mainstream is more obvious than that in the tributaries (Table 2). Additionally, the declining trends of the observed and natural streamflow in the mainstream intensify in the downstream direction. The absolute value of Slope increases gradually downstream. The Slope value for the observed streamflow series increases from about −0.69 at the

Table 2 Results of the Mann-Kendall test.

No.	Station	MK test for observed streamflow					MK test for natural streamflow				
		n	*Z*	Trend	Slope	*p*	*n*	*Z*	Trend	Slope	*p*
1	Tangnaihai	53	−1.57	↓	−0.69	0.116	53	−1.86	↓	−0.68	0.116
2	Guide	**53**	**−2.83**	↓	**−0.95**	**0.005**	**53**	**−2.12**	↓	**−0.92**	**0.033**
3	Lanzhou	**53**	**−2.75**	↓	**−1.43**	**0.006**	53	−1.73	↓	−0.95	0.084
4	Shizuishan	**53**	**−3.87**	↓	**−2.02**	**0.000**	53	−1.65	↓	−0.84	0.099
5	Hekou	**53**	**−4.07**	↓	**−2.17**	**0.000**	53	−1.89	↓	−1.05	0.058
6	Longmen	**53**	**−4.98**	↓	**−3.11**	**0.000**	**53**	**−2.10**	↓	**−1.47**	**0.036**
7	Sanmenxia	**53**	**−5.56**	↓	**−5.04**	**0.000**	**53**	**−3.09**	↓	**−2.79**	**0.002**
8	Huayuankou	**53**	**−5.19**	↓	**−5.07**	**0.000**	**53**	**−3.17**	↓	**−2.85**	**0.002**
9	Lijin	**53**	**−5.78**	↓	**−7.52**	**0.000**	**53**	**−2.68**	↓	**−2.79**	**0.007**
10	Minhe	**53**	**−2.23**	↓	**−0.08**	**0.026**	45	−0.57	↓	−0.02	0.564
11	Xiangtang	**53**	**−1.38**	↓	−0.06	0.167	45	−0.02	–	−0.00	0.984
12	Zheqiao	**53**	**−3.21**	↓	**−0.10**	**0.001**	**45**	**−3.08**	↓	**−0.13**	**0.002**
13	Hongqi	**53**	**−3.12**	↓	**−0.40**	**0.002**	**45**	**−2.63**	↓	**−0.44**	**0.009**
14	Jingyuan	**47**	**−2.02**	↓	**−0.01**	**0.043**					
15	Huangfu	**52**	**−4.20**	↓	**−0.02**	**0.000**					
16	Wenjiachuan	**52**	**−4.87**	↓	**−0.11**	**0.000**	45	−1.31	↓	−0.04	0.190
17	Baijiachuan	**52**	**−6.70**	↓	**−0.17**	**0.000**	**45**	**−2.56**	↓	**−0.05**	**0.010**
18	Hejin	**53**	**−6.02**	↓	**−0.31**	**0.000**	**45**	**−3.63**	↓	**−0.25**	**0.000**
19	Zhuangtou	**53**	**−2.68**	↓	**−0.05**	**0.007**	45	−1.17	↓	−0.04	0.240
20	Zhangjiashan	**53**	**−4.46**	↓	**−0.24**	**0.000**	45	−1.46	↓	−0.08	0.145
21	Huaxian	**53**	**−4.00**	↓	**−1.06**	**0.000**	**45**	**−2.49**	↓	**−0.70**	**0.013**
22	Heishiguan	**53**	**−3.49**	↓	**−0.33**	**0.000**	45	−1.43	↓	−0.18	0.153
23	Wudou	**53**	**−3.94**	↓	**−0.18**	**0.000**	**45**	**−3.04**	↓	**−0.15**	**0.000**

Note: Data series with significant trends at the 0.05 significance level are shown in **bold**.

Tangnaihai station to about 7.52 at the Lijin station, and the Slope value for the natural streamflow series increases from −0.68 at the Tangnaihai station to −2.85 at the Huayuankou station. The greatest decreasing rate for the observed streamflow (-8.22×10^8 m^3/year) appears at the Lijin station, according to streamflow data (not shown), and that for the natural streamflow (-3.35×10^8 m^3/year) occurs at the Huayuankou station. Furthermore, the change rate of streamflow series correlates significantly ($p < 0.01$) with the drainage area, and it is shown that the change rate declines with increasing drainage area (Fig. 2).

3.2 Abrupt changes of streamflow series

The farthest downstream station in the Yellow River basin is the Lijin station; streamflow measured at this station is usually used as a measure of water flux to the sea (Xu 2005b). According to the Pettitt test, the abrupt changes of observed and natural streamflow at the Lijin station occurred in 1985 and 1990 (Fig. 3). The average annual observed streamflow is 401.03 and 147.19 × 10^8 m^3 before and after the abrupt change time, respectively. The streamflow decreases by 63.30%, and the change ratio is reduced to 22.15% for the natural streamflow. The results of the Pettitt test for streamflow series at 23 stations are

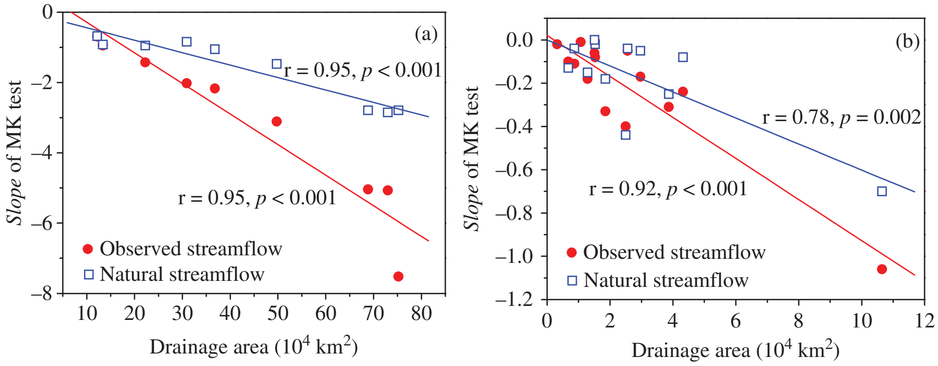

Fig. 2 Correlation between drainage area and the Slope value of the MK test: (a) in the mainstream and (b) in the tributaries.

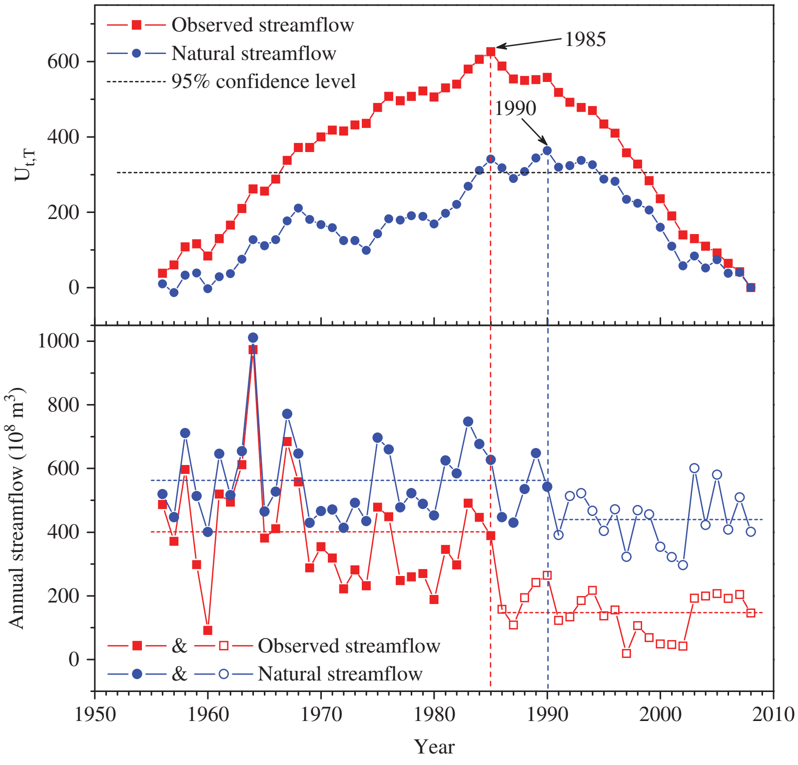

Fig. 3 Results of the Pettitt test for the observed and natural streamflow at the Lijin station.

Table 3 Results of the Pettitt tests. Data in parentheses highlight the observed streamflow results from 1956–2000 that correspond to the significant Pettitt test results for natural streamflow.

No.	Station	Pettitt test for observed streamflow					Pettitt test for natural streamflow				
		n	K_T	T	Variation	p	n	K_T	t	Variation	p
1	Tangnaihai	53	300	1989	−20.13%	0.057	53	300	1989	−20.00%	0.057
2	Guide	**53**	**378**	**1985**	**−21.26%**	**0.007**	**53**	**324**	**1989**	**−21.52%**	**0.031**
3	Lanzhou	**53**	**410**	**1985**	**−20.69%**	**0.003**	**53**	**322**	**1989**	**−17.00%**	**0.033**
4	Shizuishan	**53**	**502**	**1985**	**−28.05%**	**0.000**	**53**	**324**	**1989**	**−16.90%**	**0.031**
5	Hekou	**53**	**536**	**1985**	**−37.28%**	**0.000**	**53**	**352**	**1989**	**−19.36%**	**0.015**
6	Longmen	**53**	**592**	**1985**	**−37.39%**	**0.000**	**53**	**360**	**1989**	**−19.35%**	**0.012**
7	Sanmenxia	**53**	**610**	**1985**	**−43.08%**	**0.000**	**53**	**388**	**1985**	**−20.54%**	**0.005**
8	Huayuankou	**53**	**600**	**1985**	**−42.57%**	**0.000**	**53**	**372**	**1985**	**−20.50%**	**0.008**
9	Lijin	**53**	**626**	**1985**	**−63.30%**	**0.000**	**53**	**364**	**1990**	**−22.15%**	**0.011**
10	Minhe	**53**	**288**	**1990**	**−20.51%**	**0.075**	45	104	1990	−11.46%	0.500
11	Xiangtang	53	226	1990	−11.52%	0.265	45	75	1980	−6.26%	0.500
12	Zheqiao	**53**	**364**	**1986 (1979)**	**−32.25%**	**0.011 (0.026)**	**45**	**256**	**1979**	**−27.94%**	**0.029**
13	Hongqi	**53**	**406**	**1986 (1986)**	**−29.98%**	**0.003 (0.015)**	**45**	**272**	**1986**	**−29.50%**	**0.017**
14	Jingyuan	47	221	1970	−36.56%	0.126	no data				
15	Huangfu	**52**	**416**	**1984**	**−53.74%**	**0.001**	no data				
16	Wenjiachuan	**52**	**470**	**1979**	**−46.30%**	**0.000**	45	126	1985	−22.45%	0.500
17	Baijiachuan	**52**	**569**	**1979**	**−34.56%**	**0.000**	45	189	1979	−9.80%	0.200
18	Hejin	**53**	**576**	**1979 (1971)**	**−65.87%**	**0.000 (0.000)**	**45**	**309**	**1971**	**−31.49%**	**0.004**
19	Zhuangtou	**53**	**358**	**1994**	**−29.80%**	**0.013**	45	143	1994	−29.08%	0.500
20	Zhangjiashan	**53**	**438**	**1985**	**−34.61%**	**0.001**	45	126	1970	−16.31%	0.500
21	Huaxian	**53**	**430**	**1990 (1970)**	**−46.22%**	**0.001 (0.020)**	45	228	1990	−30.68%	0.070
22	Heishiguan	**53**	**386**	**1990**	**−46.97%**	**0.006**	45	148	1964	−41.02%	0.488
23	Wudou	**53**	**416**	**1976 (1971)**	**−62.51%**	**0.002 (0.006)**	**45**	**258**	**1976**	**−31.33%**	**0.027**

Note: Data series with significant abrupt changes at the 0.05 significance level are shown in **bold**.

shown in Table 3. In the mainstream, the results of the Pettitt test are significant at the 95% confidence level everywhere except at the Tangnaihai station, and the pattern is the same as that shown using the MK test. All the abrupt change times appear in the middle and latter half of the 1980s, and the abrupt change time is somewhat earlier for observed streamflow compared with the natural streamflow. In the tributaries, both the significant abrupt changes for observed and natural streamflow series occur at the Hejin station. The abrupt change in the tributaries is weak compared with the mainstream, especially for the natural streamflow series. For the observed streamflow in the tributaries, the time when the abrupt change appeared is not concentrated and occurred from the 1970s to the 1990s. If the focus is placed only on the observed streamflow from 1956 to 2000, the abrupt time is almost synchronous with the natural streamflow (data in parentheses in Table 3).

4 DISCUSSION

It is generally accepted that some characteristics of hydrological time series influence the trend detection results and its test for significance. The characteristics mainly include autocorrelation of each hydrological time series (Yue *et al*. 2002), and the multiple significance (or hypothesis) test for collective hydrological time series (Ventura *et al*. 2004). In this study, the TFPW approach is used to remove the effect of serial correlation before running the Mann-Kendall test. However, the TFPW approach is based on the assumption that the time series of observed and natural streamflow could be adequately described by an autoregressive process of order one (Khaliq *et al*. 2009), which is a debatable assumption because time series of hydrological variables could be better described by various other formulations of the time series models (Salas *et al*. 1980). Although the TFPW approach neglects the effects of higher-order dependencies (e.g. Yue *et al*. 2002), previous studies had indicated that TFPW procedure provides a better assessment of the significance of the trends for serially correlated data than the other approaches, such as pre-whitening (PW), or the variance correction approach (VCA) (Yue *et al*. 2002, Yue and Wang 2004, Zhang and Lu 2009). Hence, the TFPW approach is widely applied to eliminate the effect of serial correlation on the Mann-Kendall test results (Burn and Cunderlik 2004, Leclerc and Ouarda 2007, Wu *et al*. 2008, Xu *et al*. 2008, Zhang and Lu 2009). However, we also carried out the multiple significance tests by using the method of false discovery rate (FDR; Benjamini and Hochberg 1995), which controls the proportion q of falsely rejected null hypotheses relative to the total number of rejected hypotheses (Shi *et al*. 2011). This was done because some data are absent for the natural streamflow, and only 11 natural streamflow series present decreasing trends at 5% confidence level. Here, we conducted FDR tests for the 23 observed streamflow series by setting a significance level of $q = 0.05$. As for the Mann-Kendall test results, 21 observed streamflow series showed a significant decreasing trend (except for Tangnaihai and Xiangtang stations), which verified the monotonic trend in this research.

With regard to the trend in hydrological variation, the Mann-Kendall test results show that the observed and natural streamflow series show significant downward trends in the whole Yellow River basin, and that the decreasing rates are intensified downstream (Table 2). Figure 4 shows that the temperature in the Yellow River increased significantly under the conditions of global warming, despite the fact that higher temperatures can significantly increase evaporation and extend the growing season. It is generally believed that the reduction in streamflow can be mainly attributed to decreasing precipitation and intensification of human activities (Yang *et al*. 2004). However, only a slight and insignificant reduction in annual precipitation was observed from 1956 to 2008 in the Yellow River basin (Fig. 4). The Mann-Kendall and Pettitt tests were applied to analyse annual precipitation series in every catchment, where the precipitation recorded at a hydrological station indicates the precipitation occurring in the drainage area above the station (Table 4). Except for the Jingyuan, Baijiachuan and Huaxian stations, there is no significant decreasing trend in annual precipitation series in the mainstream and tributaries. In fact, an increasing trend appears in the headwater catchment

Table 4 Results of Mann-Kendall and Pettitt tests for regional annual precipitation.

No.	Station	MK test			Pettitt test	
		Trend	Slope	*P*	*T*	*p*
1	Tangnaihai	↑	0.23	0.876	1985	0.500
2	Guide	↑	0.19	0.840	1985	0.500
3	Lanzhou	↑	0.11	0.844	1989	0.500
4	Shizuishan	↓	0.03	0.830	1989	0.500
5	Hekou	↓	−0.16	0.760	1985	0.500
6	Longmen	↓	−0.48	0.445	1969	0.500
7	Sanmenxia	↓	−0.78	0.220	1985	0.465
8	Huayuankou	↓	−0.70	0.180	1985	0.316
9	Lijin	↓	−0.72	0.111	1985	0.221
10	Minhe	↑	1.38	0.062	1991	0.132
11	Xiangtang	↓	−0.25	0.770	1961	0.500
12	Zheqiao	↓	−0.41	0.450	1968	0.451
13	Hongqi	↓	−0.79	0.351	1985	0.398
14	Jingyuan	↓	**−2.8**	**0.000**	**1990**	**0.001**
15	Huangfu	↓	−1.45	0.223	1971	0.127
16	Wenjiachuan	↓	−1.06	0.345	1971	0.500
17	Baijiachuan	↓	**−2.18**	**0.016**	**1971**	**0.045**
18	Hejin	↓	−2.02	0.052	1976	0.256
19	Zhuangtou	↓	−0.95	0.315	1967	0.327
20	Zhangjiashan	↓	−1.44	0.143	1976	0.316
21	Huaxian	↓	**−2.38**	**0.013**	1992	0.054
22	Heishiguan	↓	−1.60	0.127	1985	0.247
23	Wudou	↓	−0.32	0.848	2002	0.500

Note: Data series with significant abrupt changes at the 0.05 significance level are shown in **bold**.

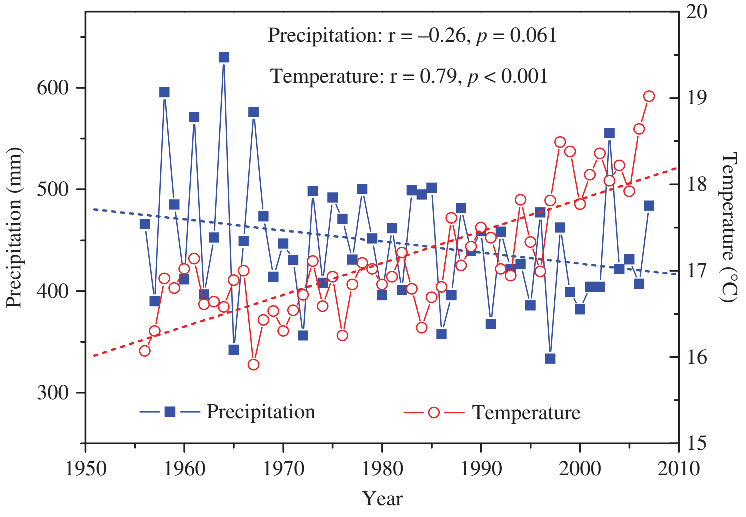

Fig. 4 Annual regional precipitation and temperature in the Yellow River basin from 1956 to 2008.

of the Yellow River basin (e.g. the Tangnaihai, Guide and Lanzhou stations, Table 4). Similar results are detected with the Pettit test; almost no abrupt changes are observed in all stations (Table 4). Insignificant precipitation change corresponds to the significant variation of streamflow. This suggests that the fluctuating precipitation is not the only direct reason for the declining trend and abrupt change of the streamflow, although less precipitation always results in less runoff.

If the runoff coefficient is defined as streamflow divided by the simultaneous precipitation, then the natural and the observed runoff coefficients at the Lijin station are variable (Fig. 5). Since the 1970s, the natural runoff coefficient has begun to decrease slightly, and the decreasing degree increases with time. Combined with the drainage area at the Lijin station, the natural runoff coefficient is calculated, and the average natural runoff coefficient is 0.16 for 1956–1969, and decreased to 0.13 for 1990–2008. Although the annual precipitation shows a slight reduction, the significant decreasing trend and abrupt change of natural streamflow are mainly attributed to the combined effects of decreasing precipitation and land-use change in the Yellow River basin. The stronger decrease in natural runoff coefficient results in the abrupt change time of natural streamflow being earlier compared with the observed streamflow (Fig. 3).

In the headwater catchments of the Yellow River basin, the population is small due to the comparatively inhospitable natural conditions (high altitude, low temperature, etc.) and, hence, human activities are relatively few (Miao *et al*. 2011). The weak human activities result in the insignificant change in observed and natural streamflow at the Tangnaihai station. Additional monitoring data from Zheng *et al*. (2009) also illustrate this point. However, due to the serious soil erosion and the fragile eco-environment in the Yellow River basin, humans have developed some measures to conserve soil and water since 1949 (Liu 2005), and the areas involved in conservation measures have been expanded yearly. The measures against soil erosion include afforestation, grass-planting, creation of level terraces, contour ploughing, non-tillage, ridge reconstruction, and building of check dams. By 2004, it was reported that the cumulative area of afforestation, grass-planting and basic farmland had reached 8.87, 2.67 and 6.47 × 10^4 km^2, respectively, more than 0.11 million check dams were built, and the preliminary soil erosion control area had reached 0.2 × 10^6 km^2 (Ran 2006). These measures have been noticeably effective since the 1970s (Liu and Zhang 2004). Implementing soil and water conservation measures results in changes in land use and land cover, thereby changing the conditions for runoff generation (Xu 2005a, Zhang and Schilling 2006). The creation of level terraces, contour ploughing and ridge reconstruction will reshape the micro-topography, reduce slope gradient and elongate the runoff movement path. As a result, rainfall infiltration will be greatly enhanced due to the slowing or capturing effects of the measures. Experiments conducted in the middle reaches of the Yellow River showed that land terracing can reduce surface runoff by 70–90% compared to the sloping cultivated land (Xu and Niu 2000). Observations in the Tianshui area (a city in the Upper Yellow River basin) suggest that contour ploughing and ridge reconstruction can reduce the runoff by 19–39% and 75%, respectively (Chen *et al*. 2004).

After trees and grass were planted on bare slopes, the runoff generation process was primarily influenced by absorption, interception and infiltration. Plants absorb water during growth; precipitation can be intercepted by crown surfaces and trunks, but part of the intercepted precipitation is evaporated later; the remaining precipitation infiltrates into the soil. Although the amount of interception depends on the vegetation density and canopy height, it is a primary means of water loss because it represents water that never enters the soil. Finally, the roots of vegetation ameliorate soil structure and consequently increase the water holding power of the soil. Improving vegetation cover reduces the probability of runoff generation. Several experiments in the middle reaches of the Yellow River basin show that reforestation can reduce

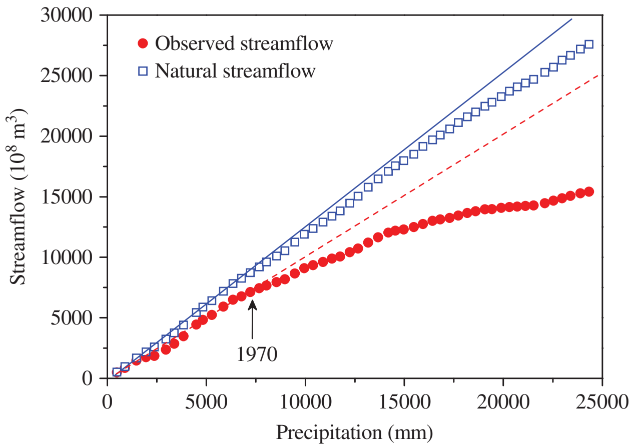

Fig. 5 Double mass curves for annual precipitation and streamflow at the Lijin station.

surface runoff by 30.8–75.1%, and grass planting – by 17.2–58.9% (Xu and Niu 2000). The vegetation cover in the Yellow River basin (expressed as NDVI) increased by the rate of 0.075% per year from 1982 to 2006 (Miao *et al*. 2012), due to the "Grain for Green (GFG)" programme, and it has increased further since 1999.

In the Yellow River basin, the discharge above the Lanzhou station accounts for 56.4% of the river flow for the whole basin (Ye 1994). The natural streamflow decrease in the upper reaches and the natural runoff coefficient in the middle to lower reaches result in the natural streamflow downstream having an intensified declining rate (Table 2). Additionally, due to the different measures implemented to combat soil erosion and improve natural conditions, the abrupt change times in the tributaries are asynchronous (Table 3).

Compared with the natural streamflow, the more significant and higher change rate for the observed streamflow is attributed to increasing water diversion, which includes agricultural, industrial and domestic water. The Yellow River basin contains 15% arable land and is developed as a production base for wheat, soybean, corn and cotton. However, because most of the drainage area of the Yellow River is subjected to a semi-arid climate, the demand for agricultural water use is mainly met by extensive irrigation (Miao *et al*. 2011). Agricultural irrigation accounts for 85% of the entire water consumption (Xu and Ma 2009). The Yellow River basin has undergone rapid population growth over the past 50 years: the population doubled from 41 million to 84 million between 1953 and 1982, climbed to approximately 107 million by 1997 (Fu *et al*. 2004), and is estimated to reach 120 million by 2030 (YRCC 2002). To meet the food demand that accompanies such sharp population growth, cultivated land area (especially irrigated area) has expanded markedly (Liu and Zhang 2004). The amount of irrigated land increased between 1959 and 1969 at a rate of up to 616 km^2/year, and grew to 1340 km^2/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 0.80×10^4 km^2 in 1950 to 7.35×10^4 km^2 in 1999. In contrast, agricultural cultivation with low-efficiency (no more than 40%) water use has been ignored for a long time. As a result, the gap between natural streamflow and observed streamflow (net water diversion) has gradually increased (Fig. 6), and has remained at a high and constant level since 1985. This is partly responsible for the abrupt change time of the observed streamflow in the mainstream that occurred in 1985 (except at Tangnaihai station). Xu (2006) found that the total quantity of water diversion represented 50–60% of the total annual natural runoff of the whole Yellow River basin in the 1990s. Water consumption increased with decreasing natural streamflow from 1956 to 2008 and, therefore, the observed streamflow exhibits a downward trend with a more significant decreasing rate (Table 2).

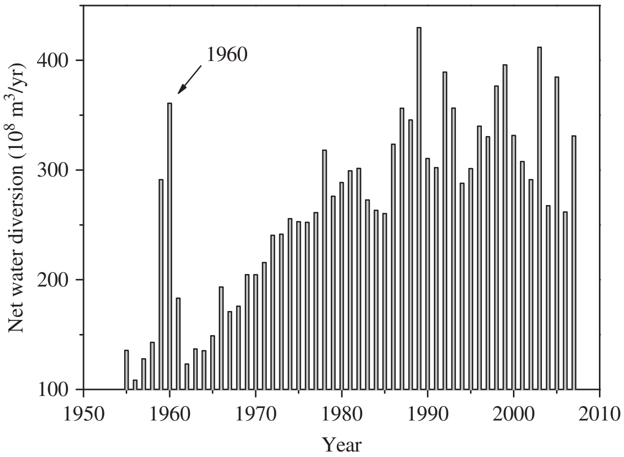

Fig. 6 Variation in net water diversion in the Yellow River basin. Data from Miao *et al.* (2010).

In addition to the above-mentioned human activity, the construction of reservoirs in the basin is another non-negligible factor affecting the runoff. More than 3147 reservoirs, with a combined storage capacity of 57.4 km^3, have been built in the Yellow River basin to generate electricity, store water, trap sediments, mitigate floods and sluice sediment (Zhang *et al*. 2001). Twenty-four large dams and reservoirs with individual storage capacities exceeding 0.1 km^3 are scattered widely throughout the river basin (such as the Liujiaxia, Longyangxia, Sanmemxia and Xiaolangdi reservoirs). The net water diversion in 1960 reached an abnormal value (Fig. 6) when the Sanmenxia Reservoir was completed and began to work. A large quantity of runoff was stored in the reservoir, and the decreasing observed streamflow (because of water storage) and unaffected natural streamflow resulted in the large value for net water diversion in 1960. Unfortunately, the reservoir water had to be released between 1962 and 1964 because of severe siltation in the Sanmenxia Reservoir. This water release directly resulted in a reduction of net water diversion during that same period (Fig. 6). In contrast to adjusting the interannual runoff in the Sanmenxia Reservoir, the primary effect of most reservoirs in the Yellow River basin is to redistribute the intra-annual runoff, i.e. the runoff is stored during the flood season, or discharged during the dry season of the same year. The storage–discharge amount in the same year cannot influence the annual observed streamflow.

5 CONCLUSIONS

In this study, the Mann-Kendall and Pettitt tests are used to reveal the variations of observed streamflow and natural streamflow from 23 hydrological stations in the Yellow River basin. The following conclusions were obtained:

1. Both observed and natural streamflow in the whole basin show a downward trend from 1956 to 2008. However, the trend is not significant in some areas, especially the natural streamflow in tributaries. In the mainstream, the declining trend of streamflow (observed and natural) is intensified from the Upper Yellow River to the Lower Yellow River. The decreasing rate of observed streamflow is higher than that of the natural streamflow. The change rates of streamflow series and the drainage area are significantly correlated ($p < 0.01$), and a larger drainage area results in a higher declining rate.
2. Except for the Tangnaihai station, the streamflow (observed and natural) in the mainstream appears to change abruptly, but the characteristic of the abrupt change is weakened in the tributaries. In the mainstream, all the significant abrupt changes appear in the middle and latter half of the 1980s. The abrupt change in time is somewhat earlier for observed streamflow compared with the natural streamflow. In the tributaries, the significant abrupt change for the observed streamflow is almost isochronous with the natural streamflow and occurs between the 1970s and 1990s.
3. Aside from the slight precipitation decrease, land-use and land-cover changes are the main reasons for the natural streamflow change. Numerous measures taken to prevent soil erosion may decrease the runoff generation. Based on this, increased net water diversion is responsible for the observed streamflow change.

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REFERENCES

Burn, D.H. and Cunderlik, J.M., 2004. Hydrological trends and variability in the Liard River basin. *Hydrological Sciences Journal*, 49 (1), 53–69.

Benjamini, Y. and Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society*, 57B, 289–300.

Chen, J.N., Wang, Y.Z., and Xu, J.H., 2004. *The influences of soil and water conservation on the water resource and sediment in the Loess Plateau*. Zhengzhou: Yellow River Conservancy (in Chinese).

Chen, X.G., Shi, C.X., and Zhang, H.Y., 2001. A review on the planning for water resources development in the Yellow River basin. *In*: C.M. Liu, *et al*., eds. *Evolving law and maintaining mechanism of renewable capacity of water resources in the Yellow River basin*. Zhengzhou: Yellow River Conservancy (in Chinese).

Cong, Z.T., *et al*., 2009. Hydrological trend analysis in the Yellow River basin using a distributed hydrological model. *Water Resources Research*, 45, W00A13, doi:10.1029/2008wr006852.

Dou, L., Huang, M.B., and Hong, Y., 2009. Statistical assessment of the impact of conservation measures on streamflow responses in a watershed of the Loess Plateau, China. *Water Resources Management*, 23 (10), 1935–1949.

Fu, G.B., *et al*., 2004. Hydro-climatic trends of the Yellow River Basin for the Last 50 Years. *Climatic Change*, 65 (1), 149–178.

Gilbert, R.O., 1987. *Statistical methods for environmental pollution monitoring*. New York: Van Nostrand Reinhold.

Hu, D., Saito, Y., and Kempe, S., 1998. Sediment and nutrient transport to the coastal zone. *In*: J.N. Galloway, *et al*., eds. *Asian change in the context of global climate change: impact of natural and anthropogenic changes in Asia on global biogeochemical cycles*. Cambridge: Cambridge University Press.

Hu, Q. and Feng, S., 2001. A southward migration of centennial-scale variations of drought/flood in eastern China and western United States. *Journal of Climate*, 14, 1323–1328.

Kahya, E. and Kalayci, S., 2004. Trend analysis of streamflow in Turkey. *Journal of Hydrology*, 289, 128–144.

Kendall, M.G., 1948. *Rank correlation methods*. New York: Hafner.

Khaliq, M.N., *et al*., 2009. Identification of hydrological trends in the presence of serial and cross correlations: a review of selected methods and their application to annual flow regimes of Canadian rivers. *Journal of Hydrology*, 368 (117), 117–130.

Kiely, G., 1999. Climate change in Ireland from precipitation and streamflow observation. *Advances in Water Resources*, 23, 141–151.

Kiely, G., Albertson, J.D., and Parlange, M.B., 1998. Recent trends in diurnal variation of precipitation at Valentia on the west coast of Ireland. *Journal of Hydrology*, 207, 270–279.

Leclerc, M. and Ouarda, T.B.M.J., 2007. Non-stationary regional flood frequency analysis at ungauged sites. *Journal of Hydrology*, 343, 254–265.

Lettenmaier, D.P., Wood, E.F., and Wallis, J.R., 1994. Hydro-climatological trends in the continental United States 1948–1988. *Journal of Climate*, 7, 586–607.

Liu, C.M., 1989. Problems in management of the Yellow River. *Regulated Rivers: Research and Management*, 3, 361–369 (in Chinese).

Liu, C.M. and Zhang, X.C., 2004. Causal analysis on actual water flow reduction in the mainstream of the Yellow River. *Acta Geographica Sinica*, 59 (3), 323–330 (in Chinese).

Liu, C.M. and Zheng, H.X., 2004. Changes in components of the hydrological cycle in the Yellow River basin during the second half of the 20th century. *Hydrological Processes*, 18 (12), 2337–2345.

Liu, Z., 2005. Small watersheds integrated management for soil and water conservation in China: review and prospective. *Chinese Water Resources*, 22, 17–20 (in Chinese).

Mann, H.B., 1945. Non-parametric test against trend. *Econometrika*, 13, 245–259.

Matalas, N.C. and Langbein, W.B., 1962. Information content of the mean. *Journal of Geophysical Research*, 67 (9), 3441–3448.

Miao, C.Y., Ni, J.R., and Borthwick A.G.L., 2010. Recent changes of water discharge and sediment load in the Yellow River basin, China. *Progress in Physical Geography*, 34 (4), 541–561.

Miao, C.Y., *et al*., 2011. A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. *Global and Planetary Change*, 76 (3–4), 196–205.

Miao, C.Y., Yang L., and Chen, X.H., 2012. The vegetation cover dynamics (1982–2006) in different erosion regions of the Yellow River basin, China. *Land Degradation and Development*, 23 (1), 62–71.

Mitchell, J.M., *et al*., 1966. Climatic change. (Report of a working group of the Commission for Climatology). Geneva, Switzerland: World Meteorological Organization, WMO Technical note no.79.

Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. *Applied Statistics*, 28 (2), 126–135.

Ran, D.C., 2006. Macro analysis on sediment reduction through soil and water conservation measures conducted in the Middle Yellow River. *Yellow River*, 28 (11), 39–41.

Salas, J.D., *et al*., 1980. *Applied modeling of hydrologic time series*. Littleton. CO: Water Resources Publications.

Serrano, V.L., Mateos, V.L., and García, J.A., 1999. Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921–1995. *Physics and Chemistry of the Earth (B)*, 24 (2), 85–90.

Shi, X., Lu, C., and Xu, X., 2011. Variability and trends of high temperature, high humidity, and sultry weather in the warm season in China during the period 1961–2004. *Journal of Applied Meteorology and Climatology*, 50, 127–134.

Vörösmarty, C.J., *et al*., 2000. Global water resources: vulnerability from climate change and population growth. *Science*, 289, 284–288.

Ventura, V., Paciorek, C.J., and Risbey, J.S., 2004. Controlling the proportion of falsely rejected hypotheses when conducting multiple tests with climatological data. *Journal of Climate*, 17, 4343–4357.

Wang, G.X. and Cheng, G.D., 2000. Eco-environmental changes and causative analysis in the source regions of the Yangtze and Yellow River, China. *Environmentalist*, 20, 221–232.

Wang, S.J., Hassan, M.A., and Xie, X.P., 2006. Relationship between suspended sediment load, channel geometry and land area increment in the Yellow River delta. *Catena*, 65, 302–314.

Wu, B.S., *et al*., 2008. Response of bankfull discharge to discharge and sediment load in the Lower Yellow River. *Geomorphology*, 100, 366–376.

Xu, J.X., 2005a. Temporal variation of river flow renewability in the Middle Yellow River and the influencing factors. *Hydrological Processes*, 19, 1871–1882.

Xu, J.X., 2005b. The water fluxes of the Yellow River to the sea in the past 50 years, in response to climate change and human activities. *Environmental Management*, 35 (5), 620–631.

Xu, J.X., 2006. Land accretion of the Yellow River Delta as influenced by drainage basin factors. *Geografiska Annaler*, 88, 31–42.

Xu, J.X. and Ma, Y.X., 2009. Response of the hydrological regime of the Yellow River to the changing monsoon intensity and human activity. *Hydrological Sciences Journal*, 54 (1), 90–100.

Xu, J.X. and Niu, Y., 2000. *Impacts of soil and water conservation measures on runoff and sediment in the 'Coarse Sediment Producing Area' of the Yellow River*. Zhengzhou: Yellow River Conservancy (in Chinese).

Xu, Z.X., Li, J.Y., and Liu, C.M., 2007. Long-term trend analysis for major climate variables in the Yellow River basin. *Hydrological Processes*, 21, 1935–1948.

Xu, Z.X., *et al*., 2002. Sustainability analysis for Yellow River water resources using the system dynamics approach. *Water Resources Management*, 16 (3), 239–261.

Xu, Z.X., Zhao, F.F., and Li, J.Y., 2008. Response of streamflow to climate change in the Headwater catchment of the Yellow River basin. *Quaternary International*. doi:10.1016/j.quaint.2008.09.001.

Yang, D.W., *et al*., 2004. Analysis of water resources variability in the Yellow River of China during the last half century using historical data. *Water Resources Research*, 40: W06502, doi:10.1029/2003wr002763.

Yang, T., *et al*., 2010. Temporal and spatial patterns of low-flow hydrological components in the Yellow River during past 50 years. *Stochastic Environment Research and Risk Assessment*, 24, 297–309.

Ye, Q.C., 1994. *Researches on environmental changes of the Yellow River basin and laws of water and sediment transportation*. Jinan: Shandong Science and Technology Press (in Chinese).

YRCC (Yellow River Water Conservancy Commission), 2002. *Information made available to International Water Management Institute (IWMI) during project meeting*, Zhengzhou, 7 September.

Yue, S., *et al*., 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes*, 16, 1807–1829.

Yue, S. and Wang, C.Y., 2004. The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management*, 18, 201–218.

Zhang, Q., Xu, C.Y., and Yang, T., 2009a. Variability of water resource in the Yellow River Basin of past 50 years, China. *Water Resources Management*, 23 (6), 1157–1170.

Zhang Q., *et al*., 2010. Changing properties of hydrological extremes in south China: natural variations or human influences? *Hydrological Processes*, 24, 1421–1432.

Zhang, S. and Lu, X. X., 2009. Hydrological responses to precipitation variation and diverse human activities in a mountainous tributary of the lower Xijinag, China. *Catena* 77, 130–142.

Zhang, W., *et al*., 2009b. Temporal and spatial variability of annual extreme water level in the Pearl River Delta region, China. *Global and Planetary Change*, 69 (1–2), 35–47.

Zhang, X., Wang, L., and Si, F., 2001. Prediction water consumption in the Huanghe river basin. *Water Resources and Hydropower Technology*, 6, 8–13 (in Chinese).

Zhang, Y.K. and Schilling, K.E., 2006. Increasing streamflow and baseflow in Mississippi River since the 1940s: effect of land use change. *Journal of Hydrology*, 324 (1–4), 412–422.

Zheng, H.X., *et al*., 2007. Changes in stream flow regime in headwater catchments of the Yellow River basin since the 1950s. *Hydrological Processes*, 21 (7), 886–893.

Zheng, H.X., *et al*., 2009. Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. *Water Resources Research*, 45, W00A19, doi:10.1029/2007wr006665.