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Changing trends and regime shift of streamflow in the Yellow River basin

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Abstract Water shortages have become one of the most severe problems in semi-arid regions throughout the world. Although semi-arid regions have always been dry, human activities and climate change are acerbating the problem. In Chinese Yellow River basin, the river is the major source of freshwater for those living there, and they have long suffered from serious water shortages. However, increasing population and decreasing streamflow are making these shortages more acute. This study seeks to quantify changes in available water in the Yellow River basin over the last 100 years and attempts to determine causes for these changes. To do this, the study evaluated changing trends and regime shifts of streamflow using long term historical records at different hydrological stations in the Yellow River basin over the past century. The results show that annual streamflow has a significant decreasing trends ($P < 0.01$) in the mid-lower reaches of the basin. Streamflow decomposition by the breaks for additive seasonal and trend approach suggest that this trend can be decomposed into four distinct annual stages (1919–1933, 1934–1969, 1970–1986 and 1987–2011), while the seasonal component demonstrated an evident regime shift in 1986. This regime shift is mainly related to the construction of large reservoirs in the basin. The flow duration curves illustrate a decrease in the magnitude of streamflow over the last century with a relatively uniform flow regime at all stations. The reconstructed streamflow at Toudaoguai station suggests that agricultural irrigation is predominantly responsible for streamflow reductions between Lanzhou and Toudaoguai stations with approximately 9.1 km^3/a of water extracted between 1997 and 2006. Meanwhile, a decrease of incoming water from upper reaches and soil and water conservation measures were responsible for the significant decline in annual streamflow at mid-lower reaches station. The result of this paper should be of use for water resources planning, watershed management and climate adaptation as they demonstrate how natural and anthropogenic drivers influence water availability in semi-arid regions.

Keywords Yellow River · Streamflow · Temporal trend · Regime shift · Human activities

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1 Introduction

A lack of adequate water resources has become one of the major factors restricting the development of societies and economies in many parts of the world (Oki and Kanae

2006). Water resource systems and the hydrological cycle are extensively influenced by climate variability and human activities (Dettinger and Diaz 2000). Hence these factors have the potential to affect the water resources available in any part of the world. For example, it has been reported that climate change will alter the global hydrological cycle leading to changes in precipitation, temperature and runoff (Milliman et al. 2008). An outcome of these changes is that the global annual average runoff is expected to increase 10–40 % in high latitude regions, but decrease by 10–30 % in the middle latitudes in the twenty-first century (IPCC 2007). Meanwhile, intensive human activities such as land cover changes (deforestation and afforestation), agricultural irrigation, reservoirs construction and water-transfer projects have altered natural flow regimes resulting in shifts in the magnitude, timing and duration of flood events (Xu 2005; Wang et al. 2006).

Consequently, there have been numerous studies focusing on the changes of streamflow in different rivers throughout the world at various spatiotemporal scales to try and resolve how the dual influences of climate and anthropogenic activity affect water resources and flow regimes (Burn and Elnur 2002; Fu et al. 2007; Mu et al. 2012; Zhao et al. 2013a; Dyer et al. 2014). Milly et al. (2005, 2008) investigated the changing trends of streamflow at a global scale and found increasing streamflow in southern through central North America and northern Australia and decreasing streamflow in southern Australia, southern Europe, South America and sub-Sahara Africa largely as a result of human activities. Similar studies have also been undertaken for Chinese rivers (Zhang et al. 2011; Zheng et al. 2007). Piao et al. (2010) showed that declining runoff in the lower reaches of Yellow River are largely a results of climate change with increased water withdrawals explaining about 35 % of the decline in runoff over several decades. Yang et al. (2010) reported that climate change, uneven temporal-spatial patterns of precipitation, jointly with highly intensified water resource utilization, were the main factors that led to the decrease of low-flow in the middle-lower reaches of the Yellow River in recent decades. Zhang et al. (2011) assessed water resources variations in ten large rivers across China, and found that the mean annual streamflow decreased in arid and semiarid regions of north China and increased in south and southwest China. Again these changes are largely climatic in nature although human activities play a role in decreasing water availability in arid and semi-arid regions.

The Yellow River basin is regarded as the cradle of Chinese civilization and plays an important role in the development of the regional economy as the major source of freshwater for a large amount of people living there (Zhao et al. 2013b; Jia et al. 2015). However, the river basin has long suffered from serious water shortages (Zheng et al. 2007; Yang et al. 2010). According to statistics, the Yellow River basin is home to some 110 million people or around 9 % of China's total population (Miao et al. 2010), while its mean annual streamflow accounts for only about 2 % of the water resources in China. This obvious shortfall is exacerbated by long term declines in available water resources in the basin (Xu 2005; Wang et al. 2006). Observations have indicated that both streamflow and sediment load have declined significantly in this region (Yang et al. 2004; Fu et al. 2007; Zhang et al. 2009; Miao et al. 2010; Liang et al. 2013; Guo et al. 2014; Zhao et al. 2014). For example, the average annual streamflow at Lijin station (40 km from the river mouth) was 33.1 km^3 between 1950 and 2000, but decreased to 15.8 km^3 between 2001 and 2011.

Although previous studies have identified and quantified the decline of streamflow in the Yellow River basin, (e.g., Fu et al. 2007; Miao et al. 2010; Mu et al. 2012; Liang et al. 2013; Guo et al. 2014), it is still unclear whether the streamflow will continue to decrease in the future, and to what extent climate change and human activities are responsible for the declines. Furthermore, few studies have considered potential regime shifts of the streamflow in the Yellow River basin, which has long been perturbed by intensive human activities. Thus, the objectives of this study are:

(a) to statistically analyze the spatiotemporal trends of annual streamflow in the Yellow River basin over the past century;

(b) to decompose the streamflow time series to identify the hydrological regime shifts;

(c) and to assess potential effects of human activities and climate change on streamflow changes in the basin.

2 Study area and data

2.1 Study area

The Yellow River is the second longest river in China with a length of 5464 km covering a drainage area of 75.2 × 10^4 km^2. The river originates from the Qinghai–Tibetan Plateau in western China, and flows eastward through the Loess Plateau and the North China Plain and enters into the Bohai Sea (Fig. 1). The upper reaches of the basin extend from the headwaters to Toudaoguai (a length of 3472 km) and accounts for an area of 38.6 × 10^4 km^2. These upper reaches are the predominant source for both water and sediment in the basin with 61.1 % of the runoff (22.6 km^3, 1919–2011) and 9.3 % of the sediment (110.02 Mt, 1919–2011) originating there. The middle reaches lies between Toudaoguai and Huayuankou stations

Fig. 1 Location of the study area and hydrological stations
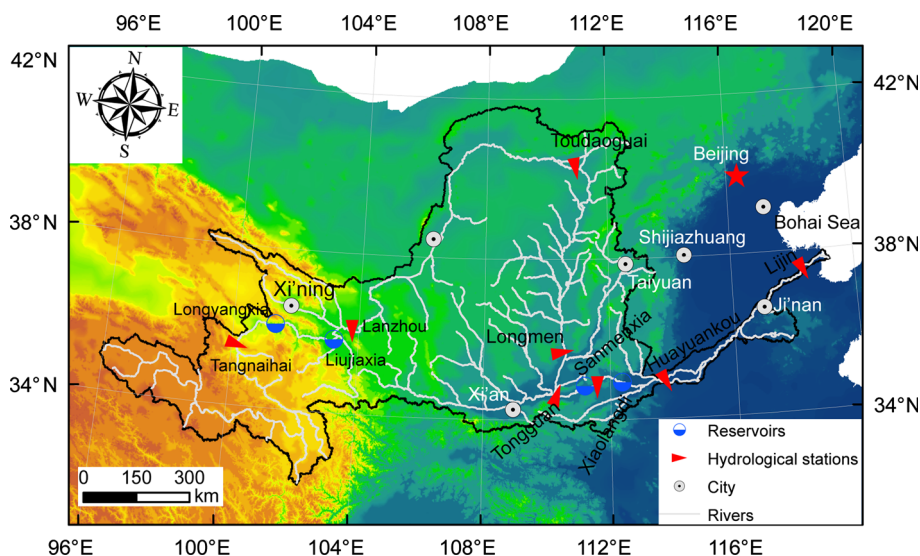
Fig. 2 Monthly streamflow in the upper and middle reaches of the Yellow River basin from 1919 to 2011
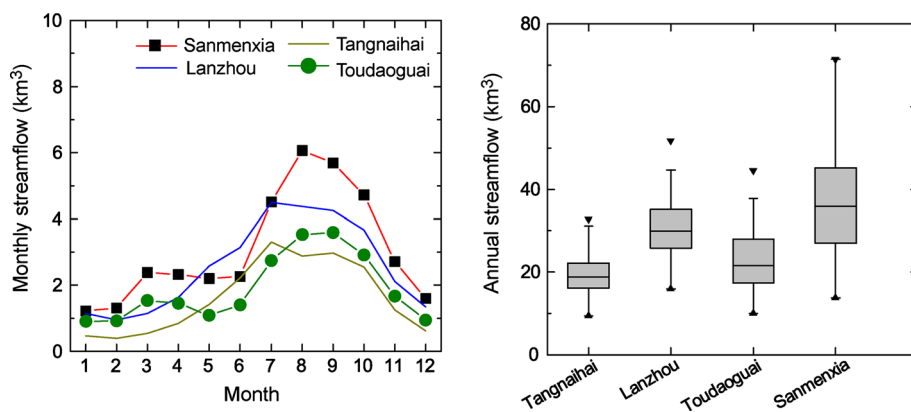
with an area of 34.4×10^4 km^2, and flows through the Loess Plateau. More than 30 tributaries with an area larger than 1000 km^2 in the middle reaches contribute an average annual water discharge of 14.4 km^3, but 1121.36 Mt sediment (more than 90 %, 1919–2011) to the Yellow River. The lower reaches is covered by a relative flat flood alluvial plain from Huayuankou to the river mouth with an area of 2.3×10^4 km^2 (Fig. 1). The river channel in the lower reaches has become a narrow corridor and "suspended" river segment since the dominant deposition process of sediment led to the channel bottom rising above the ground level.

The Yellow River basin lies in a temperate continental climate zone, and most parts of the basin belong to arid or semi-arid regions. In summer, the Southeast Asian summer monsoon brings majority of moisture to the lower reaches, and the Southwest Indian monsoon can reach the upper reaches. In winter, the upper and middle reaches of the Yellow River basin is mainly influenced by the west lies. Precipitation has large spatiotemporal variation within the whole river basin. Relative higher rainfall in the river source and lower reaches ranges from 520 to 640 mm and extreme dry region in the Mu US Desert has an average annual rainfall of approximately 280 mm (1951–2011). Streamflow is greatly characterized by the summer monsoon, which normally starts to influence the river basin in June and retreats in October and brings more than 60 % of annual total rainfall to the basin (Fig. 2). The average annual streamflow at Toudaoguai station is 22.6 km^3/a from 1919 to 2011, is lower than that of Lanzhou station (30.8 km^3/a). This is mainly due to the large area of irrigation in the segment (Wang et al. 2006).

2.2 Dataset

The monthly streamflow at four hydrological stations (Tangnaihai, Lanzhou, Toudaoguai, Sanmenxia) are applied to examine the changing trends and regime shifts along the mainstream of the Yellow River (Table 1). Long term measurement data are available at Shaanxian station since 1919, and starts from 1934 at Lanzhou station. By 1949, there have been several hydrological gauges starting

Table 1 List of hydrological stations used in this study

Stations	Latitude (N)	Longitude (E)	Period	Annual runoff (km³)	Drainage area (10^4 km²)
Tangnaihai	35°30′	100°09′	1919–2011	19.5	12.20
Lanzhou	36°04′	103°49′	1919–2011	30.8	22.26
Toudaoguai	40°16′	111°04′	1919–2011	22.6	36.79
Sanmenxia	34°49′	111°22′	1919–2011	37.0	68.84
Longmen	35°40′	110°33′	1919–2011	28.3	49.45
Tongguan	34°35′	110°18′	1952–2011	33.8	69.97
Huayuakou	34°54′	113°40′	1919–2011	41.0	72.35
Lijin	37°31′	118°18′	1952–2011	29.9	75.19

the measurements (e.g. Longmen, Tongguan Huayuankou and Lijin stations et al.) in the Yellow River basin. While most of the stations started to observe the runoff and water level since the 1950s when the hydrological gauges network was built. Streamflow time series at the stations without observations during 1919–1949 were filled up and published by the Yellow River Conservancy Committee (YRCC 1962). The monthly streamflow were derived from daily discharge from the Yellow River Bulletin (YRCC 1950–1989, 2006–2011), and parts of the data (1990–2005) were provided by the Yellow River Conservancy Committee. The average annual precipitation was provided by Mu et al. (2012), who interpolated rainfall data at numerous stations in the upstream of the Sanmenxia station. Except for the above mentioned four stations, long term streamflow data at Longmen, Tongguan, Huayuankou and Lijin stations along the mainstream of the Yellow River were also selected for trends and regime shift investigation to further validate the results. All these data used in the study have been checked to guarantee their consistency and quality.

3 Methodology

A non-parametric method, the Mann–Kendall test (Kendall 1975; Mann 1945) was to detect the temporal trends of streamflow. We applied the breaks for additive seasonal and trend (BFAST) model to decompose the regime shifts of streamflow series. The BFAST method is a phenological change detection model (Verbesselt et al. 2010a, b), and can be used for identifying the changing trends and seasonal fluctuation of time series. In addition, a simple multi-variables regression model was applied to reconstruct the natural streamflow in different sections along the Yellow River.

3.1 Mann–Kendall trend analysis

The Mann–Kendall (MK) trend test has been widely applied to detect trends of hydro-climatic variables (Burn and

Elnur 2002; Kundzewicz 2004; Mu et al. 2007; Zhao et al. 2010). The rank-based Mann–Kendall test is a non-parametric approach, which does not require the normal distribution of the data. A simplified description of the procedure for the MK test is given as follows:

Given a hydro-climatic time series $x_1, x_2, \ldots, x_n$, the MK statistics S can be calculated as:

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

where the sign function is:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & if \ x_j - x_i > 0 \\ 0 & if \ x_j - x_i = 0 \\ -1 & if \ x_j - x_i < 0 \end{cases} \tag{2}$$

It has been documented that the statistics S is approximately normally distributed when $n \geq 8$ with the mean $E(S) = 0$ and the variance:

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{n} t_k k(k-1)(2k+5)}{18} \tag{3}$$

where t_k is the number of tie of extent k. The standardized test statistic Z is estimated as:

$$Z = \begin{cases} \dfrac{S-1}{Var(S)} & if \ S > 0 \\ 0 & if \ S > 0 \\ \dfrac{S+1}{Var(S)} & if \ S < 0 \end{cases} \tag{4}$$

When the significance levels are set at 0.01, 0.05 and 0.1, $|Z_\alpha|$ are 2.58, 1.96 and 1.65, respectively. A positive or negative significant trend is detected if $|Z| > |Z_\alpha|$. However, the limitation of the MK test is that the serial correlation in time series data will affect the ability of the MK test to assess the significance of trends (Burn and Elnur 2002). Thus, we applied the trend-free pre-whitening (TFPW) procedure to remove the autocorrelation component of the time series which was proposed by Yue et al. (2002, 2003).

In the method, the Kendall slope can estimate the magnitude of the monotonic change by using the Theil-Sen approach (TSA) (Yue et al. 2002):

$$\psi = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad \forall i < j \quad 1 < i < j < n \quad (5)$$

where ψ is the median over all combination of record pairs for the whole data denoting the slope of the trend.

3.2 Hydrological time series decomposition

The BFAST method is a decomposition model to detect long term phonological change in climatic, hydrological and satellite image time series (Verbesselt et al. 2010a). The model integrates the iterative decomposition of time series into trend, seasonal and remainder components for examining changes within time series. Compared to other methods like wavelet transform and empirical mode decomposition, the BFAST method has the advantage to decompose the time series, not only for trends analysis, but also detecting the regime shift of seasonal data. A simple introduction of this model is given below with a more complete description presented by Verbesselt et al. (2010b). The general form of the model can be expressed as:

$$Y_t = T_t + S_t + \phi_t, \quad t = 1, \ldots, n \quad (6)$$

where Y_t is the observed data at time t, T_t and S_t are the trend and seasonal component, and the remainder component ϕ_t denotes the remaining variation in the data beyond that in the seasonal and trend components.

If m breakpoints $\tau_1, \ldots, \tau_m$ are examined in the trend component T_t, the segment-specific slopes and intercepts can be calculated on each segment. Then, the trend component can be approximated as:

$$T_t = \alpha_i + \beta_i t \quad (\tau_{i-1} < t \le \tau_i) \quad (7)$$

where $i = 1, \ldots, m$ and we define $\tau_0 = 0$ and $\tau_{m+1} = n$.

Similarly, the seasonal component is fixed between breakpoints, but can vary across breakpoints.

A harmonic model to parameterize the seasonal component has been proved to be more suitable and robust to detect periodical changes for seasonal time series (Verbesselt et al. 2010b). Give the seasonal breakpoints by $t_1 \ldots t_p$, and define $t_0 = 0$ and $t_p = n$, then the seasonal component S_t can be calculated as:

$$S_t = \sum_{k=1}^{K} \gamma_k \sin\left(\frac{2\pi kt}{f} + \delta_k\right) \quad (8)$$

where the unknown parameters are the segment-specific amplitude γ_k and phase δ_k and f is the known frequency (e.g. $f = 12$ monthly observations for streamflow).

It is better to examine whether breakpoints exist in the time series before fitting the piecewise linear models. The ordinary least squares residuals based moving sum (MOSUM) test, is selected to test for whether one or more breakpoints occur (Zeileis 2005). To determine the number and position of breakpoints, the BFAST model parameters are estimated by iterating through the following steps:

Step 1 If breakpoints occur in the trend component via the OLS-MOSUM test, the number and position of the trend breakpoints $\tau_1, \ldots, \tau_m$ are estimated through least squares from the seasonally adjusted data $Y_t - \hat{S}_t$. The trend component in each segment can be estimated by Eq. (7). Then, the trend coefficient α_i and β_i for different segments are calculated using robust regression based on M-estimation to account for potential outliers.

Step 2 If the breakpoints occur in the seasonal component via the OLS-MOSUM test, the number and position of the seasonal breakpoints $t_1, \ldots, t_p$ are estimated by least squares from the de-trended data $Y_t - \hat{T}_t$, where $t = 1, \ldots, n$. The seasonal component in each segment can be estimated via Eq. (8), and then the seasonal coefficients γ_k, δ_k are computed using a robust regression based on M-estimation.

3.3 Annual streamflow reconstruction

To better understand and quantify the effect of human activities (such as reservoirs and soil and water conservation measures) on streamflow in the river basin, reconstruction of natural streamflow records is necessary. There have been various methods developed for reconstructing streamflow data in regulated watersheds including hydrologic and statistic models (Peters and Prowse 2001; Ye et al. 2003). However, it is very difficult to reconstruct the natural streamflow records of the Yellow River by using hydrologic modelling due to its large stretch with complex terrain, limited basin information and the lack of available data on both reservoir design/operation. We therefore decided to use statistical methods to determine the relationship of upstream and downstream flows along with precipitation records for the pristine period (with limited human activities) to reconstruct the downstream flow data for the changing period. Due to insignificant change of streamflow at Tangnaihai station, we used its streamflow and region-averaged precipitation within different reaches to determine the regression model parameters associated with downstream water discharge. This simple approach enables us to estimate the impact of human activities on streamflow within the Yellow River basin.

4 Results

4.1 Temporal changes in annual streamflow

Figure 3 shows temporal changes in average annual streamflow at Tangnaihai, Lanzhou, Toudaoguai and Sanmenxia stations with smoothed trends. The long term variation of annual streamflow can be divided into three different periods according to their fluctuations shown in Fig. 3. Using Sanmenxia station as an example, a relative dry period can be clearly seen between 1919 and 1933. This is most strongly pronounced between 1928 and 1932 where the average annual streamflow was only 28.0 km^3/a, much lower than that of 1919–1960 (42.4 km^3/a). The streamflow showed insignificant changes from the mid-1930s to the end of 1960s when the Liujiaxia Reservoir was constructed. The third period from the late 1960s until now is widely considered as a changing period in many studies (Wang et al. 2007, 2013). During this period, the annual streamflow at Lanzhou, Toudaoguai and Sanmenxia stations all exhibit a significant decrease, particularly after the 1980s (Zhao et al. 2013b).
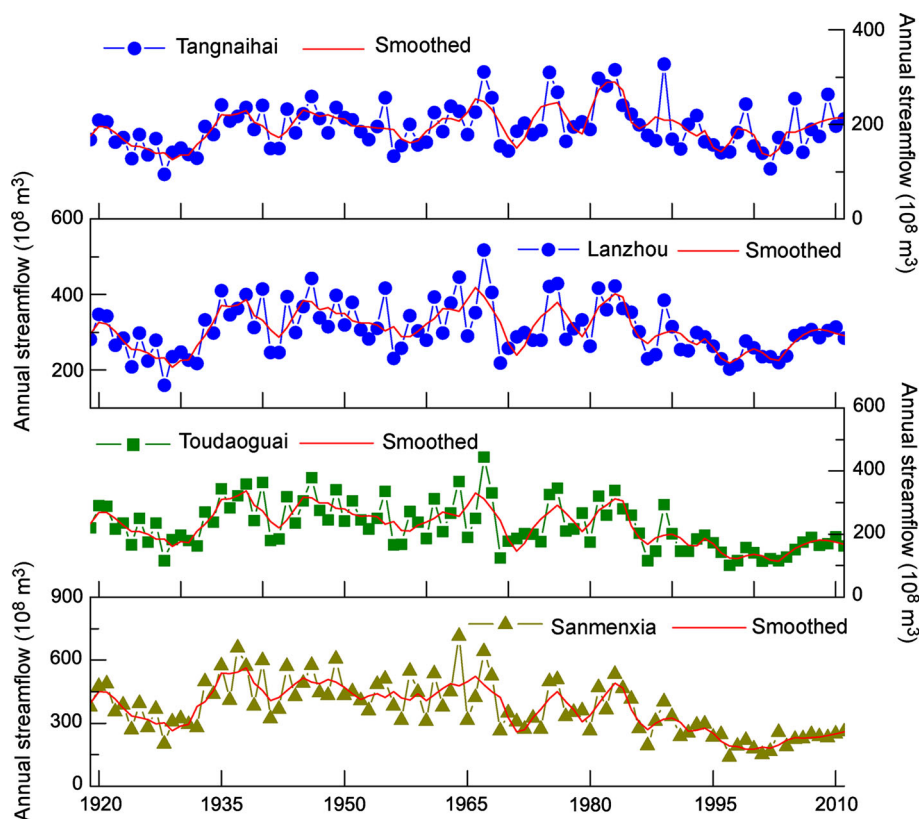
Table 2 shows the temporal changes of annual streamflow from 1919 to 2011 at eight stations along the mainstream of the Yellow River detected by the Mann–Kendall test (The discharge data is unavailable from 1919 to 1951 at Tongguan and Lijin station). Overall, the average annual streamflow exhibits significant decreasing trends (P < 0.05) in the middle-lower reaches of the Yellow River basin. As shown in Table 2, the average reduction rates are mostly lower than −0.2 km^3/a, particularly for the Lijin station with the rate of −0.732 km^3/a. Taking the Sanmenxia station as an example, the average annual streamflow at Sanmenxia station was 43.4 km^3/a in the 1950s, and decreased approximately to 50.2 % (21.8 km^3/a) after 2000 with Toudaoguai station also displaying a significant decreasing trend. The streamflow at Lanzhou station, in contrast, displayed only a gently decreasing trend, while an insignificant increase occurred in the streamflow at Tangnaihai station (Table 2). Importantly, these two stations are located in the headwater of the Yellow River, and so are subject to only limited influences from human activities. However, Lanzhou station have two large reservoirs in operation (Liujiaxia and Longyangxia Reservoirs) which may account for the insignificant decline in streamflow observed there.

4.2 Streamflow decomposition and regime changes detection

To identify possible regime shifts and clarify trigger mechanisms for such shifts in the Yellow River basin, we applied the BFAST method to the long term streamflow series at the stations over the period from 1919 to 2011.

Fig. 3 Trends analysis of annual streamflow at four stations in the Yellow River basin

**Table 2** Temporal changes of annual streamflow in the Yellow River basin

Stations	Z value	ψ Value (km³/a)
Tangnaihai	0.88	0.017
Lanzhou	−1.01	−0.102
Toudaoguai	−3.93	−0.177
Sanmenxia	−5.25	−0.243
Longmen	−5.34	−0.258
Tongguan	−5.76	−0.428
Huayuankou	−5.47	−0.301
Lijin	−6.21	−0.732

Figure 4 illustrates different components decomposed by the BFAST method for the monthly streamflow at Sanmenxia station. The original observed time series is shown in Fig. 4a. Figure 4b and c display the estimated seasonal and trend components respectively. The remainder noise is shown in Fig. 4d. From these data it can be clearly seen that a regime shift occurred in 1986 in the fitted seasonal component. This can be largely attributed to the construction of Longyangxia Reservoir (Wang et al. 2006). In contrast, the fitted trend component (Fig. 4c) demonstrates four different periods: 1919–1933, 1934–1969, 1970–1986 and 1987–2011. A significant decrease ($P < 0.001$) with

reduction rate of −0.1 km³/a was detected from 1919 to 1933. This can be attributed to the extreme drought in the late of 1920s. The streamflow showed a natural stage without abrupt changes from 1934 to 1969 according to the BFAST (Here we did not consider the dyke breach in 1938 in the downstream of Huayuankou station). An evident reduction was then found in 1969 due to the trapping effect of Liujiaxia Reservoir. In the fourth period (1987–2011), a significant decreasing trend ($P < 0.01$) was found with reduction rate of −0.03 km³/a.

The BFAST test is also applied to the monthly streamflow at other stations, and the results are presented as supplementary to save the space. It indicates that there are no significant changes in seasonal components of monthly streamflow in the upper reaches stations. Trend components exhibit significant changes ($P < 0.05$) due to climate changes. Monthly streamflow at Toudaoguai and Longmen stations show similar seasonal changes to that of Sanmenxia station. Both of them suggest significant reduction in 1969 and 1986 due to large reservoirs construction, while the trends components display different features because of distinct human activities. Seasonal components of monthly streamflow at Tongguan, Huayuankou and Lijin stations demonstrate significant changes ($P < 0.05$) in 1986, which is apparently led by the operation of Longyangxia Reservoir. While the trends components

Fig. 4 Monthly streamflow decomposition at Sanmenxia station
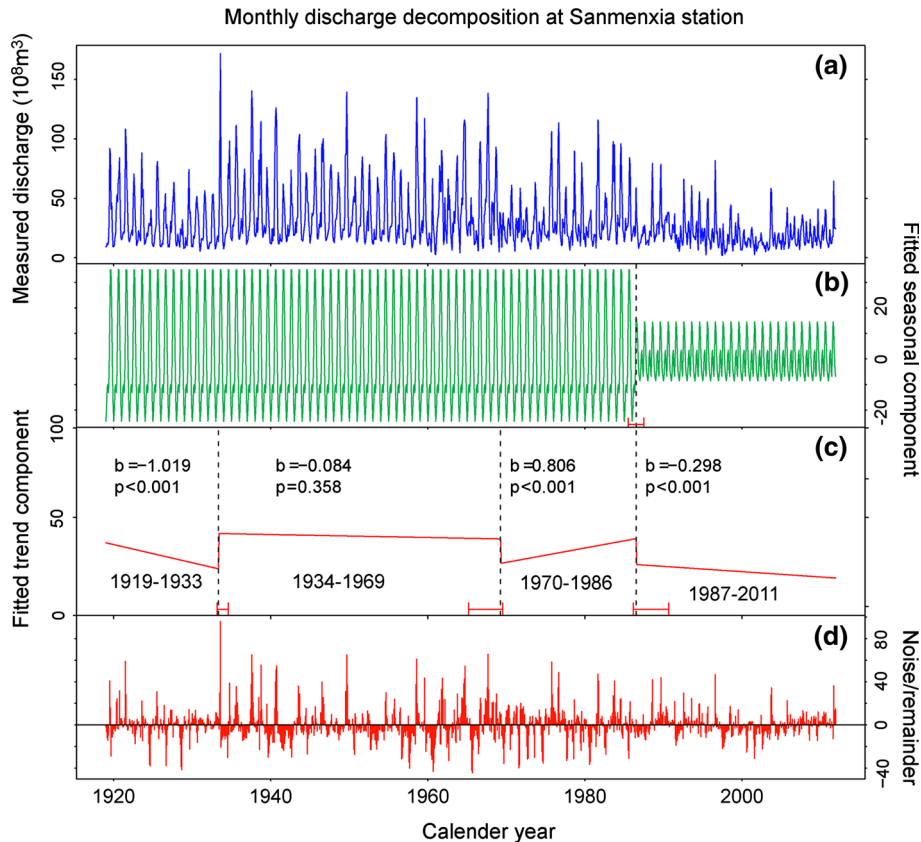
show heterogeneity at these stations since the hydrological processes are influenced by different human activities in each river sections.

4.3 Variation in hydrological regimes

The flow duration curve (FDC) is applied to the monthly streamflow to further quantify the temporal variation of the hydrological regimes in the Yellow River basin. The FDC shows the percent time a specific discharge is equaled or exceeded. The FDC is considered as a simple, yet comprehensive approach to streamflow analysis that gives a graphical view of the overall variability associated with streamflow over a period of time.

According to the BFAST analysis, the hydrological time series were divided into two periods: before and after 1986. Figure 5 shows the FDCs for monthly streamflow at Lanzhou, Toudaoguai and Sanmenxia stations during these two periods. Overall, the results indicated that there was a decline in the magnitude of the monthly streamflow at all stations. This decline in most evident for the high flows especially those that occur less frequently than 30 % of the time. Rather than exhibiting a diverse range of flows including very large flows as was the case from 1919 to 1985, the river now tends to be characterized by a more uniform

runoff regime as a result of anthropogenic activities. However, the precise nature of the changing trends is not always the same among the three stations. For example, at Lanzhou station, the lower flow values (to the right of the curve) between 1987 and 2011 actually exceed those in the earlier time period whilst at the other two stations (Toudaoguai and Sanmenxia) low flow values in both time periods are nearly the same.

4.4 Streamflow reconstruction to detect effects of human activities

A simple multi-variants regression model was established according to the relationship among streamflow values at Tangnaihai, basin-averaged precipitation and downstream water discharge from 1919 to 1968. Figure 6 and Table 3 show the simulation results for model validation at Lanzhou, Toudaoguai and Sanmenxia stations. The results illustrate a good correlation between measured and simulated annual streamflow at three stations (Table 3). This is also demonstrated by the relatively high correlation coefficient ($R^2 > 0.85$) and Nash-Suttcliffe efficiency values (NS > 0.75).

Using this regression model, we then reconstructed annual streamflow over the period from 1969 to 2011 at three
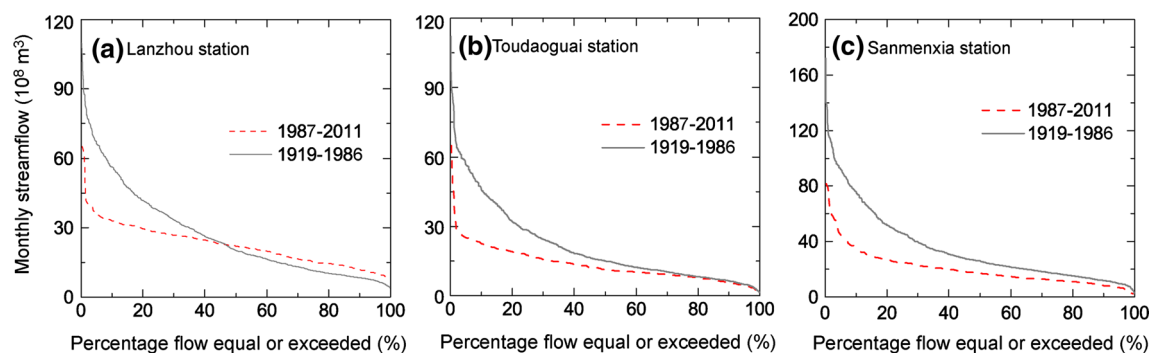
Fig. 5 FDC analysis for the monthly streamflow at three stations along the Yellow River
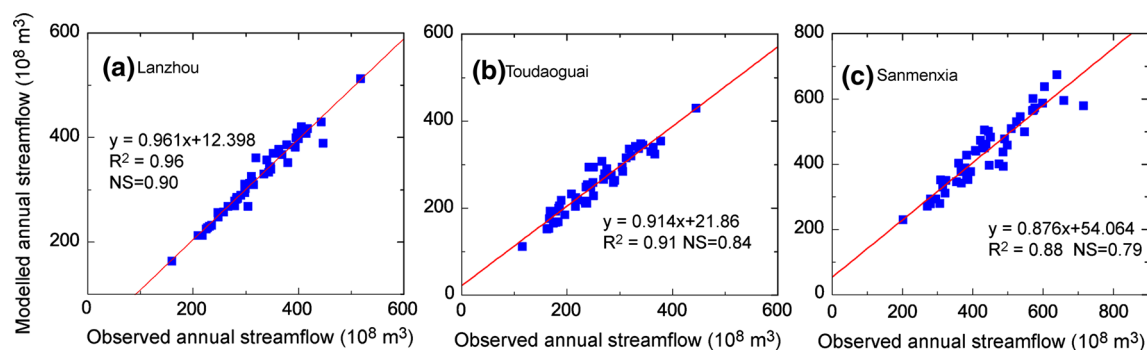

Fig. 6 Annual streamflow reconstructions for model validation at three stations

Table 3 Multi-variables regression model for streamflow reconstruction

Stations	Regression model*	Average precipitation (P/mm)	Observed streamflow (10^8m^3/a)	Simulated streamflow (10^8m^3/a)
Lanzhou	$Q = 1.540Q_{tang} + 0.09P - 12.9$	412.9	321.3	319.5
Toudaoguai	$Q = 1.342Q_{tang} + 0.16P - 58.7$	398.0	255.5	262.2
Sanmenxia	$Q = 1.617Q_{tang} + 0.51P - 110.6$	460.2	435.7	434.0

* Q denotes reconstructed annual streamflow, and P denotes the regional average annual precipitation
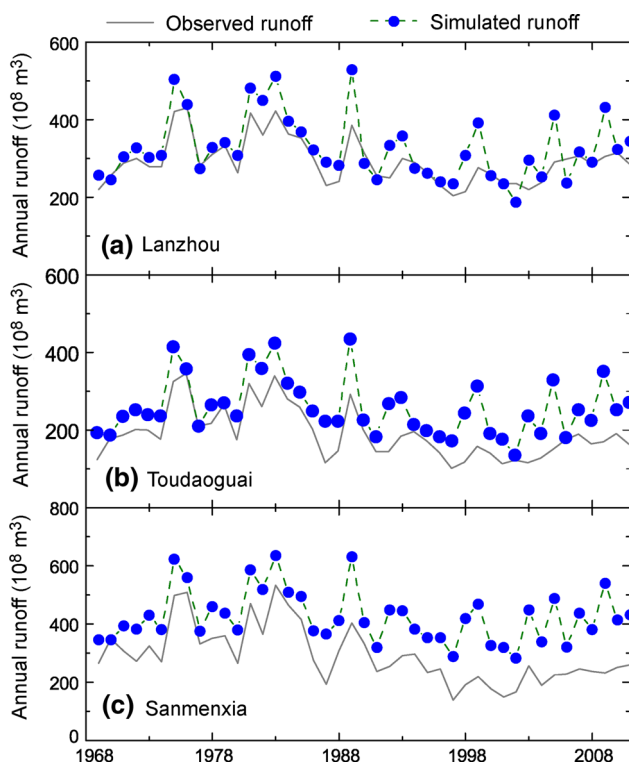
Fig. 7 Reconstructed streamflow at Lanzhou, Toudaoguai and Sanmenxia stations

stations along the Yellow River. Figure 7 shows the hydrographs of the observed and modeled discharges at these stations. For Lanzhou station, reconstructed streamflow is generally consistent with the observations except for a few discrepancies where simulated values were much higher than those observed. These results are consistent with the annual water balance of the large reservoirs (and the records of stored and released water from these reservoirs: Liujiaxia and Longyangxia Reservoirs) in the river upstream of Lanzhou station (YRCC 1998–2011).

At Toudaoguai station (Fig. 7b), the reconstructed natural average annual streamflow is 26.0 km^3/a, which is somewhat higher than the measured average of 19.4 km^3/a. Here, the difference is largely attributable to agricultural irrigation in the section between Lanzhou and Toudaoguai stations. There are two irrigation districts with a total area

of 1.09 million ha, that extracted approximately 9.1 km^3/a of water from this portion of the river between 1997 and 2006 (Yao et al. 2011). This is consistent with the difference between reconstructed (21.7 km^3/a) and observed streamflow (13.2 km^3/a) at Toudaoguai station.

As shown in Fig. 7c, there is an obvious difference between reconstructed and observed annual streamflow at Sanmenxia station. The average annual reconstructed streamflow was 39.4 km^3/a, while the observed streamflow is only 21.9 km^3/a between 1997 and 2011. However, it is clear from the observed streamflow data that flow, as recorded at Sanmenxia station, began a significant and steady decline from the 1980s. It is this decline that has caused a difference between observed and reconstructed streamflow. About half of this decline (8.8 km^3/a) is attributed to a reduction of incoming water from the upper reaches, while the remainder of the decline is likely the result of the implementation of a series of soil and water conservation measures across the Loess Plateau, but mostly impacting on the downstream stations only (Zhao et al. 2013b). As reported by Yao et al. (2011), various soil and water conservation measures reduced streamflow by approximately 7.5 km^3/a water elsewhere on the Loess Plateau. If a similar magnitude of flow reduction occurred here as a result of these measures it would account for the remainder of the observe reduction in streamflow at Sanmenxia station.

5 Discussion

5.1 Impacts of climate changes on streamflow

Most of the temporal variations in streamflow at all of the observed stations in the early part of the hydrologic record (1919–1960s) are caused by climatic variability with only limited human activities affecting the streamflow over this period (Mu et al. 2012). For example, the extreme low runoff values during 1928 and 1932 were attributed to severe drought in the Yellow River basin. After the 1960s, however, a significant increase in human activity has been reported by other studies in the Yellow River (Fu et al. 2007; Piao et al. 2010; Zhao et al. 2014) (Fig. 8).

Fig. 8 Changing trends of annual precipitation and temperature in the Yellow River basin
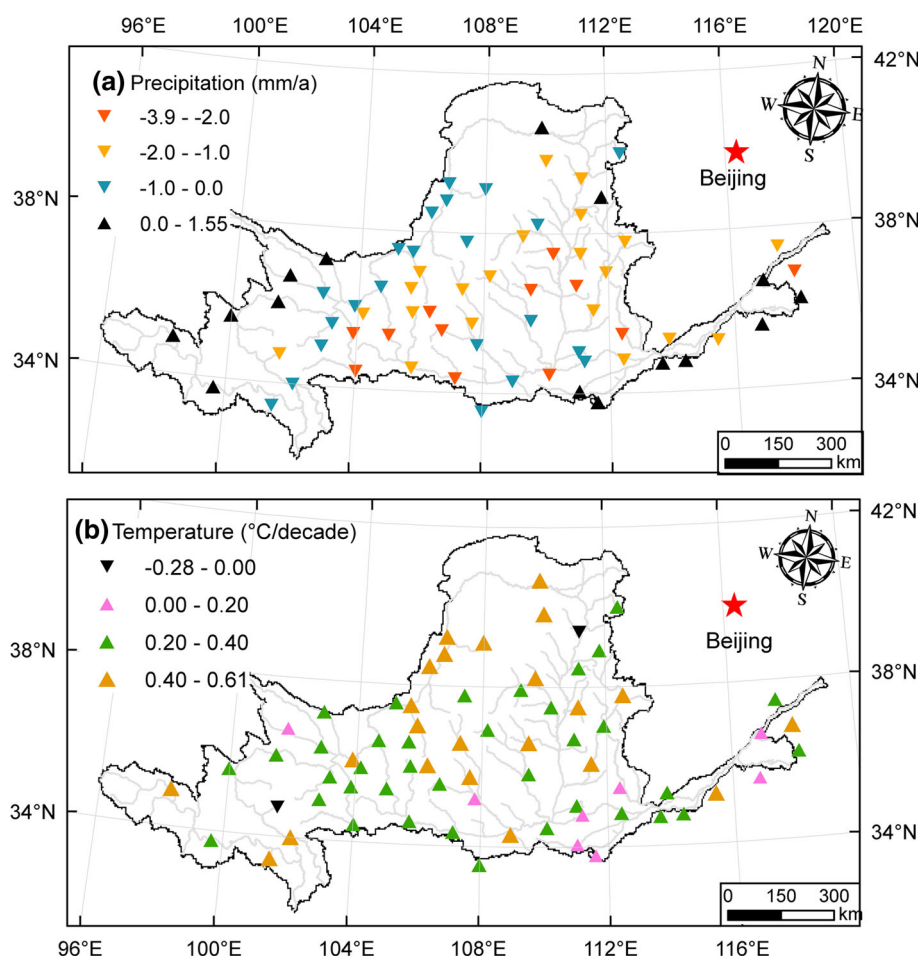
To better understand the climatic variables changes and their effects on streamflow, we analyzed the spatial variation of annual precipitation and temperature at 70 stations in the whole river basin from 1950s to 2011. The least-squares slopes for the average annual precipitation displayed significant decrease in the middle reaches of the Yellow River basin, increasing precipitation were only found at some stations in the upper and lower reaches. The relative higher decrease (< − 1.5 mm/a) occurred at the stations within Shaanxi, Shanxi and Gansu Provinces (between Lanzhou and Sanmenxia stations), and the most significant increase (>1.0 mm/a) were found at stations in Qinghai Province (upstream of Lanzhou station). Consistent with previous studies, Zhao et al. (2013b) and Xin et al. (2011) addressed an average decrease of −1.27 and −0.97 mm/a in annual precipitation on the Loess Plateau region. Temperature displayed homogenously upward trends within the whole basin except for two stations. The increasing rates range from 0.01 to 0.61 °C per decade and nearly 80 % of the stations have relative high increasing rates above 0.02 °C/year. Similar results were found by Yang et al. (2004). An average increase of 0.02 °C/a was found in annual temperature, only a little higher than the global average increasing rate. Zhao et al. (2013b) reported that the Loess Plateau experienced warmer period within the past six decades as a result of increasing annual temperature ranging from 0.028 to 0.057 °C/a. It was reported that rising temperature led to more snowmelt from the permanent glaciers, and was offset to runoff reduction in the headwater are (Zheng et al. 2007). Zhao et al. (2014) addressed that decreasing precipitation and increasing temperature would increase more surface water and soil water evaporated, and contributed a range of 6.4–56.2 % of runoff reduction in the middle reaches of the Yellow River.

In addition, temporal changes of precipitation indicated a relative dry period around 1987, and the drought was reported as a result of strong ENSO event (Wang et al. 2007; Liu and Yang 2010). However, our results suggested that water trapping by the Longyangxia Reservoir should be largely responsible for the regime shift of streamflow in 1986 in the downstream reaches. The Longyangxia reservoir is the largest man-made reservoir with total storage of 24.7 km³ and 178 m high dam wall in the Yellow River

basin. An average of 16.8 km^3/a of water was stored in the reservoir between 1986 and 2010 (YRCC 1998–2011).

5.2 Anthropogenic impacts on streamflow

Numerous studies addressed that human activities, including agricultural irrigation, reservoir construction, the implementation of soil and water conservation measures and domestic utilization, tend to become a dominant factor for streamflow reduction after 1960s (Wang et al. 2007; Zhang et al. 2009; Zhao et al. 2013a; Zhao et al. 2014). Zhang et al. (2008) reported that land use and land cover changes accounted for more than 50 % of the reduction in mean annual runoff in most studied catchments in the middle reaches. They concluded that various soil and water conservation (including terracing, afforestation and check-dam construction) with associated water extraction appeared to be the main cause of the reduced streamflow. Guo et al. (2014) and Liang et al. (2013) investigated the impacts of climate changes and human activities on runoff variation in the Kuye River and Wei River basin, respectively. The results indicated that human activities contributed more than 60 % of variation in annual runoff changes, and their impacts are becoming greater.

The BFAST analysis indicated that regime shifts mostly occurred during the time when large reservoirs were built in the Yellow River basin. Abrupt decline in annual streamflow at the stations suggested substantial trapping effects of major reservoirs along the Yellow River. Prominent examples are Longyangxia reservoir with storage capacity of 27.6 km^3 (1986) and Liujiaxia reservoirs with storage capacity of 5.7 km^3 (1969), which strongly influenced the hydrological regime in the Yellow River basin. On the other hand, the magnitude and variability of streamflow at these stations have been altered by large reservoirs. This can be clearly seen from flow duration curve at Lanzhou station. Large reservoirs capture high flows during the wet season decreasing these flow volumes and releasing water during the dry season thereby increasing low flow volumes. Furthermore, more than 3150 registered reservoirs in the whole basin have been built for electricity, agricultural irrigation, flood control. These reservoirs not only redistribute the seasonal water discharge within any given year, but also adjust the inter-annual distribution of water balance in regional scale (He et al. 2013).

In the middle reaches, a series of soil and water conservation measures, including both engineering works (e.g. terraces and dams) and biological measures (e.g. afforestation and grassing), have been implemented since the late 1950s. Recent statistics indicate that an area of approximately 0.2 million km^2 is covered by various soil and water conservation measures, including more than 1800

key hydraulic projects and 110,000 check dams (Yao et al. 2011). Zhao et al. (2014) addressed that an average of 7.45 km^3/a of streamflow reduction can be attributed to soil and water conservation between 2000 and 2011. This inferred that large scale of soil conservation measures on the Loess Plateau resulted in significant decrease in streamflow at mid-lower stations.

Additionally, increasing water demands associated with the rapid development of the regional economy and the expansion of irrigated land have led to the over-exploitation of both river runoff and groundwater (He et al. 2013). According the Yellow River Water Resources Bulletin (YRCC 1998–2011), average annual withdraw from the Yellow River is about 48.9 km^3/a, in which surface water withdraw reached up to 35.7 km^3/a (73.0 %), and ground water withdraw takes up 27.0 %. Water consumption by agricultural irrigation is approximately 22.9 km^3/a, accounting for nearly 80.0 % of whole water consumption, and the industry, urban and rural domestic sectors consume the remaining 20 %.

6 Conclusion

This study applied several statistical methods to investigate changing trends and regime shifts in streamflow in the Yellow River basin using continuous long flow series. The results demonstrated that the streamflow had significant decreasing trends (P < 0.05) in the mid-lower reaches of the Yellow River. The BFAST method decomposed monthly streamflow into three components: trend, seasonal and noise components. Three abrupt points of change (1933, 1968 and 1986) were observed in the trend component, while the seasonal component indicated that a hydrological regime shift occurred in 1986. The abrupt changes in the trends component were attributed to both climate change and reservoirs construction. FDC analysis indicated a decline in high discharge at all the stations with low flows generally remaining unchanged. However, the low flow increased between 1987 and 2011 (relative to earlier period) at Lanzhou station. The regime shift observed in the seasonal data (in 1986) is attributed to the trapping effects from the Longyangxia reservoir while agricultural irrigation is largely responsible for the significant decline in water discharge between Lanzhou and Toudaoguai stations. In contrast, both decreased incoming water from upper reaches and the implementation of soil and water conservation measures led to the reduction of streamflow mid-lower reaches stations. The findings provide an example of hydrologic non-stationarity and will be valuable for effective promotion of climate adaptation and water resource management initiatives.

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