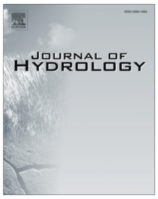
Journal of Hydrology 519 (2014) 387–398

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



# Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin, China

Guangju Zhao [a,b,c], Peng Tian [d], Xingmin Mu [a,b,*], Juying Jiao [a,b], Fei Wang [a,b], Peng Gao [a,b]

[a] *Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling 712100, Shaanxi Province, China*
[b] *Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, 26 Xinong Road, Yangling 712100, Shaanxi Province, China*
[c] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[d] *College of Resources and Environment, Northwest A&F University, Yangling 712100, Shaanxi Province, China*

ARTICLE INFO

*Article history:*
Received 8 August 2012
Received in revised form 1 September 2013
Accepted 10 July 2014
Available online 24 July 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Harald Kunstmann, Associate Editor

*Keywords:*
Streamflow
Climate variability
Human activities
Middle reaches of the Yellow River basin

SUMMARY

The middle reaches of the Yellow River basin (MRYRB) contribute significantly to the total streamflow and sediment discharge of the Yellow River. Significant changes in streamflow have been detected; these changes result in part from large number of soil and water conservation measures implemented over the past six decades in this area. This study investigates streamflow variations and evaluates the impacts of climate variability and human activity on the mean annual flow in the MRYRB. The non-parametric Mann–Kendall test and Pettitt's test are applied to characterize the trends and abrupt changes of hydro-climatic variables in the MRYRB. The analysis was performed on streamflow data taken over the period from the 1950s to 2010 at 18 hydrological stations and on precipitation, temperature and potential evapotranspiration (PET) data from 43 climate stations. We find that 16 of these stations recorded significant decreases in annual streamflow, with reduction rates ranging from 0.10 mm/yr to 1.61 mm/yr over the study period. Precipitation at all of the stations also had negative trends, with changes ranging from −4.7 mm/yr to −0.19 mm/yr. Temperature increased significantly at most stations, while PET showed a mixed of upward and downward trend. Abrupt changes in streamflow at mainstream stations occurred when large reservoirs were built, while breakpoints of streamflow at tributary stations were mainly driven by the implementation of soil and water conservation measures. We used both Budyko's curve (a simple water balance model) and linear regression to evaluate the potential impacts of climate variability and human activities on mean annual streamflow. Climate variability has a greater effect on the streamflow reduction in the Beiluo River and Yan River, while human activities accounted for more of the streamflow changes in other tributaries, especially in the northern catchments. In general, human activities, including soil and water conservation projects, the operation of dams and reservoirs, and water consumption, are found to be the dominant factors responsible for the significant decline in the annual streamflow in the MRYRB over the last six decades.

## 1. Introduction

Observational evidence in most regions throughout the world indicates that hydrological cycles are being affected by climate change and human activities (Huntington, 2006). Brutsaert and Parlange (1998) showed that climate change is likely to give rise to warmer atmospheric temperatures and accelerated hydrological cycles globally. Climate variability has also led to changes in precipitation patterns throughout the world, while human activities have altered the spatial–temporal distribution of water resources (Jiang et al., 2010; Milly et al., 2005; Wang et al., 2013a). Because of the importance of avoiding and minimizing the economic loss of frequently occurring floods and severe drought disasters, investigation into the effects of climate change and human activities on streamflow has become an important scientific issue. Understanding these issues is also crucial if water resources management systems are to achieve sustainability.

As a results of the recent strong warming and significant regional precipitation variation as well as the intensification of human activities, such as agricultural irrigation, drinking water extraction, hydraulic projects and soil and water conservation measures, considerable attention has been paid to assessing the impacts of

---

* Corresponding author at: Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling 712100, Shaanxi Province, China.
*E-mail address:* xmmu@ms.iswc.ac.cn (X. Mu).

http://dx.doi.org/10.1016/j.jhydrol.2014.07.014
0022-1694/© 2014 Elsevier B.V. All rights reserved.

climate variability and human-induced land use changes on water resources (Hang et al., 2011; Ma et al., 2008; Milly et al., 2008; Mu et al., 2007; Tao et al., 2011; Zhai et al., 2010). Assessments of the impacts of climate change on river streamflow are usually performed using hydrological models or by analyzing the variation of hydro-climatic variables. Hydrological models, such as the Soil and Water Assessment Tool (SWAT), the Variable Infiltration Capacity (VIC) model, the Xinanjiang model, the HBV model and the SLURP (Semi-distributed Land Use-based Runoff Processes) model, have been commonly applied to assess the impacts of climate change and human activities such as land use changes on streamflow under various scenarios (Choi et al., 2009; Fohrer et al., 2005). Although hydrological models can provide accurate results, a large number of parameters cannot be obtained from field measurements. Additionally, hydrological modeling requires a large number of input data sets and is often seen as time consuming for model calibration and validation Due to these limitations, new attempts assess the effect of climate variability and human activities have recently been made. In recent years, both the hydrological sensitivity method and a simple water balance model known as Budyko's curve have been widely applied to separate the effects of climate change and human activities on streamflow (Dooge et al., 1999; Milly and Dunne, 2002; Wang et al., 2013b; Zhang et al., 2008).

The Yellow River basin has served as the "cradle of Chinese civilization" over the past millennia and continues to play a critical role in the development of China (Zhao et al., 2013). The Yellow River is a major source of freshwater for the approximately 107 million people who live within the river basin. However, streamflow in the Yellow River basin displays evident decline, particularly in the recent ten years after the "Grain for Green" project launched in 1999. The middle reaches of the Yellow River basin (MRYRB) between Toudaoguai and Huayuankou stations are an important section that contributes significantly to the total streamflow and sediment discharge of the Yellow River. In the last six decades, numerous soil and water conservation measures have been implemented in the MRYRB, including the construction of check-dams, reservoirs and terraces, returning croplands to grasslands and reforestation. Significant reductions in both streamflow and sediment flux in this region have been detected at rates of decrease up to 60% and 80%, respectively (Zhao et al., 2012).

Thus, many studies have investigated the variability of MRYRB streamflow in response to climate changes and human activities to support future water resource management and to strategize approaches to maintaining the aquatic ecosystems of the rivers (Liu and Zheng, 2004; Wang et al., 2013a; Zhao et al., 2012). Piao et al. (2010) showed that climate was the dominant factor controlling runoff; increased withdrawals can explain approximately 35% of the declining runoff observed at the Huayuankou station in the lower reaches of Yellow River over the last half-century. Wang et al. (2006) found that human activities referring to the construction of dams and reservoirs and increasing water consumption were responsible for the decreased streamflow in the Yellow River. Gao et al. (2011) assessed the changes in streamflow between the Toudaoguai and Huayuankou stations, and found that a decrease in precipitation was responsible for 28% of the decrease in streamflow from 1986 to 2008 in the MRYRB, while the remaining 72% was due to human activities. However, most of these studies primarily analyzed streamflow variations by using the mainstream gauging stations (Liu and Cui, 2011; Lu, 2004). The changing streamflow properties and their connection to natural and anthropogenic impacts in the MRYRB have not been extensively analyzed, especially after the "Grain for Green" project launched by Chinese government in 1999. Furthermore, the scientific community still disagrees on how climate change and human activities affect the regional water resources in the Yellow River basin. The objectives of this study, therefore, are (1) to assess the spatial and temporal variation of streamflow in the MRYRB and (2) to quantify the effects of climate variability and human activities on streamflow there.

## 2. Study area and data

### 2.1. Geographic setting

The middle reaches of the Yellow River are located between Toudaoguai and Huayuankou hydrological stations, a section of the mainstream river 1234 km in length (Fig. 1). The drainage area covers six provinces (Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi and Henan) and an area of 362,000 km$^2$. There are more than 30 large tributaries (catchment areas larger than 1000 km$^2$) along the middle reaches; these tributaries contribute nearly 44% of the total discharge of the Yellow River. The middle reaches of the Yellow River flow through the Loess Plateau, where severe erosion occurs. The large amounts of mud and sand discharged into the river here accounting for 88% of the total sediment in the Yellow River and make it the most sediment-laden river in the world (Zhao et al., 2012). The basin lies in a semi-arid climate zone that is dominated by the Southeast Asian summer monsoon. The spatial and temporal distribution of the precipitation within the middle reaches of the Yellow River basin is uneven. Average annual precipitation ranges from 320 mm in the north to 836 mm in the south, and the potential evapotranspiration (PET) ranges from 810 to 1260 mm. The rainfall in the rainy season, from May to October, accounts for more than 70% of the total annual rainfall.

The sustainable development of the region's society and economy over the past six decades has been restricted by changes that occurred in the Yellow River (Song et al., 2007; Zhao et al., 2013). As shown in Fig. 2, the annual runoff of the Yellow River has decreased significantly since the 1980s due to climate change and intensive human activities. For example, at Huayuankou station, the annual runoff was 23.56 km$^3$/yr in 2000–2010, which was only 51.43% of that observed in 1950–1960 (Fig. 2). To meet the demands of the large regional population, agriculture and industry, the average annual water withdrawal from the river was approximately 47.80 km$^3$ over the period from 2000 to 2009 (YRCC, 2013). The amount of water used to fill reservoirs increased rapidly over the past 60 years and has reached up to more than 30 km$^3$/yr in recent years. Three large reservoirs with total storage capacity of 43.05 km$^3$, Longyangxia, Liujiaxia and Xiaolangdi (shown in Fig. 2), have greatly reduced the annual streamflow due to their extraordinary trapping effects (Yao et al., 2011). In addition, large-scale soil and water conservation measures have been applied to control severe soil erosion in the upper-middle reaches of the Yellow River basin since the 1950s and particularly after the 1980s. By 2006, various soil and water conservation measures had been applied to approximately $1.03 \times 10^5$ km$^2$ of the catchment; these measures have significantly altered the hydrological regime of the river. Thus, there is a great need to quantitatively assess the changes in water resources and the potential effects of climate changes and anthropogenic measures in the Yellow River basin over the past decades.

### 2.2. Data

The hydrological data include monthly observed streamflow at gauging stations located in the mainstream and tributaries (Table 1) throughout the study area (Fig. 1). Stations with data records less than 54 years in length were excluded from this analysis. Hydrological data at 4 mainstream stations and 14 stations in the tributaries from the 1950s to 2010 were provided by Yellow

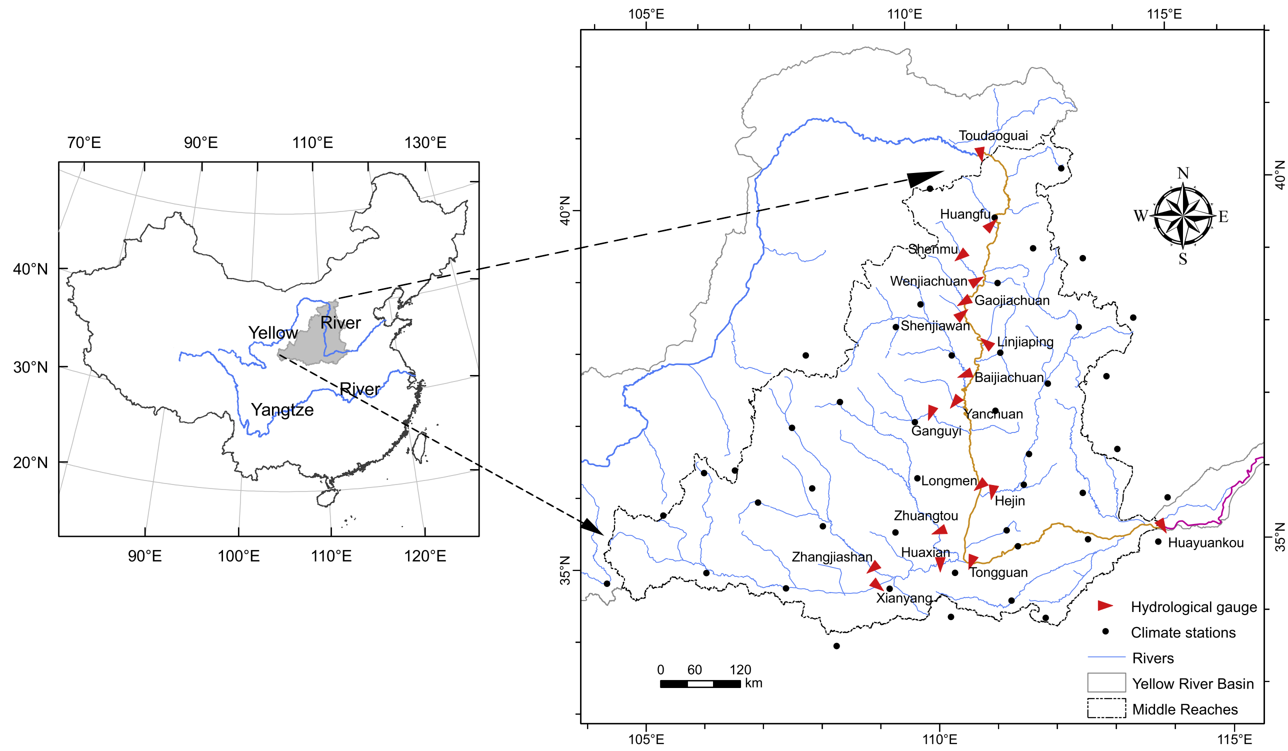


**Fig. 1.** Location of the study area and hydro-meteorological stations.

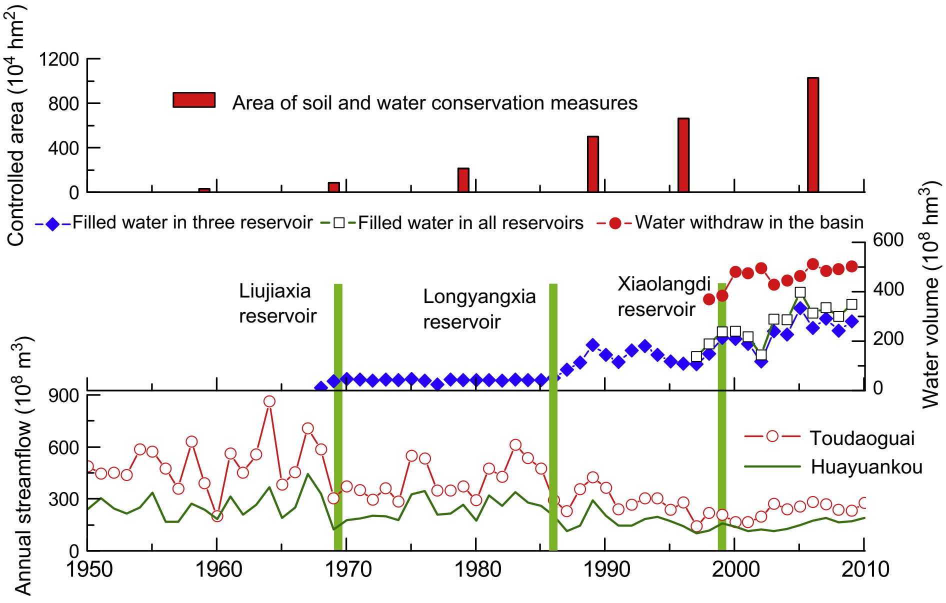


**Fig. 2.** Decrease in annual streamflow associated with various anthropogenic measures.

River Conservancy Commission (YRCC) and are shown in Table 1. The homogeneity and reliability of the data were checked and firmly controlled by the YRCC before the data were released.

Daily meteorological data were obtained from 43 stations in and around the middle reaches of the Yellow River basin from the 1950s to 2010. Six climate variables (precipitation, temperature, relative humidity, sunshine duration, actual vapor pressure and wind speed) were provided by the National Climate Centre of China Meteorological Administration (CMA). Potential evapotranspiration was calculated using the Penman–Monteith equation following the procedure outlined in FAO-56 (Allen et al., 1998).

## 3. Methodology

### 3.1. Trend detection

This study applies the non-parametric Mann–Kendall test to detect trends in the hydro-climatic time series (Kendall, 1975; Mann, 1945). The method has been commonly used to examine trends in hydro-meteorological time series such as streamflow, precipitation and temperature in various regions throughout the world (Mu et al., 2007; Yue and Wang, 2004; Zhao et al., 2010). For the given time series $X(x_1, x_2, \ldots, x_n)$, the statistic $S$ is defined as:

**Table 1**
List of hydrological stations used in this study.

| Stations | Location | Period | Average rainfall (mm/yr) | Average runoff (km$^3$/yr) | Drainage area (10$^4$ km$^2$) |
|---|---|---|---|---|---|
| Toudaoguai | | 1950–2010 | | 21.36 | 36.79 |
| Longmen | Mainstream | 1950–2010 | | 26.36 | 49.76 |
| Tongguan | | 1950–2010 | | 34.31 | 68.22 |
| Huayuankou | | 1950–2010 | | 37.69 | 73.00 |
| Xianyang | Wei River | 1950–2010 | 540.1 | 4.07 | 4.68 |
| Huaxian | Wei River | 1950–2010 | 587.3 | 6.80 | 10.65 |
| Zhangjiashan | Jing River | 1950–2010 | 510.8 | 1.61 | 4.32 |
| Zhuangtou | Beiluo River | 1950–2010 | 536.7 | 0.70 | 2.56 |
| Shenmu | Kuye River | 1956–2010 | 429.2 | 0.43 | 0.73 |
| Baijiachuan | Wuding River | 1953–2010 | 409.5 | 1.14 | 2.97 |
| Ganguyi | Yan River | 1952–2010 | 495.6 | 0.20 | 0.59 |
| Gaojiachuan | Tuwei River | 1956–2010 | 406.4 | 0.33 | 0.33 |
| Wenjiachuan | Kuye River | 1954–2010 | 429.2 | 0.54 | 0.86 |
| Yanchuan | Qingjian River | 1954–2010 | 514.7 | 0.14 | 0.36 |
| Hejin | Fen River | 1950–2010 | 504.7 | 10.06 | 3.87 |
| Shenjiawan | Jialu River | 1957–2010 | 395.4 | 0.59 | 0.11 |
| Huangfu | Huangfu River | 1954–2010 | 389.5 | 1.34 | 0.32 |
| Linjiaping | Qiushui River | 1954–2010 | 498.5 | 0.70 | 0.17 |

$$S = \sum_{i=2}^{n}\sum_{j=1}^{i-1}\operatorname{sgn}(x_i - x_j) \text{ where } \operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & x_j > x_i \\ 0 & x_j = x_i \\ -1 & x_j < x_i \end{cases} \tag{1}$$

Mann (1945) and Kendall (1975) addressed that the statistic $S$ is approximately normally distributed. Its variance is calculated as:

$$var(S) = \frac{n(n-1)(2n+5)}{18} \tag{2}$$

The standardized statistic is:

$$Z = \begin{cases} (S-1)/\sqrt{var(S)} & S > 0 \\ 0 & S = 0 \\ (S+1)/\sqrt{var(S)} & S < 0 \end{cases} \tag{3}$$

A positive values of $Z$ indicates an upward trend, while a negative $Z$ indicates a downward trend. The null hypothesis of no trend is rejected if $|Z| > 1.96$ at 5% significance level. The effects of the serial correlation on the MK test were eliminated by using the Trend-Free pre-whitening procedure (Yue and Wang, 2004). According to the calculated autocorrelation coefficients at lag-1 for each annual time series, the hydro-climatic series are time-independent.

### 3.2. Breakpoint analysis

The Pettitt's test (Pettitt, 1979) is a non-parametric method widely applied to detect the abrupt changes of hydro-climatic variables (Gao et al., 2011). For a given time series $X(x_1, x_2, \ldots, x_n)$, divided into two samples $x_1, x_2, \ldots, x_t$ and $x_{t+1}, x_{t+2}, \ldots, x_n$, the Pettitt's test uses a version of the Mann–Whitney statistic $U_{t,n}$ calculated as:

$$U_{t,n} = \sum_{i=1}^{t}\sum_{j=1}^{n}\operatorname{sgn}(x_t - x_j) \quad \text{if} \quad t = 2, \ldots, n \tag{4}$$

where the sgn() function is the same as mentioned in the MK test. The breakpoint is defined to be where $|U_{t,n}|$ reaches its maximum value, $K_n$:

$$K_n = Max|U_{t,n}| \tag{5}$$

The significance level associated with $K_n$ is determined approximately by:

$$P = \exp\left(\frac{-6(K_n)^2}{n^3 + n^2}\right) \tag{6}$$

### 3.3. Separating the impact of climate change and human activity on streamflow

To quantitatively analyze the effects of climate variability and human activities on streamflow, both the water balance based Budyko model (1974) and a simple linear regression method were applied to the hydro-climatic series during the two periods identified by the Pettitt's test.

The water balance in a catchment scale can be quantified as:

$$Q = P - E_a - \Delta S \tag{7}$$

where $P$ is the precipitation (mm), $E_a$ is the actual evapotranspiration (mm), $Q$ is the runoff depth (mm), and $\Delta S$ is the changes in the catchment water storage (mm), which is assumed to be zero over a long period. Following an assumption similar to that made by Budyko (1974), the actual evapotranspiration can be estimated as (Fu, 1981):

$$\frac{E}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^m\right]^{1/m} \tag{8}$$

where $m$ is a model parameter estimated based on the vegetation type, hydraulic property, and topography (Fu, 1996). A detailed description of the values is available in Zhang et al. (2001).

A change in the observed mean annual streamflow $\Delta\overline{Q}_{total}$ may result from climate variability $\Delta\overline{Q}_{clima}$ or from human activities $\Delta\overline{Q}_{human}$.

$$\Delta\overline{Q}_{total} = \Delta\overline{Q}_{clima} + \Delta\overline{Q}_{human} \tag{9}$$

To assess the effects of climate change and human activities, we divided the streamflow records for each catchment that has undergone significant changes in qualities such as land use, dams, afforestation or deforestation into two periods. The first period represents the baseline, when no significant human activities occurred, while the second represents the changed period and is associated with significant human activities. Thus, a change in the average annual streamflow is calculated as:

$$\Delta\overline{Q} = \overline{Q}_2 - \overline{Q}_1 \tag{10}$$

where $\Delta\overline{Q}$ denotes the change in average annual streamflow and $\overline{Q}_1$ and $\overline{Q}_2$ are the average annual streamflow during the baseline period and changed period, respectively.

Precipitation and PET are the primary climatic variables determining the annual water balance (Zhang et al., 2004). Variations in these variables could lead to changes in the annual streamflow. The relationship between these variables can be estimated as:

$$\Delta\overline{Q}_{clima} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET \tag{11}$$

where $\Delta P$ and $\Delta PET$ are the changes in precipitation and PET, respectively. Consequently, the impact of climate change on streamflow can be quantified as:

$$\frac{\partial Q}{\partial P} = P^{(m-1)}(PET^m + P^m)^{1/m-1} \tag{12}$$

$$\frac{\partial Q}{\partial PET} = PET^{(m-1)}(PET^m + P^m)^{1/m-1} - 1 \tag{13}$$

In contrast, simple linear regression is a statistical method that does not consider the physical hydrological processes that were also established between streamflow and precipitation within the two periods (the changing period and the reference period). The regression equation between annual streamflow ($Q_{ref}$) and basin-averaged annual precipitation ($P_{ref}$) in the reference period can be expressed as follows:

$$Q_{ref} = aP_{ref} - b \tag{14}$$

By extending these regression equations between streamflow and precipitation in the changing period, the contribution to streamflow changes by human activities and precipitation can be estimated as:

$$\Delta Q^h = \overline{Q}_{fit} - \overline{Q}_{change} \quad \text{where} \quad \overline{Q}_{fit} = a\overline{P}_{change} + b \tag{15}$$

$$\Delta Q^p = \overline{Q}_{change} - \overline{Q}_{ref} \tag{16}$$

where $\overline{Q}_{fit}$ is the calculated mean streamflow, $\overline{Q}_{change}$ is the observed mean streamflow and $\overline{P}_{change}$ is the precipitation during the changing period, and parameters $a$ and $b$ are the same as those in Eq. (14).

## 4. Results

### 4.1. Trends in annual hydro-meteorological variables

Fig. 3 shows trends in streamflow, precipitation, temperature and PET, estimated by the MK test and the least square method. Overall, the average annual streamflow shows a significant decreasing trend ($P < 0.05$) at most stations except Zhuangtou and Yanchuan stations. As shown in Fig 3a, the annual streamflow at Gaojiachuan, Shenjiawan and Wenjiachuan stations decreases the most, with average reduction rates of −1.49 mm/yr, −1.61 mm/yr and 1.48 mm/yr, respectively. The streamflow at Zhuangtou and Yanchuan stations shows a more gently decreasing trend with average rates of decrease of −0.10 mm/yr and −0.22 mm/yr, respectively. Previous studies have shown that significant reductions in streamflow during the past decades were mainly the result of intensive human activities such as agricultural irrigation, industrial development, urbanization and reservoirs construction and soil and water conservation control implementation (Wang et al., 2011; Zhao et al., 2012).

To better understand climate changes, we analyzed trends of the climatic variables including precipitation, temperature and PET during the past several decades in the MRYRB. The results are shown in Fig. 3b–d. Precipitation at all of the stations exhibited negative trends, with rates of decrease ranging from −4.7 mm/yr to −0.19 mm/yr (Fig. 3b) over the study period. Significant downward trends are detected at some stations in the Wuding River basin, the Fen River basin and the western Wei River basin. Decreased precipitation throughout the middle reaches of the Yellow River basin indicated that the region experienced a relative dry period during the last half century. Temperature at most stations increased by 0.03–0.59 °C per decade; only one station exhibited a downward trend. The PET has a positive trend in the western MRYRB, with increases from 0.26 mm/yr to 3.65 mm/yr over the study period. Significant downward trends in PET are detected at several stations in the eastern MRYRB, though, with rates of decrease ranging from −4.5 mm/yr to −0.15 mm/yr. These mixed changing trends in PET may be caused by several climatic variables. Significant temperature increases are responsible for the positive PET in the western MRYRB, while an evident reduction in sunshine duration leads to negative PET in the eastern MRYRB. These changes in sunshine duration are not shown in this work.

### 4.2. Abrupt changes in streamflow

Pettitt's test was applied to examine abrupt changes in annual streamflow at both mainstream and tributary stations. Fig. 4 shows the abrupt changes in annual streamflow at 18 stations on both the mainstream and tributaries of the Yellow River. At the mainstream stations, these abrupt changes mostly occurred in the mid-1980s; this pattern can be largely attributed to the operation of the Longyangxia reservoir, which has a storage capacity of 24.7 km$^3$, in the upper reaches of the Yellow River. The abrupt changes in annual streamflow in the tributaries occurred intensively between the 1980s and 1999, which likely predominantly resulted from large scale soil and water conservations practices. Accordingly, these breakpoints divide the study period for all the catchments into two periods: the pre-change and post-change periods.

### 4.3. Changes in streamflow regime

A Flow duration curve (FDC) provides a simple but comprehensive graphical view of streamflow variability and is the complement of the cumulative distribution function of daily flow (Li et al., 2007). To further examine changes in the flow regime of the catchments, we plotted the FDCs using daily streamflow records that we divided into pre-change and post-change periods as defined by the abrupt change analysis described in the previous section.

Fig. 5 shows the daily FDCs for the pre-change and post-change periods for Huaxian and Shenmu stations. These two stations are typical in terms of their catchment areas, precipitation, and the timing of the abrupt changes in annual streamflow. The magnitude of the daily flow during the post-change period was generally less than that in the pre-change period at both stations. Specifically, the 5th percentile of daily flow ($Q_5$) dropped by 47.1% and 67.3%, and $Q_{50}$ dropped by 51.1% and 63.9% at Huaxian and Shenmu stations, respectively.

### 4.4. Periodic streamflow changes associated with ENSO events

The El Niño/La Niña-Southern Oscillation (ENSO) is a quasi-periodic climate pattern that occurs across the tropical Pacific Ocean. A number of previous studies have detected significant linkages between ENSO and hydro-climatic variables at inter-annual timescales (Trenberth, 1997; Chiew and McMahon, 2002; Wang et al., 2006). In this study, we used wavelet transform analysis to examine the variation of periodicities in monthly streamflow at Longmen and Huayuankou stations and in the ENSO series to investigate the possible linkage between ENSO and streamflow in the Yellow River basin.

As shown in Fig. 6a and b, the wavelet power spectrum of the streamflow illustrates continuous periodicities of 0.5 and 1 year at both stations at 95% confidence level during 1950–1968 and 1974–1985. However, discontinuous cyclicities in the streamflow wavelet analysis at Longmen and Huayuankou stations were observed from 1969 to 1973 and after 1986. This phenomenon is

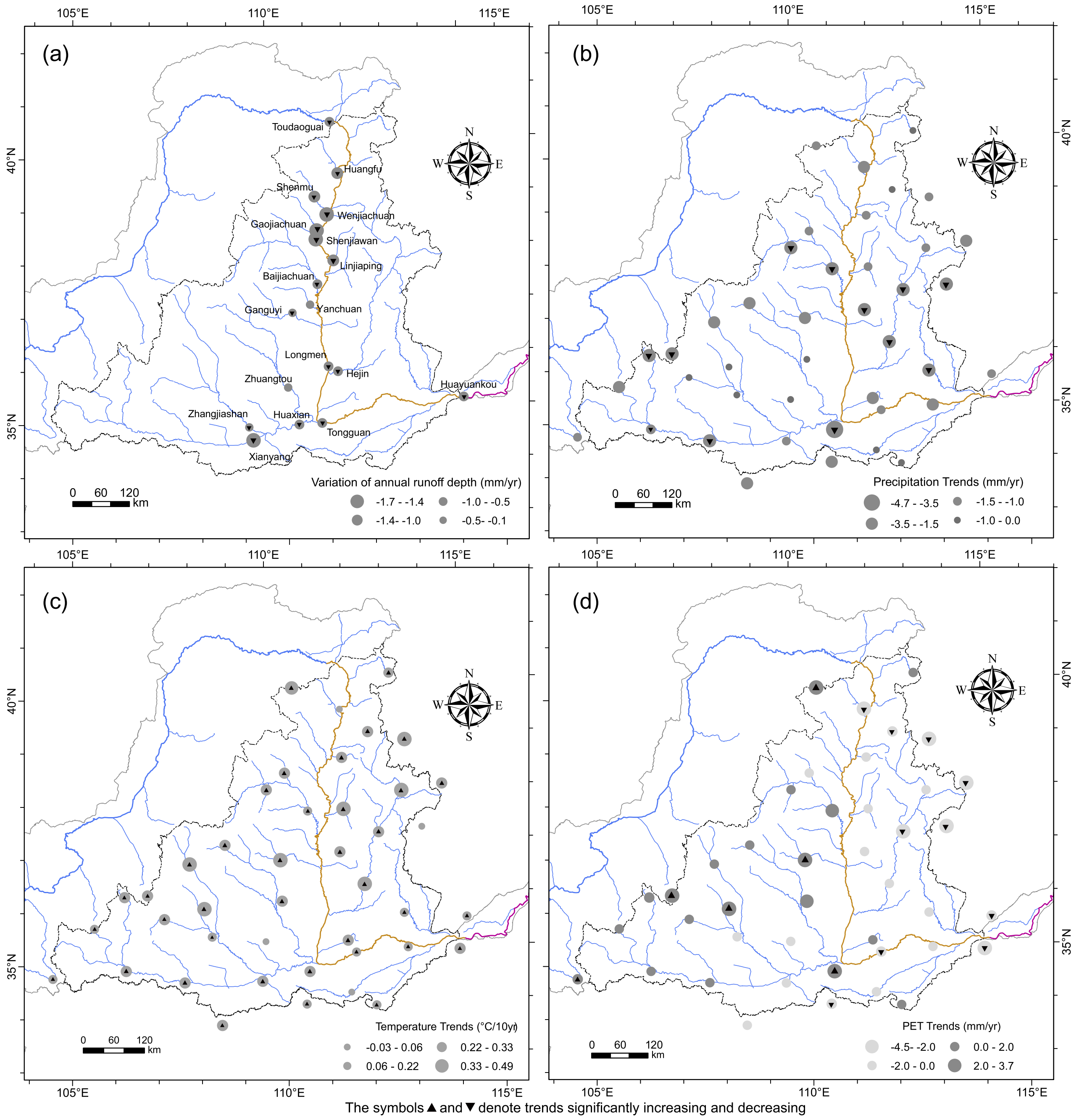


**Fig. 3.** Trend analysis of hydro-climatic variables in the MRYRB. (Trends in annual runoff (a); precipitation (b); temperature (c) and potential evapotranspiration (d)).

most likely caused by intensive human activity in the upper and middle reaches of the Yellow River basin. The discontinuity suggests notable trapping effects of two large reservoirs: Liujiaxia (since 1968) and Longyangxia (since 1986), which have a total storage capacity of 30.4 km$^3$. Furthermore, numerous soil and water conservation measures were implemented over the past several decades, especially after the 1980s. These measures greatly altered hydrological processes in the MRYRB and may have led to the discontinuous periodicities in streamflow.

In addition, a 4-year periodicity was detected in the early 1970s; this pattern is likely related to the variance in ENSO. The wavelet power spectra for the El Niño 3 SST is shown in Fig. 6c, and reveals that power is broadly distributed with peaks in the 2- to 8-year range at 95% confidence level. ENSO has relative low wavelet power in the 4-year band from 1963 to 1970 and in the 7- to 8-year band from the late of 1960s to the mid-1990. The opposite phases can be clearly seen during the same periods in the streamflow wavelet analysis in Fig. 6a and b. Studies consistently suggest that most moderate and strong ENSO events correspond to relatively low precipitation and annual streamflow (Wang et al., 2006; Lu, 2004). In the MRYRB, extremely strong ENSO events were detected in 1982–1983, 1997, and 2008 and were linked to relative low precipitation and streamflow. Thus, ENSO may have a strong linkage with streamflow changes and may affect regional runoff discharge by shifting the pattern of precipitation throughout the global climate system (Lu, 2004).

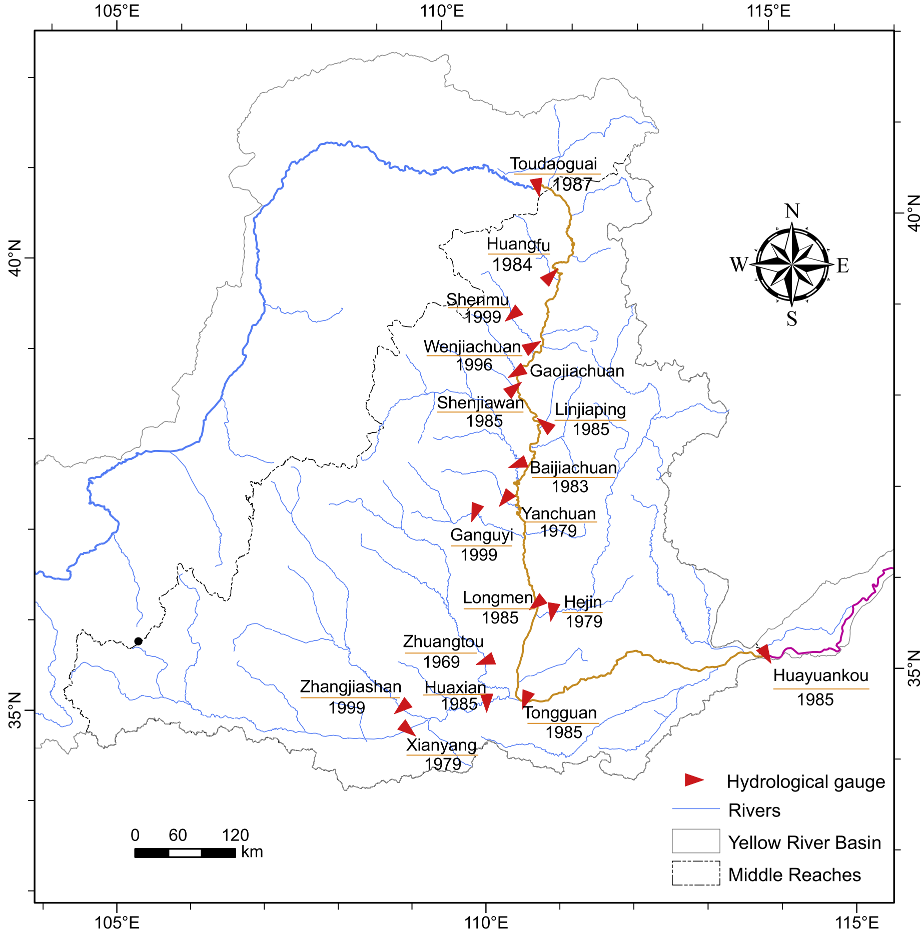


**Fig. 4.** Abrupt changes in annual streamflow detected by Pettitt's test at four stations in the MRYRB.

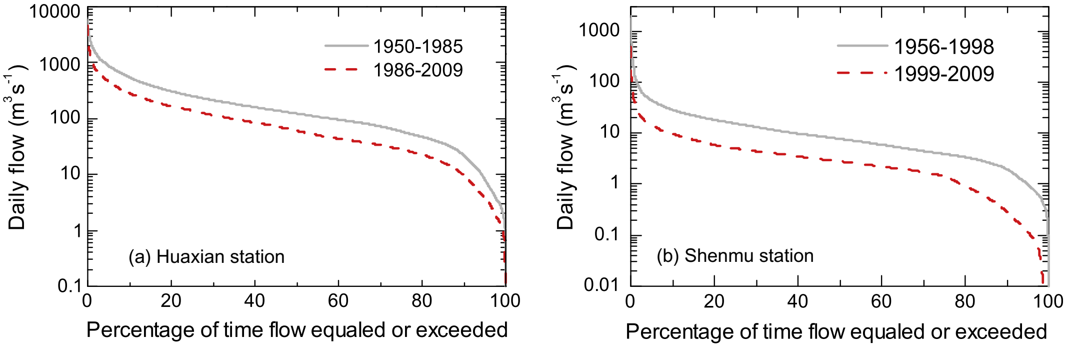


**Fig. 5.** Flow duration curves of daily streamflow at two stations over different periods.

### 4.5. Effects of climate variability and human activities on streamflow

Changes in streamflow for a given study area are affected by many factors that can be attributed to climate variability and human activity. The percentage change in average annual streamflow attributable to climatic variability and human activity are shown in Table 2. Streamflow at most stations is decreasing at extremely high rates (18–76%), which may be partly affected by significant decreases in precipitation. Human activities are expected to account for more of this reduction in mean annual streamflow than are the effects of climate change; this prediction is true at most stations, but not at Zhuangtou station in Beiluo River. Specifically, climate variability ($\Delta Q^c$) contributed 5.2–62.4% of the change in mean annual streamflow for the catchments in MRYRB. Although most catchments had larger decreases in annual precipitation, less than 50% of the streamflow reduction was attributable to climate change. This observation is particularly applicable in the northern part of the study area (e.g., Gaojiachuan, Wenjiachuan, Huangfu and Shenjiawan), where climate variability accounts for less than 20% of the reduction in streamflow.

## 5. Discussions

### 5.1. Impacts of climate change and human activity on streamflow discerned from double mass curves

To further address the impacts of human activity on streamflow, double mass curves (DMCs) and linear regression lines were

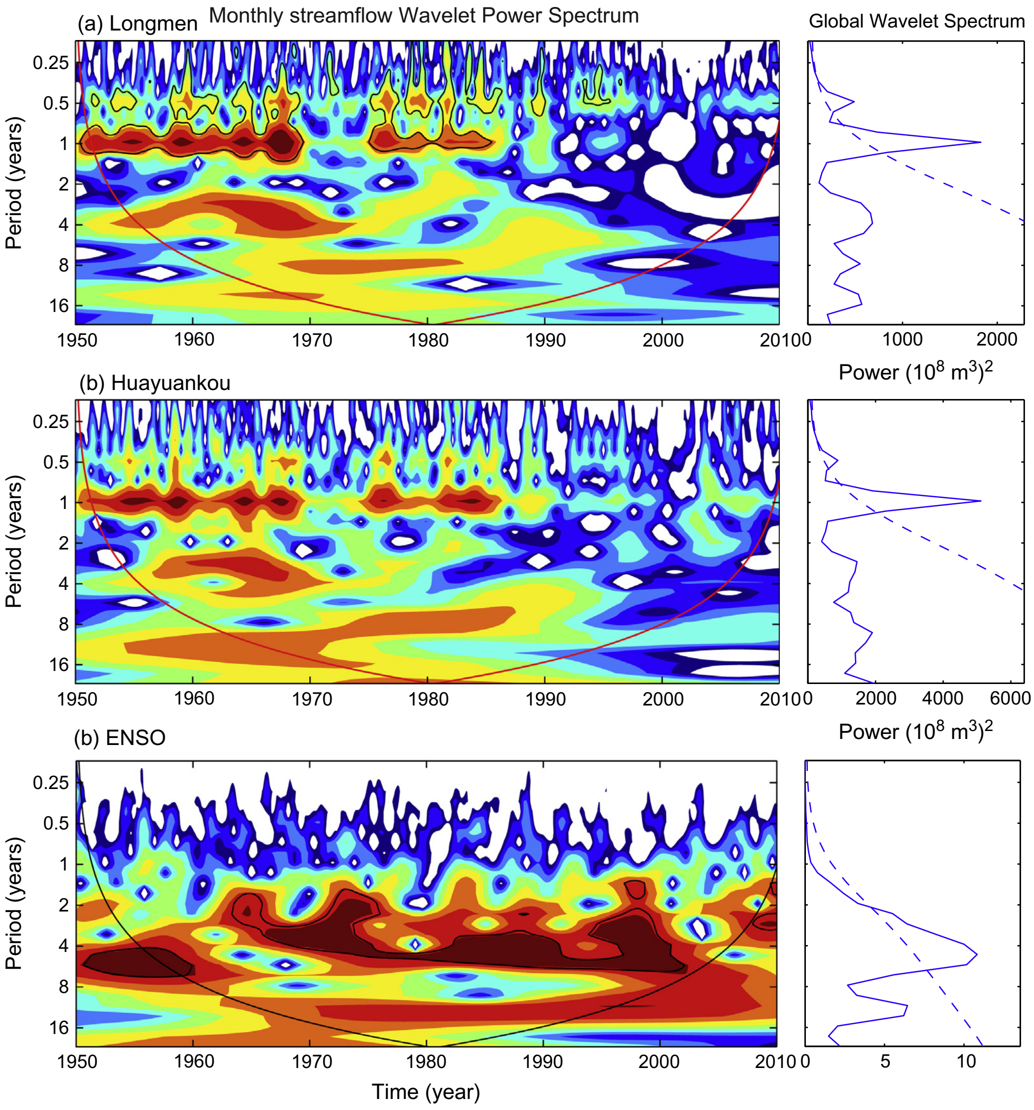


**Fig. 6.** Wavelet transform analysis of streamflow at Longmen (a), Huayuankou (b) stations and ENSO index (c).

plotted to show the correlation between cumulative annual streamflow and precipitation. In general, the DMC was expected to be a straight line if streamflow was not influenced by human activities. The curves show the best fit between streamflow and precipitation (Zhang and Lu, 2009). However, in most cases, evident abrupt breakpoints can be identified in the DMCs, suggesting that the variations in hydrological processes were not only influenced by precipitation but also by human activities.

Fig. 7 shows the DMCs between cumulative annual streamflow and precipitation at six stations in both the mainstream and tributaries. Some abrupt changes in the DMCs are evident (shown in Fig. 7). The relationships between runoff and precipitation are well represented by two straight lines with different slopes before and after the times of abrupt change. As shown in Fig. 7, the slopes of the regression lines are lower after the transition years than before for the DMCs at most stations, which suggests large reductions in streamflow in periods following the transition years. Specifically, the DMCs at all of the mainstream stations turn downward around 1986, which correlates with the construction of the Longyangxia reservoir, although soil and water conservation measures have significantly affected water discharge between Toudaoguai and Huayuankou (Gao et al., 2011). Previous studies have confirmed that the Longyangxia reservoir, the largest reservoir in the Yellow River basin, has significant effects on the streamflow regime of stations downstream of it (Yao et al., 2011; Zhao et al., 2012). The abrupt breakpoints identified in the DMCs mostly agree well with those from the Pettitt's test, suggesting that the results detected are reasonable and meaningful. In contrast, the DMCs at tributary stations display abrupt changes in the mid-1980s or around 1999. This observation may imply that intensive human activities have greatly altered hydrological processes in the MRYRB. The impact of human activities (e.g., irrigation, industrial development, urbanization, and the construction of reservoirs) has increased in recent years. These activities have led to the withdrawal or consumption of a large proportion of the water resources in the study area.

### *5.2. Estimation of climate and anthropogenic contributions by linear regression between streamflow and precipitation*

The simple linear regression method assessed the relative contributions of precipitation and human activity in the MRYRB to changes in streamflow (Table 3). Generally, the contributions of human activities and variations in precipitation are consistent with the results from Budyko's curve, summarized in Table 2. Human

**Table 2**
Effects of climate variability and human activities on streamflow in the MRYRB.

| Stations | Period | $P$ (mm/yr) | PET (mm/yr) | $Q$ (mm/yr) | $\Delta Q^c$ (%) | $\Delta Q^h$ (%) |
|---|---|---|---|---|---|---|
| Huaxian | Pre-1985 | 569.1 | 985.6 | 78.0 | | |
| | Post-1986 | 513.0 | 1025.7 | 45.2 | 37.3 | 62.7 |
| Wenjiachuan | Pre-1996 | 395.8 | 1230.1 | 73.4 | | |
| | Post-1997 | 351.3 | 1334.1 | 19.1 | 10.3 | 89.7 |
| Zhangjiashan | Pre-1999 | 512.6 | 1036.9 | 40.0 | | |
| | Post-2000 | 497.9 | 1093.8 | 23.9 | 32.7 | 67.3 |
| Zhuangtou | Pre-1969 | 581.5 | 1101.9 | 31.5 | | |
| | Post-1970 | 531.4 | 1127.5 | 25.8 | 46.4 | 53.6 |
| Baijiachuan | Pre-1983 | 429.3 | 1255.9 | 46.0 | | |
| | Post-1984 | 382.2 | 1239.8 | 30.0 | 14.6 | 85.4 |
| Gaojiachuan | Pre-1988 | 417.7 | 1194.4 | 117.2 | | |
| | Post-1989 | 386.9 | 1186.9 | 76.5 | 5.2 | 94.8 |
| Ganguyi | Pre-1999 | 538.1 | 1127.4 | 36.3 | | |
| | Post-2000 | 501.1 | 1276.6 | 24.6 | 56.2 | 43.8 |
| Yanchuan | Pre-1979 | 490.2 | 1116.8 | 41.8 | | |
| | Post-1980 | 443.0 | 1191.4 | 34.4 | 35.0 | 65.0 |
| Huangfu | Pre-1984 | 420.4 | 1264.7 | 51.3 | | |
| | Post-1985 | 310.4 | 1263.9 | 12.3 | 16.6 | 83.4 |
| Linjiaping | Pre-1985 | 479.5 | 1199.9 | 56.5 | | |
| | Post-1985 | 403.2 | 1251.1 | 24.3 | 33.6 | 66.4 |
| Hejin | Pre-1979 | 507.7 | 1206.9 | 39.4 | | |
| | Post-1980 | 445.1 | 1130.5 | 19.4 | 14.1 | 85.9 |
| Shenjiawan | Pre-1985 | 412.3 | 1253.9 | 72.3 | | |
| | Post-1986 | 382.8 | 1243.6 | 30.3 | 6.4 | 93.6 |

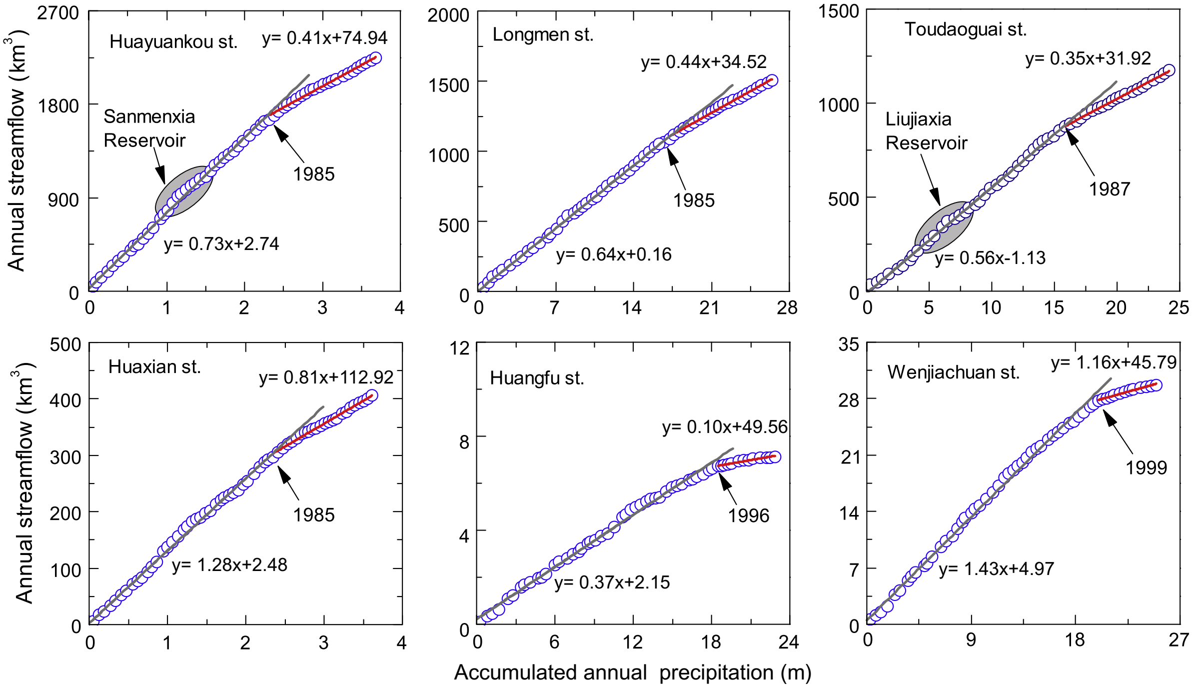


**Fig. 7.** Double mass curve analysis between streamflow and precipitation at different stations.

activities played a dominant role in the reduction of streamflow for most catchments, especially in the north. At the Huaxian, Zhuangtou and Linjiaping stations, however, significant decreases in precipitation and relatively slight reductions in streamflow (shown in Table 3) suggest that climate variability was the dominant cause of the of streamflow changes. However, the linear regression and Budyko's curve methods do not agree on the contribution fractions at all stations; they disagree at Huaxian and Yanchuan stations, for example. This discrepancy may be caused by changes in PET, as the linear regression equation only considers precipitation.

Li et al. (2007) found that soil conservation measures were responsible for 87% of the total reduction in mean annual streamflow, while the remaining 13% was attributable to climate variability in the Wuding River basin. This observation is consistent with our results. However, our results do not completely agree with Zhang et al. (2008). They found that climate variability and soil conservation measures had contributed almost equally to the streamflow reduction for the whole MRYRB during the period from the 1950s to 2000. The discrepancies may be due to different lengths of the streamflow time series. Additionally, advances in soil

**Table 3**
Relative contribution to changes of streamflow from precipitation and human activity using linear regression in the MRYRB.

| Stations | Period | $Q_{change}$ (mm) | Linear regression equation | | $Q_{fit}$ (mm) | $\Delta Q^p$ (mm) | $\Delta Q^h$ (mm) | $\Delta Q^p$ (%) | $\Delta Q^h$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | | $Eq_{fit}$ | $R^2$ | | | | | |
| Huaxian | 1986–2010 | 45.2 | $0.315P_{ref} - 101.16$ | 0.77 | 60.42 | −17.57 | −15.23 | 53.6 | 46.4 |
| Wenjiachuan | 1997–2010 | 22.3 | $0.169P_{ref} + 8.69$ | 0.41 | 67.95 | −8.22 | −45.62 | 15.3 | 84.7 |
| Zhangjiashan | 2000–2010 | 23.9 | $0.122P_{ref} - 22.87$ | 0.71 | 37.83 | −2.20 | −13.89 | 13.7 | 86.3 |
| Zhuangtou | 1970–2010 | 25.8 | $0.100P_{ref} - 24.74$ | 0.74 | 27.28 | −4.12 | −1.48 | 64.2 | 35.8 |
| Baijiachuan | 1984–2010 | 30.0 | $0.076P_{ref} + 12.22$ | 0.61 | 42.42 | −3.60 | −12.41 | 22.5 | 77.5 |
| Gaojiachuan | 1989–2010 | 76.5 | $0.121P_{ref} + 66.50$ | 0.39 | 113.44 | −3.7 | −36.68 | 9.1 | 90.9 |
| Ganguyi | 2000–2010 | 24.6 | $0.058P_{ref} + 5.14$ | 0.30 | 34.16 | −2.13 | −9.53 | 18.2 | 81.8 |
| Yanchuan | 1980–2010 | 34.4 | $0.110P_{ref} - 8.92$ | 0.44 | 39.99 | −4.86 | −5.57 | 46.6 | 53.4 |
| Huangfu | 1985–2010 | 12.3 | $0.186P_{ref} - 10.49$ | 0.52 | 47.18 | −4.16 | −34.84 | 10.7 | 89.3 |
| Linjiaping | 1986–2010 | 24.3 | $0.238P_{ref} - 63.02$ | 0.74 | 37.63 | −18.85 | −13.36 | 58.5 | 41.5 |
| Hejin | 1980–2010 | 19.4 | $0.109P_{ref} - 15.31$ | 0.42 | 33.29 | −6.11 | −20.28 | 23.2 | 76.8 |
| Shenjiawan | 1986–2010 | 30.3 | $0.176P_{ref} - 0.05$ | 0.44 | 67.14 | −5.19 | −36.87 | 12.3 | 87.7 |

and water conservation practices and the spatial and temporal heterogeneities of precipitation may lead to inconsistent results. It should be noted that streamflow decreased more significantly in recent years, especially after the "Green for Grain" project launched in 1999.

### 5.3. Anthropogenic impacts on streamflow in the MRYRB

#### 5.3.1. Impacts of soil and water conservation on streamflow

A series of soil and water conservation practices have been carried out in the MRYRB since the late 1950s, including engineering structures such as terraces and dams and biological measures such as afforestation and planting grass. The engineering measures affect the streamflow by reducing flood peaks and storing water within check-dams and reservoirs. These measures consequently decrease both the magnitude and the variability of the streamflow. The biological measures may have delayed these effects on streamflow because the plants take up water and accelerate its evapotranspiration with their growth (Zhang et al., 2008).

Table 4 shows the statistics of soil and water conservation measures in the MRYRB over the past six decades. These measures have been implemented at variable rates that were slower before the 1970s and accelerated significantly afterwards due to various government-sponsored conservation projects (Mu et al., 2007). The area protected by soil and water conservation measures doubled or tripled from the 1970s to 1989, reaching approximately 4.99 million hm$^2$, which is 18.1% of the area between Toudaoguai and Tongguan stations (not counting the Fen River basin). The measures included 1.0 million hm$^2$ of terraces, 3.33 million hm$^2$ of afforestation, 0.55 hm$^2$ of planted grassland and 0.10 million hm$^2$ of check-dams (Table 4). By 2006, approximately 37.2% of the region had been controlled by various soil and water conservation measures. The dramatically increased soil and water conservation measures are likely responsible for the decreased streamflow in those catchments, particularly after the 1980s. The statistics show that the engineering measures occupy a smaller area than the biological measures do (Table 4); however, their effects on streamflow are substantial because they have direct and immediate effects on hydrological processes.

**Table 4**
Statistics of soil and water conservation measures between Toudaoguai and Tongguan ($10^4$ hm$^2$).

| Year | Terrace | Forests | Pasture | Check-dam |
|---|---|---|---|---|
| 1959 | 5.30 | 19.66 | 4.15 | 0.36 |
| 1969 | 24.12 | 52.13 | 6.55 | 1.85 |
| 1979 | 56.22 | 135.58 | 15.70 | 4.67 |
| 1989 | 100.62 | 333.11 | 55.14 | 10.09 |
| 1996 | 144.09 | 444.03 | 63.73 | 12.24 |
| 2006 | 285.40 | 586.14 | 140.73 | 13.10 |

Statistic data was collected from Wang and Fan (2002) and Yao et al. (2011). Data in Fen River basin was not available.

#### 5.3.2. Influences of reservoirs on streamflow

The regulation of streamflow through dams and reservoirs is the human activity that most directly influences streamflow regimes and regional water balances. At the global scale, approximately 70% of rivers are intercepted by large reservoirs to meet a range of social, economic and environmental demands, including hydropower generation, agricultural irrigation, flood control and domestic consumption (Nilsson et al., 2005). More than 45,000 dams over 15 m in height have been in operation since the 20th century.

By the year 2000, more than 3150 reservoirs had been built in the Yellow River basin; 171 of these are large- or medium-sized and have total storage capacity of 33.6 km$^3$ (Xu et al., 2010). A recent statistical report estimates the total storage capacity of all registered reservoirs was to be approximately 72 km$^3$, which is much higher than the basin's 2000–2010 mean annual streamflow of 23.6 km$^3$ (Zhang et al., 2005). There are 24 particularly large reservoirs (storage capacity greater than 0.10 km$^3$) scattered in the Yellow River basin, three of which are along the mainstream and are the most influential: the Liujiaxia, Longyangxia and Xiaolangdi reservoirs (Wang et al., 2006). Wavelet analysis of monthly streamflow at Huayuankou station from 1950 to 2010 shows that the seasonal dynamics have been completely altered since 1986, which is mainly due to the operations of large dams and reservoirs (Fig. 6b). Furthermore, the seasonal variability of the streamflow has been reduced, which is largely the result of regulation by dams and reservoirs in the Yellow River basin. The observed streamflow in flood seasons accounted for more than 70% of the annual streamflow in the 1950s, but decreased to 51% after 2000. This change occurred because most of the reservoirs reduced the flood peaks dramatically through water storage in the rainy season and water release in the dry season for agricultural irrigation.

#### 5.3.3. Long-term water consumption in the MRYRB

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. The average annual withdrawal from the Yellow River basin has been approximately 50 km$^3$, of which approximately 74% was from surface water and 26% was from groundwater (Giordano et al., 2004). Groundwater withdrawal data from the Bulletin of Water Resources in China (1998–2008) indicated that groundwater withdrawal in the Yellow River basin was approximately 13 km$^3$/yr (Xu et al., 2010). Agricultural production in the semi-arid Yellow

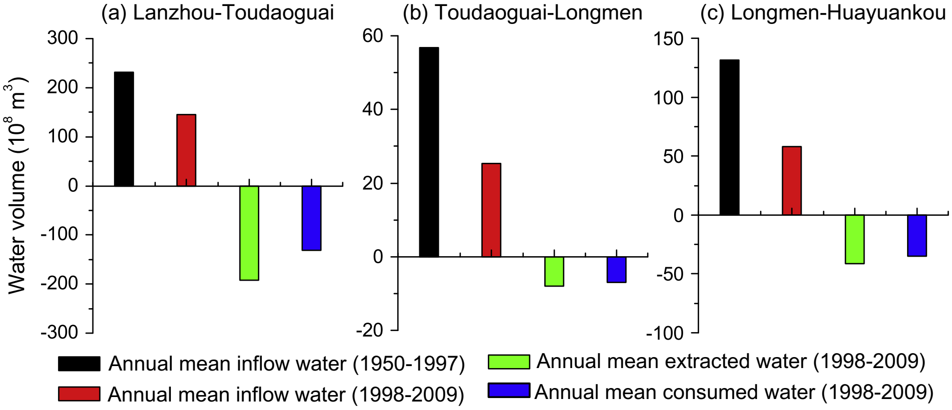


**Fig. 8.** Water consumption in different sections of the Yellow River basin (Water consumption in the section Lanzhou-Toudaoguai (a); section Toudaoguai-Longmen (b) and section Longmen-Huayuankou (c)).

River basin is heavily dependent on irrigation. Agriculture is by far the largest user of water, accounting for 80% of the total withdrawal; industrial, urban and rural domestic sectors share the remaining 20% (Giordano et al., 2004). Previous studies have found that the irrigation areas expanded from 800,000 $hm^2$ in 1949 to 7.51 million $hm^2$ by 1997 (Cai and Rosegrant, 2004). In addition, a considerable number of dams, reservoirs pump-sites and wells have been built in the basin over the last 60 years.

Fig. 8 displays the mean annual inflow, water extracted and water consumed in various river sections. Compared with the period before 1997, there is a general decrease in the mean annual inflow in each section from 1998 to 2009, particularly in the section between Toudaoguai and Longmen stations (Fig. 8b). The total water consumed within the river basin now exceeds the streamflow currently observed to enter the Bo Sea. Agricultural irrigation and the operation of reservoirs play an important role in the reduction of streamflow in the sections in the upper reaches and between the Longmen and Huayuankou stations (Fig. 8). In contrast, numerous soil and water conservation measures must be responsible for the significant reduction of streamflow in the section from Toudaoguai to Longmen, because water consumed from 1998 to 2009 is lower than it is in the other two sections. Three large irrigation areas: the Ningxia, Inner Mongolia and Guanzhong irrigation districts are scattered in the upper and middle reaches of the Yellow River basin. These irrigation districts consumed approximately 6.41, 7.59 and 1.32 $km^3$/yr, respectively, from 1997 to 2006, which accounts for 71.4% of the total streamflow at Huayuankou during that period (Yao et al., 2011).

## 6. Conclusions

This study examines the spatial distribution and temporal variation of precipitation, PET, temperature and streamflow by using hydro-climatic series from the 1950s to 2010 in the MRYRB. Individual impacts of climate variability and human activities were investigated using Budyko's curve, and potential causes for the streamflow changes were identified. The conclusion of our study can be summarized as follows.

A general decrease in the annual precipitation and a rising temperature trend have been detected in the MRYRB. Precipitation at all the stations illustrates decreases ranging from −4.7 mm/yr to −0.19 mm/yr from the 1950s to 2010. The increasing temperature and decreasing precipitation suggest that the study area has been experiencing a relative warm, dry period over the last 60 years. Variable trends in PET are observed in different regions of the MRYRB. The strong ENSO events and monsoon activities, which primarily affect regional precipitation, together with global climate change influence the hydrological cycle in the MRYRB.

The average annual streamflow shows a significant decrease ($P < 0.05$) at all stations except Zhuangtou and Yanchuan; the decreases range from 0.10 mm/yr to 1.61 mm/yr over the study period. Abrupt changes in streamflow occurred in the mid-1980s and around 1999 in the tributaries, which may have resulted from the implementation of soil and water conservation measures. Streamflow at mainstream stations showed abrupt changes in 1985 that were evidently due to the trapping effects of reservoirs. Flow duration curves and wavelet transform analysis indicate significant changes in both streamflow regimes and periodicities.

Climate variability and human activities are two distinct contributors to the observed streamflow reduction. Consistent results were obtained from the Budyko's curve equation and linear regression analysis. Generally, climate variability had a greater effect on streamflow reduction in the Beiluo and Yan Rivers, while human activities accounted for more of the streamflow changes in other tributaries. The adoption of large-scale soil and water conservation measures since the early 1980s altered the natural streamflow regimes and led to an abrupt reduction in streamflow. The significant decline in streamflow at mainstream stations in the year 1985 coincided well with the operation of reservoirs. The overall results show that human activities, such as soil and water conservation projects, the construction of key water control projects and agricultural irrigation seem to be the major causes of the significant decline in the annual streamflow in the MRYRB over the last six decades.

## Acknowledgements

The work was supported by National Natural Science Foundation of China-China (Nos.: 41201266, 41271295), the Major Programs of the Chinese Academy of Sciences (KZZD-EW-04), the Program for Excellent Youth Scholars in the Institute of Soil and Water Conservation (A315021394), Open Research Fund Program of Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy Sciences (WL2011004) and the Fundamental Research Funds for the Central Universities (QN2013071). The authors would like to express their great appreciation to the National Climatic Centre and the Hydrology Bureau of the Yellow River Water Resources Commission for providing valuable climatic and hydrological data. The authors would also thank for the very valuable comments from reviewers which greatly improved the quality of the paper.

## References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO.

Brutsaert, W., Parlange, M.B., 1998. Hydrologic cycle explains the evaporation paradox. Nature 396, 30.

Budyko, M.I., 1974. Climate and Life. Academic Press, New york, CA.

Cai, X.M., Rosegrant, M.W., 2004. Optional water development strategies for the Yellow River Basin: Balancing agricultural and ecological water demands. Water Resour. Res. 40 (8), W08S04, doi: http://dx.doi.org/10.1029/2003WR002488.

Chiew, F.H.S., McMahon, T.A., 2002. Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. Hydrol. Sci. J. 47 (3), 505–522.

Choi, W., Rasmussen, P.F., Moore, A.R., Kim, S.J., 2009. Simulating streamflow response to climate scenarios in central Canada using a simple statistical downscaling method. Climate Res. 40 (1), 89–102.

Dooge, J.C.I., Bruen, M., Parmentier, B., 1999. A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. Adv. Water Resour. 23 (2), 153–163.

Fohrer, N., Haverkamp, S., Frede, H.G., 2005. Assessment of the effects of land use patterns on hydrologic landscape functions: development of sustainable land use concepts for low mountain range areas. Hydrol. Process. 19 (3), 659–672.

Fu, B.P., 1981. The calculation of the evaporation from land surface. Chinese J. Atmos. Sci. 5 (1), 23–31.

Fu, B.P., 1996. On the calculation of evaporation from land surface in mountainous area. Scientia Meteorologica Sinica 6 (4), 322–335.

Gao, P., Mu, X.M., Wang, F., Li, R., 2011. Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrol. Earth Syst. Sci. 15 (1), 1–10.

Giordano, M., Zhu, Z., Cai, X., Hong, S., Zhang, X., Xue, Y., 2004. Water management in the Yellow River Basin: background, current critical issues and future research needs. Comprehensive Assessment Research Report 3. Comprehensive Assessment Secretariat. 36. Colombo, Sri Lanka.

Hang, Y.F., Guan, D.X., Jin, C.J., Wang, A.Z., Wu, J.B., Yuan, F.H., 2011. Analysis of impacts of climate variability and human activity on streamflow for a river basin in northeast China. J. Hydrol. 410 (3–4), 239–247.

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: review and synthesis. J. Hydrol. 319 (1–4), 83–95.

Jiang, T., Fischer, T., Lu, X.X., 2010. Large Asian rivers: climate change, river flow and watershed management. Quanternary Int. 226, 1–3.

Kendall, M.G., 1975. Rank Correlation Methods. Charles Griffin, London.

Li, L.J., Zhang, L., Wang, H., Wang, J., Yang, J.W., Jiang, D.J., Li, J.Y., Qin, D.Y., 2007. Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. Hydrol. Process. 21 (25), 3485–3491.

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

Liu, Q., Cui, B.S., 2011. Impacts of climate change/variability on the streamflow in the Yellow River Basin, China. Ecol. Model. 222 (2), 268–274.

Lu, X.X., 2004. Vulnerability of water discharge of large Chinese rivers to environmental changes: an over view. Region. Environ. Changes 4, 182–191.

Ma, Z.M., Kang, S.Z., Zhang, L., Tong, L., Su, X.L., 2008. Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China. J. Hydrol. 352 (3–4), 239–249.

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

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Climate change – stationarity is dead: whither water management? Science 319, 573–574.

Milly, P.C.D., Dunne, K.A., 2002. Macroscale water fluxes – 2. Water and energy supply control of their interannual variability. Water Resour. Res. 38 (10), 1206. http://dx.doi.org/10.1029/2001WR000760.

Milly, P.C.D., Dunne, K.A., Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438, 347–350.

Mu, X.M., Zhang, L., McVicar, T.R., Chille, B.S., Gao, P., 2007. Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China. Hydrol. Process. 21 (16), 2124–2134.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308, 405–408.

Pettitt, A., 1979. A nonparametric approach to the change-point problem. Appl. Stat. 28, 126–135.

Piao, S.L., Ciais, P., Huang, Y., Shen, Z.H., Peng, S.S., Li, J.S., Zhou, L.P., Liu, H.Y., Ma, Y.C., Ding, Y.H., Friedlingstein, P., Liu, C.Z., Tan, K., Yu, Y.Q., Zhang, T.Y., Fang, J.Y., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467, 43–51.

Song, J.X., Xu, Z.X., Liu, C.M., Li, H.E., 2007. Ecological and environmental instream flow requirements for the Wei River – the largest tributary of the Yellow River. Hydrol. Process. 21, 1066–1073.

Tao, H., Gemmer, M., Bai, Y.G., Su, B.D., Mao, W.Y., 2011. Trends of streamflow in the Tarim River Basin during the past 50 years: human impact or climate change? J. Hydrol. 400 (1–2), 1–9.

Trenberth, K.E., 1997. The definition of El Niño. Bull. Am. Meteorol. Soc. 78 (12), 2771–2777.

Wang, G., Fan, Z., 2002. Variation of Streamflow and Sediment Flux in the Yellow River. Yellow River Conservancy Press, Zhengzhou.

Wang, H.J., Saito, Y., Zhang, Y., Bi, N.S., Sun, X.X., Yang, Z.S., 2011. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. Earth Sci. Rev. 108 (1–2), 80–100.

Wang, H.J., Yang, Z.S., Saito, Y., Liu, J.P., Sun, X.X., 2006. Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: connections to impacts from ENSO events and dams. Global Planet. Change 50 (3–4), 212–225.

Wang, Y., Ding, Y.J., Ye, B.S., Liu, F.J., Wang, J., 2013a. Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. Sci. China: Earth Sci. 56, 1398–1412.

Wang, W.G., Shao, Q.X., Yang, T., Peng, S.Z., Xing, W.Q., Sun, F.C., Luo, Y.F., 2013b. Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River Basin, China. Hydrol. Process. 27 (8), 1158–1174.

Xu, K.H., Milliman, J.D., Xu, H., 2010. Temporal trend of precipitation and runoff in major Chinese Rivers since 1951. Global Planet. Change 73 (3–4), 219–232.

Yao, W.Y., Xu, J.H., Ran, D.C. 2011. Assessment of changing trends in streamflow and sediment fluxes in the Yellow River basin. 324. Yellow River Conservancy Press, Zhengzhou.

YRCC, Yellow River Conservancy Commision. Water Resources Bulletin of the Yellow River, <http://www.yellowriver.gov.cn/other/hhgb> (Accessed on August, 20, 2013).

Yue, S., Wang, C.Y., 2004. The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour. Manage 18 (3), 201–218.

Zhai, J.Q., Su, B.D., Krysanova, V., Vetter, T., Gao, C., Jiang, T., 2010. Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in ten large regions of China. J. Clim. 23 (3), 649–663.

Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37 (3), 701–708.

Zhang, L., Hickel, K., Dawes, W.R., Chiew, F.H.S., Western, A.W., Briggs, P.R., 2004. A rational function approach for estimating mean annual evapotranspiration. Water Resour. Res. 40 (2), W02502. http://dx.doi.org/10.1029/2003WR002710.

Zhang, S.R., Lu, X.X., 2009. Hydrological responses to precipitation variation and diverse human activities in a mountainous tributary of the lower Xijiang, China. Catena 77 (2), 130–142.

Zhang, X.C., Liu, C.M., Li, D.Y., 2005. Analysis on Yellow River surface runoff consumption. Acta Geographica Sinica 60 (1), 79–86.

Zhang, X.P., Zhang, L., Zhao, J., Rustomji, P., Hairsine, P., 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau. Water Resources Research, China, 44.

Zhao, G.J., Hörmann, G., Fohrer, N., Zhang, Z.X., Zhai, J.Q., 2010. Streamflow trends and climate variability impacts in Poyang Lake Basin, China. Water Resour. Manage. 24 (4), 689–706.

Zhao, G.J., Mu, X.M., Tian, P., Wang, F., Gao, P., 2012. The variation of streamflow and sediment flux in the middle reaches of Yellow River over the past 60 years and the influencing factors. Resour. Sci. 34 (6), 1070–1078 (In Chinese with English abstract).

Zhao, G.J., Mu, X.M., Wen, Z.M., Wang, F., Gao, P., 2013. Soil erosion, conservation and eco-environmental changes in the Loess Plateau of China. Land. Degrad. Dev. 24, 499–510.