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An estimate of human and natural contributions to flood changes of the Huai River

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ABSTRACT

Flooding in the Huai River Basin, China has changed because of climate change and human activity. It is important to determine how flooding has changed and what the main causes of this flood change are. In this study, daily data from 172 precipitation gauges and 1 hydrological station are analysed to detect the changes of precipitation and streamflow over the past 50 years in the Huai River Basin. Consequently, a method decomposing the influence of climate change and human activity through a distributed hydrological model is proposed. The time series of the natural streamflow are reconstructed from 1960 to 2009. Inter-annual impacts on the floods of the Huai River Basin are later separated from the impacts of human activity and climate change. Precipitation displays no significant interannual variability but displays great spatial–temporal variability in one year in the Huai River Basin; that is, precipitation is more concentrated in summer and winter in mountainous zones. Flood days in Huai River Basin have increased, whereas the flood peak displays no significant change. This phenomenon may be attributed to reservoir regulation, irrigation and urbanisation water consumption. Moreover, the quantitative assessments reveal that climate change has led to a streamflow increase of 40.8 m^3/s per year for the Huai River Basin, accounting for 55% of the streamflow change. However, human activity has led to a streamflow decrease of 33.51 m^3/s per year, accounting for 45% of the streamflow change. The effects of human activity, including water consumption, changes in land cover, and construction of reservoirs and dams, might alter the flooding in the Huai River Basin.

1. Introduction

Global warming is accelerating the global hydrological cycle, which is also changing the spatial–temporal patterns of precipitation, resulting in increased occurrences of extreme precipitation events (Easterling et al., 2000) and therefore increased occurrences of floods and droughts in many regions throughout the world. Increases in "heavy and extreme precipitation" have also been documented (IPCC, 2001) in some regions where the total precipitation has decreased or remained constant. Indeed, many regions have suffered from flood disasters. Several destructive floods occurred in the last decade in Europe (Kundzewicz, 2005). Delgado et al. (2010) demonstrated an increasing likelihood of extreme floods during the last half of the 20th century in Southeast Asia. Thus far, a large number of studies have researched the trends of precipitation (Markham, 1970; Wang and Zhou, 2005; Fan et al., 2012) and streamflow (Lin et al., 2008; Delgado et al., 2010) in many regions. Precipitation and streamflow have a high degree of correlation (Pandzic et al., 1997; Xie et al., 2005; Small et al., 2006; Chen et al., 2007; Fan et al., 2011; Ramazanipour and Roshani, 2011; Wulf, 2012). However, global and regional hydrological processes are influenced by both climatic variation and human activity (IPCC, 2007). It is very important to understand the influence of climate change and human activity on floods and quantitatively estimate those effects.

The response of rivers to climate change and human activity is a research focus in hydrology, and many studies have been performed (Jiang et al., 2012; Liu et al., 2013; Peng et al., 2013; Ye et al., 2013a,b,c). In recent years, many studies have documented concerns toward quantitative analysis of the effect of climate change and human activity on the streamflow in many regions. For example, Ma et al. (2010) found that climate impact was accountable for approximately 55% of the decreases in reservoir inflow, and the indirect impact of human activity accounted for 18% in the Huai River Basin. Ma et al. (2008) estimated that the climate variability accounted for over 64% of the reduction in mean annual streamflow in the Shiyang River Basin in the arid region of northwest China. Hydrologic models (Wang et al., 2008, 2010; Yong et al., 2013) have been used to quantitatively investigate the effects of climate change and human activity on the hydrologic cycle.

This spatial–temporal pattern of precipitation indicates a varied risk of floods and droughts across China. Whilst enjoying its rapid economic development, China has been facing increasingly severe water shortage problems (Jiang, 2010). Over the last 50 years, there was a slight

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decrease in annual precipitation in China (Zhai et al., 1999). As a result, streamflow has been reduced in some major river basins in China, such as the Yellow River Basin (Fu et al., 2004; Yang et al., 2004) and Huai River Basin (Zuo et al., 2012).

The Huai River Basin is one of the main river basins in China. Over the past 50 years, the Huai River Basin has faced the challenge of increasing extreme precipitation frequency and intensity (She et al., 2011) and more flood events (Zhao et al., 2007; Yang et al., 2012a,b). Several studies have been conducted to attempt to explain the changes of the water features in the Huai River Basin. The trend analysis and distribution characteristics of precipitation and streamflow are commonly employed for this purpose (Lu et al., 2011; Liang et al., 2012; Shi et al., 2013). These studies indicate that the annual precipitation displays a slightly increasing trend over the past 60 years, and the annual average streamflow has also increased slightly in the Huai River Basin. In addition, a number of studies have analysed the impacts of climate change (Ju et al., 2012; Zuo et al., 2012) and human activity (Yang et al., 2010; Li et al., 2013) on streamflow. However, the details are insufficient to describe the effects of climate change and human activity comprehensively and quantitatively.

To contribute to a thorough understanding of attribution of flood change in the Huai River Basin, the major objective of this study was to detect the spatial–temporal trend of precipitation and streamflow, along with underlying causes of streamflow change based on rainfall and streamflow datasets for the period 1960–2010. This paper is organised as follows: Section 2 introduces study area and data. Section 3 describes the methodology, including the Mann–Kendall test, linear regression analysis, frequency analysis, hydrological model and quantitative estimate method. Section 4 presents the results and discussion. Section 5 presents the conclusions.

2. Study area and data

2.1. Study area

The Huai River flows from west to east. The western part and southwest part of the area are mountains and hilly area, and the rest is a plain region. The Huai River Basin is also the main water supply area and the main channel for the eastern route of the south-to-north water diversion project (Ju et al., 2012).

The study area is the upper reaches of the Huai River Basin on the Bengbu station, which lies in a semi-humid monsoon climate region of eastern China approximately between 30.55°–34.85°N latitude and 111.55°–117.85°E longitude (Fig. 1). The region covers an area of approximately 270,000 km^2 with a population of approximately 165 million.

The Huai River Basin is located in the climate transition zone from north to south with an annual mean temperature fluctuating from 13.55 °C to 16.18 °C during 1951–2006 (Yang et al., 2012a,b). Its north part belongs to a warm temperate zone, whereas its south part belongs to a north subtropical zone. The mean annual precipitation is approximately 885 mm in the Huai River Basin, and approximately 50–75% occurs during the summer monsoon season (Fig. 2), which easily causes floods in the summer. Since the 1950s, several extreme flood events have occurred in the Basin, such as those in 1954, 1991 and 2003. The rainstorms that occurred in June and July 2007 over the Huai River gave rise to severe flood events in the region (Zhao et al., 2007). Some study results indicate that flood and drought events have occurred more frequently since the 1980s (Yang et al., 2012a,b).

2.2. Data

This study involves the hydrology, meteorology and topography topics. A total of 172 rain gauges adequately cover the entire basin with daily precipitation records and one streamflow station with daily flow records are available in the Huai River Basin. Fig. 1 illustrates the rain gauge and streamflow station location. These datasets are listed in Table 1 and ensure strict quality control of all the data. The discharge data of Bengbu station, which is located at the basin outlet and control the whole study basin flows (Gao et al., 2009), is from Huai River Water Resources Commission. Considering the purpose of this paper is to give insight into the flood change over the entire upstream of Bengbu station, it is suitable for detecting the change tendency in the drainage basin sufficiently. A digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) 3s Digital Elevation Database of USGS/NASA (Table 1).

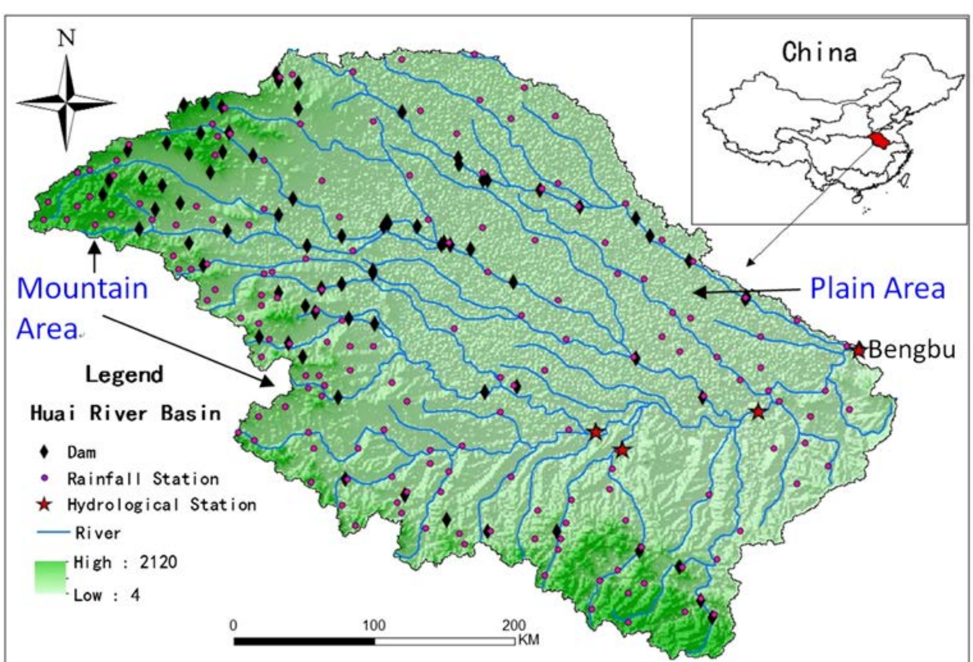

Fig. 1. Huai River Basin.

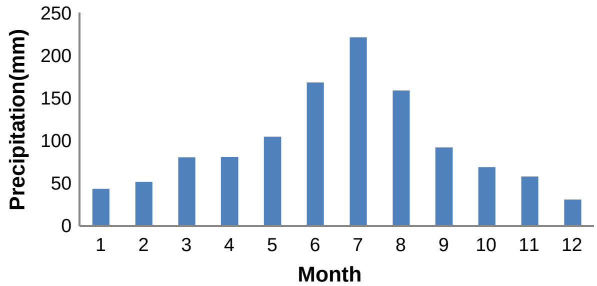

Fig. 2. The mean seasonal cycle of rainfall in the Huai River Basin.

Monthly, seasonal and annual precipitation, precipitation days and maximum daily precipitation during the period of 1960–2010 were calculated from daily precipitation data. The annual streamflow was calculated from daily streamflow datasets.

3. Methodology

In this study, trend analysis methods were used in the flood change analysis. For each station, the trend of precipitation and streamflow from 1960 to 2010 was determined by the Mann–Kendall test and linear regression analysis. Frequency analysis was applied to determine the occurrence probability of floods. To separate and quantify the influences of climate change and local human activity on floods, the distributed hydrological model and a method for the quantitative estimation of impacts were employed.

3.1. Mann–Kendall test

The Mann–Kendall test (M–K), which does not require the data to be distributed normally, is a non-parametric test for trend detection in a time series (Mann, 1945; Kendall, 1962) and has been recommended for general use by the World Meteorological Organisation. The M–K has low sensitivity to abrupt breaks because of inhomogeneous time series (Jaagus, 2006). The M–K has been employed by many studies (Tabari and Talaee, 2011; Zhang et al., 2011a,b). In this test, the null hypothesis H_0 is that the time-series $\{x_1, x_2, \ldots, x_n\}$ is a sample of n independent values and has no variation tendency. The alternative hypothesis H_1 of a two-sided test is that the distributions of x_k and x_j are not identical for all $k, j < n$ with $k \neq j$. For large samples (approximately $n > 10$), the statistic S is normally distributed with Eq. (1) and calculated using Eqs. (2) and (3).

$$E(s) = 0 \quad \mathrm{var}(s) \approx \frac{n(n-1)(2n+5)}{18} \tag{1}$$

$$s = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}\left(x_j - x_j\right) \tag{2}$$

$$\mathrm{sgn}\left(x_j - x_j\right) = \begin{cases} 1 & \left(x_j - x_j\right) > 0 \\ 0 & \left(x_j - x_j\right) = 0 \\ -1 & \left(x_j - x_j\right) < 0 \end{cases} \tag{3}$$

where n is the number of data points. If the residuals are mutually independent, in cases where the sample size $n > 10$, the standard normal variable Z is computed by using Eq. (4).

$$Z = \begin{cases} \dfrac{s-1}{\sqrt{\mathrm{var}(s)}} & s > 0 \\ 0 & s = 0 \\ \dfrac{s+1}{\sqrt{\mathrm{var}(s)}} & s < 0 \end{cases} \tag{4}$$

Positive values of Z indicate increasing trends, whereas negative Z values indicate decreasing trends. The null hypothesis was rejected for an absolute value of Z greater than $Z_{1-\alpha/2}$, which is obtained from the standard normal cumulative distribution tables (Partal and Kahya, 2006; Modarres and Silva, 2007). The α is the significance level. In this paper, a significance level of $\alpha = 0.05$ ($Z_{1-\alpha} = 1.64$) was mainly applied.

3.2. Linear regression

Linear regression analysis, along with the Mann–Kendall test, is applied to detect and analyse trends in the time series. Linear regression is a statistical approach to model the relationship between a scalar dependent variable $Y = \{y_1, y_2, \ldots, y_n\}$ and one or more explanatory variables denoted $X = \{x_1, x_2, \ldots, x_n\}$. Given a dataset $\{Y, X\}$ of n statistical units, a linear regression model assumes that the relationship between the dependent variable y_i, and the p-vector of regressive x_i is linear, which may be expressed as Eq. (5):

$$Y = \beta_0 + \beta_1 X. \tag{5}$$

The regression line can be estimated by estimating the coefficients β_0 and β_1, which can be calculated using the least squares method (Eqs. (6) and (7)) from the observed dataset.

$$\beta_1 = \frac{\sum_{i=1}^{n} x_i \cdot y_i - \frac{1}{n} \sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} \left(x_i - \overline{x}\right)^2} \tag{6}$$

$$\beta_0 = \overline{y} - \beta_1 \overline{x} \quad \overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad \overline{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \tag{7}$$

where $\overline{x}$ is the mean observed values; $\overline{y}$ is the mean predictor variable at which the observations were taken. The coefficients β_1 denotes the change degree of Y along with X.

3.3. Frequency analysis

Frequency analysis can aid in determining the design discharge and design rainfall. Data for frequency analysis can be ranked in either ascending or descending order. For a ranking in descending order, the suggested procedure is as follows: (a) Rank the total number of data in descending order according to their value x; (b) assign a serial number r to each value x (x_r, $r = 1,2,3,\ldots,n$); (c) calculate the frequency F by $F = r / n$, where n stands for total number of records, and r is the rank.

Table 1
Data properties.

Data types	Scale	Source	Data attributes
DEM	3s	USGS	Elevation
Precipitation	172 rain gauges	Huai River Water Resources Commission	Daily and monthly precipitation during 1960–2010
Streamflow	Bengbu station		Daily and monthly streamflow during 1960–2010

3.4. Distributed hydrological model

We select the distributed time-variant gain hydrological model (DTVGM), which has been successfully applied to several basins (Wang et al., 2001; Xia et al., 2003, 2005, 2007) to reconstruct natural streamflow. Studies indicate that DTVGM can explore hydrological simulation processes under environmental changes (Xia et al., 2004). In this study, the DTVGM includes two processes without considering human activity: one is runoff generation in the subbasin (Ye et al., 2010), and the other is routing (Ye et al., 2005; 2006). The DTVGM is basically a water balance model and the rainfall–runoff process considers the water balance equation as Eq. (8).

$$P_i + W_i = W_{i+1} + g_1 \left(\frac{W_{ui}}{WM_u \cdot C_j} \right)^{g_2} P_i + W_{ui} \cdot K_r + f_c \cdot \left(\frac{W_{gi}}{WM_g} \right)^{K_g} + Ep_i \cdot \left(\frac{W_{ui}}{WM_u \cdot C_j} \right) \quad (8)$$

where W is soil moisture (mm); W_u is the upper soil moisture at the sub-basin (mm); W_g is the lower soil moisture at the sub-basin (mm); WM_u is the upper saturated soil moisture (mm); u is the 'upper' soil; WM_g is the lower saturated soil moisture (mm); f_c is the soil permeability coefficient (mm/h); g_1 and g_2 are parameters ($0 < g_1 < 1, 0 < g_2$); g_1 is the runoff coefficient when the soil is saturated; g_2 is the soil moisture parameter; C is the land cover parameter; K_r is the sub-surface runoff coefficient; K_g is the groundwater runoff coefficient; K_e is the evaporation coefficient; i is a period of time; and j is the hydrological unit number.

The routing is calculated from upstream to the basin outlet for each subbasin. The routing model used is the kinematic wave model. To simplify the model, assuming that the friction slope (S_f) is equal to the ground slope (S_0) and the river flow is gradually varying unsteady flow in open channels (Ye et al., 2006, 2013a,b,c), the continuity equation is written as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (9)$$

where A is the river cross section area (m^2); t is time (s); Q is discharge (m^3/s); x is the flow path (m); and q is the lateral inflow (m^2/s).

3.5. Estimation method of quantitative impacts of climate change and human activity on streamflow

Streamflow is always affected by human activities to some degree. The observed streamflow series were a combination of climate change and human activity, whereas the simulated series only consider the climatic change. For simplicity, the difference between the observed data and the simulated data can be approximately taken as the anthropogenic impacts. The relative impact of climate change and human activity can be estimated from the comparison of the observed and simulated series. To accomplish this, the linear regression method was applied to estimate their variation. The total annual streamflow change ΔQ_t and average annual streamflow change due to climate change ΔQ_c were obtained through the linear regression Eq. (5). Based on the assumption that the human activity and climate change are independent, ΔQ_t, can be estimated as follows (Zhang et al., 2008; Zheng et al., 2009):

$$\Delta Q_t = \Delta Q_c + \Delta Q_h \quad (10)$$

where ΔQ_h is average annual streamflow change due to human activity.

The change in average annual streamflow due to various types of human activity can be calculated. Thus, the relative influencing ratio of climatic variation (P_c) and human activity (P_h) on streamflow can be calculated as follows (He et al., 2013):

$$\Delta = |\Delta Q_c| + |\Delta Q_h| \quad (11)$$

$$P_c = \frac{|\Delta Q_c|}{\Delta} \times 100\% \quad (12)$$

$$P_h = \frac{|\Delta Q_h|}{\Delta} \times 100\%. \quad (13)$$

3.6. Model performance measures

The model performance measures include the Nash–Sutcliffe efficiency (NSE) value, correlation coefficient R, and water balance coefficient B, which are computed as follows:

$$NSE = \left[1 - \frac{\sum (Q_s - Q_O)^2}{\sum \left(Q_O - \overline{Q}_O \right)^2} \right] \quad (14)$$

$$R = \frac{\sum \left(Q_s - \overline{Q}_s \right) \left(Q_o - \overline{Q}_o \right)}{\sqrt{\sum \left(Q_s - \overline{Q}_s \right)^2 \sum \left(Q_o - \overline{Q}_o \right)^2}} \quad (15)$$

$$B = \frac{SR}{OR} \quad (16)$$

where $Q_O, Q_s, \overline{Q}_O, \overline{Q}_s$ represent the observed value, simulated value, average observed value, and average simulated value (m^3/s), respectively; SR is the sum of the simulated value (m^3/s); and OR is the sum of the observed value (m^3/s). For NSE and R, the higher the values are, the better the model performance is. The perfect value for both measures is 1. For NSE, a negative value implies that the model performance is worse than the long-term average. The perfect value for B is 1. A value of less than 1 or greater than 1 for B indicates that underestimation or overestimation, respectively.

In addition, an uncertainty analysis of the hydrological model can be found in Kong et al. (2011).

4. Results and discussion

4.1. Changes of precipitation

During the past 51 years, the average annual precipitation was 885 mm, with spatial fluctuation from 704 mm to 1101 mm in the Huai River Basin. The average annual precipitation reduced from >1000 mm (the southern part) to <800 mm (the northeastern part) (Yang et al., 2010). Figs. 3–6 show the spatial–temporal change of precipitation during the period of 1960–2010. The value of Z represents the trend size, and $|Z|$ critical values of 1.28, 1.64, 1.96, 2.33 and 2.58 were used for the quantiles of 90%, 95%, 97.5%, 99% and 99.5%, respectively. The dark black triangle denotes a significantly decreasing trend, and the dark red triangle denotes a significantly increasing trend. The light grey (down) and light red (up) triangles denote insignificant decreasing and increasing trends, respectively. A larger symbol size indicates that the change trend is more significant.

Fig. 3 illustrates the trends of seasonal precipitation indices. Significantly increasing trends in summer and winter precipitation were detected in almost the whole of Huai River Basin. Significantly decreasing trends in autumn precipitation are observed in the western

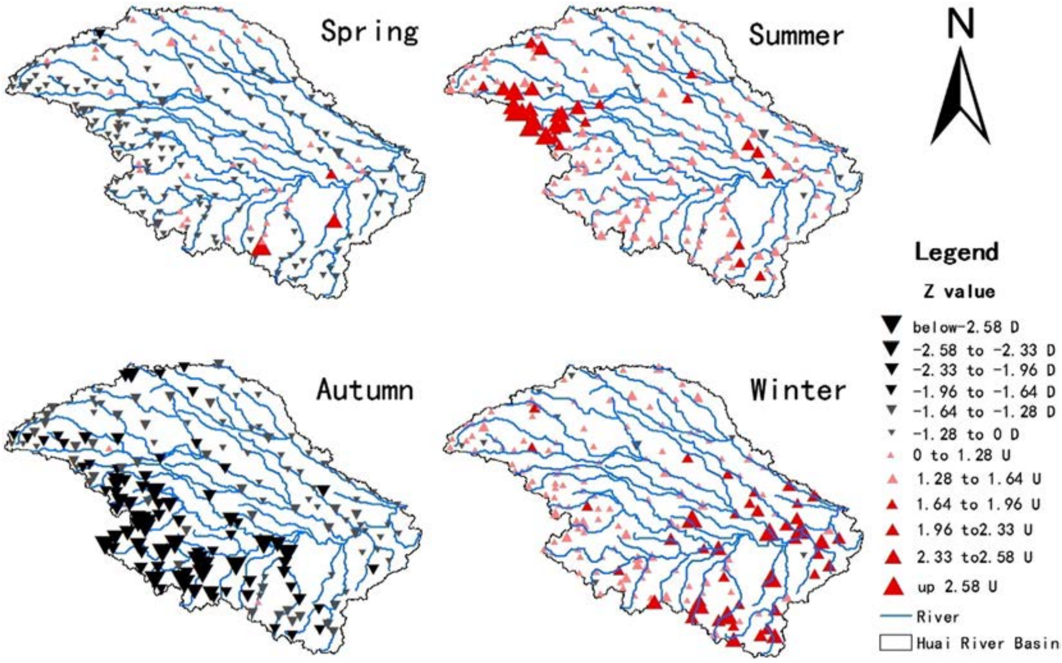

Fig. 3. M–K test trends of seasonal precipitation in the Huai River Basin. Spring is March to May. Summer is June to August. Autumn is September to November. Winter is December to February. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

mountain region. There is almost no significant trend of spring precipitation. In addition, the precipitation change is more significant in the mountain area than the plains area. Fig. 3 illustrates that precipitation in Huai River Basin has a high spatial and temporal variability. Furthermore, the study results indicate an increase in winter and summer precipitation and decrease in spring and autumn precipitation. Summer is the wet season with flooding. Greater precipitation in the summer may lead to more floods.

The spatial distributions of trends of annual precipitation in the Huai River Basin are shown in Fig. 4. Three stations had significant increases, and two stations had significant decreases. As shown in Fig. 4, the absolute values of Z (M–K statistics) were all lower than 1.64 except for only a few stations, indicating that there is no clear tread in total annual precipitation. The general long-term trends in annual precipitation indicate no significant decreasing trends along the plain area of the study area. However, an increasing trend was encountered along the mountain area of the basin (103 of 172 gauges). Thus, it can be seen that the total annual precipitation has changed slightly, but it also displays a high uneven spatial distribution.

We have noted some discrepancies between seasonal precipitation analysis and annual precipitation analysis. Although the annual precipitation analysis indicated that precipitation underwent no significant

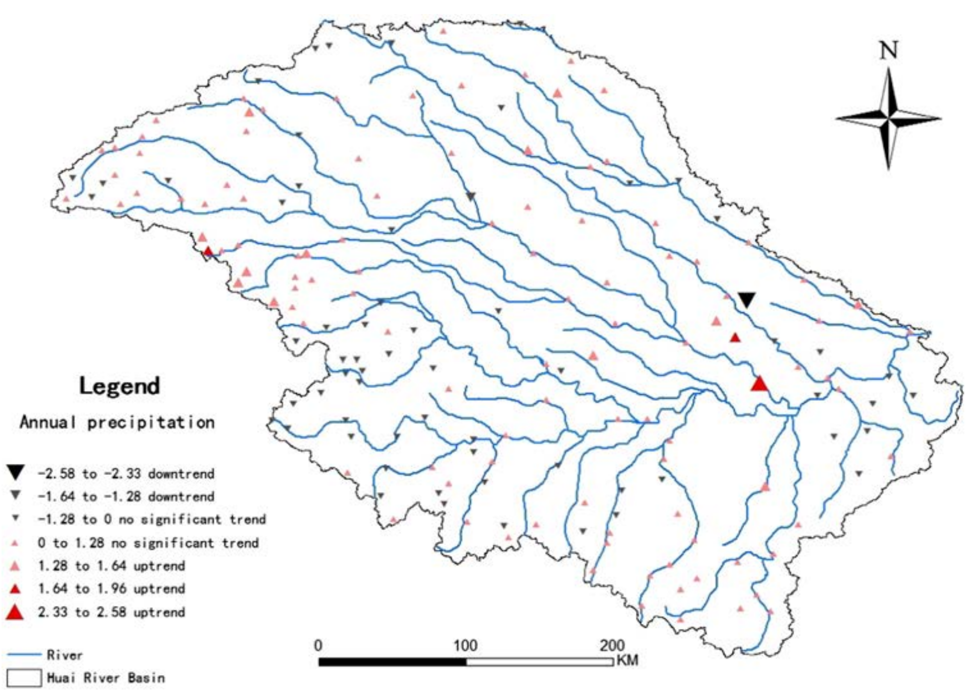

Fig. 4. M–K test trends for annual precipitation in the Huai River Basin. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

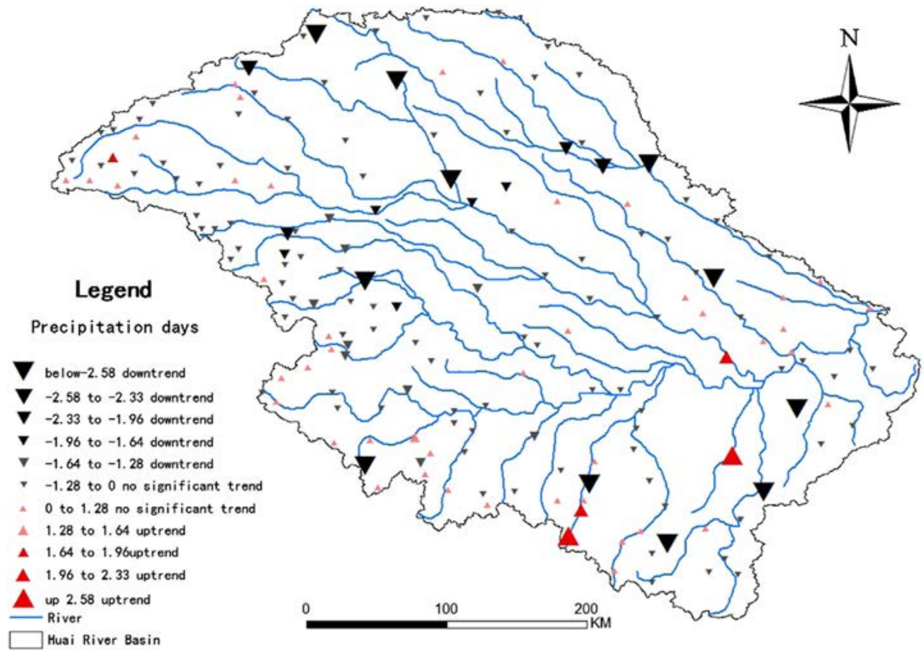

Fig. 5. M–K trends of wet days (daily precipitation > 1 mm) in the Huai River Basin. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

increase in annual precipitation during 1960 to 2010, and the seasonal precipitation analysis found precipitation concentration tends to have its seasonal peaks in summer and winter (Fig. 3).

Fig. 5 shows the trends in wet days (precipitation > 1 mm). In total, they decreased for the most parts of Huai River Basin. The wet days decreased for 72% of the 172 gauges, and there are significantly decreasing trends for 14% of gauges (25 gauges).

The trends of annual maximum daily precipitation in the Huai River Basin are shown in Fig. 6 during 1960–2010. The annual maximum daily precipitation increased in most parts of the study area, where 63% of the gauges displayed increasing tendencies. Out of these stations, 11% of the gauges display significant positive trends. The annual precipitation days decreased, and the annual maximum daily precipitation increased. It is plausible to speculate that precipitation is concentrated in terms of time. Furthermore, heavy precipitation events occur in summer and winter, and precipitation is greater in the mountain area than the plains area. These events are very likely to increase the likelihood of extreme flooding events.

4.2. Changes of observed and simulated streamflow

4.2.1. Changes of observed streamflow

The Mann–Kendall test and linear regression analysis were used to detect the trends of annual streamflow at Bengbu station. The changes

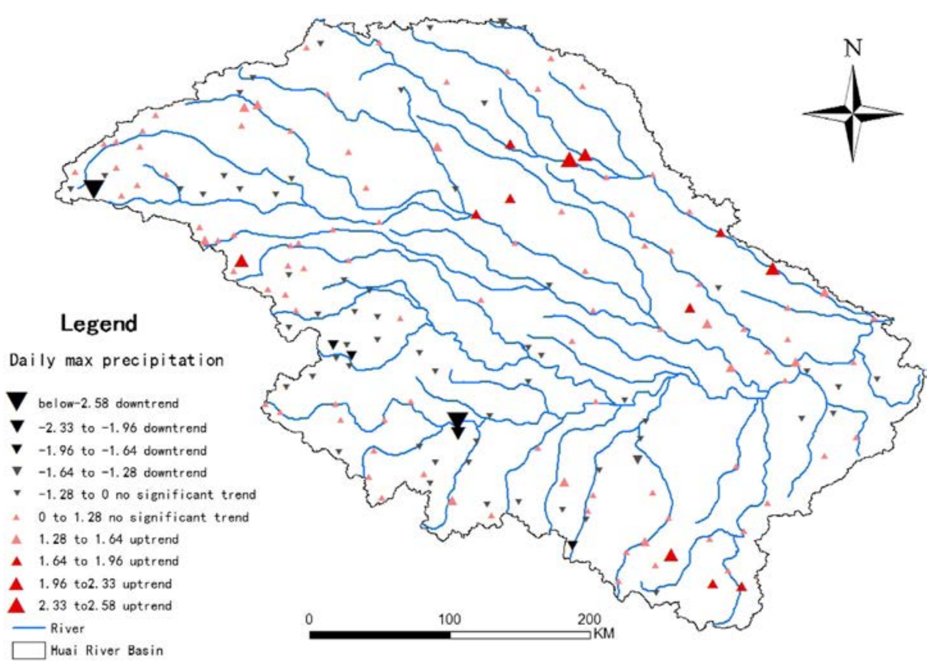

Fig. 6. M–K trends of annual maximum daily precipitation in the Huai River Basin. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

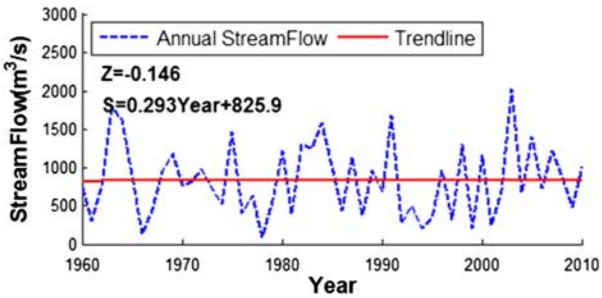

Fig. 7. Annual streamflow during 1960–2010. *S* is streamflow. *Z* is index of M–K test.

in average annual streamflow are shown in Fig. 7. The negative value of *Z* denotes a decreasing but not significant trend in the annual streamflow, indicating that annual streamflow did not significantly change in the Huai River Basin.

As can be seen in Fig. 8, the streamflow for each month at Bengbu station is significantly different in both the amount and variation tendency over the period of 1960–2010. The average monthly streamflow increased in January, February, March (winter) and July, August (summer). These phenomena were caused by precipitation change, including precipitation increases in summer and winter and decreases in spring and autumn. The most obvious trend emerges in March (increasing) and October (decreasing), which may be attributable to reservoir scheduling.

Despite there being little change in annual and monthly streamflow, this cannot be used to confirm that there was no change in flooding. Thus, we extracted the maximum daily streamflow (Fig. 11) and the flood days (Fig. 13) for each year. The M–K test index *Z* is 0.226 for the maximum daily streamflow, which indicates no significant increasing trend from 1960 to 2010. Considering the high concentration of precipitation, we believe that the presence of large number of dams and reservoirs (human activity) plays an important role in effectively reducing the flood risk. To some extent, such projects are able to offset the impact of climate change in the trunk streamflow of the Huai River.

To determine the annual flood days, we used frequency analysis to determine different streamflow thresholds. The 1% frequency streamflow is 5870 m^3/s, and the 5% frequency streamflow is 3670 m^3/s. In this paper, extreme flood is defined as a less than 5% frequency streamflow event occurring at Bengbu station. That is, the streamflow values are greater than 3670 m^3/s. The annual flood days are defined as the number of days with streamflow exceeding 3670 m^3/s.

The M–K test index *Z* is 0.617 for the annual flood days at Bengbu station. The annual flood days increased during 1960–2010. Considering the average annual streamflow, which displays no significant change, we can speculate that the flood events significantly increased in the past 50 years, especially in the most recent decade. That is, flood events are becoming more frequent, e.g., floods in 2003, 2005, and 2007 (Zhao et al., 2007; Yang et al., 2012b), as heavier precipitation concentrations occur in the Huai River Basin.

4.2.2. Model calibration results

There was no change point detected in the Huai River Basin during 1960–2010. However, we know that human activity has influenced the Huai River Basin more dramatically since 1978. More than 5700 dams and 5000 floodgates have been constructed to control flooding and relieve drought in the Huai River Basin. The total storage capacity of the dams and floodgates in the basin is 303 billion m^3, which accounts for 51% of the annual runoff (Zhang et al., 2010). The construction reached its peak from 1970 to 1980 (Zhang et al., 2010). Therefore, the period of 1960–1964 was taken as the baseline (benchmark) period in which the intensity of human activity was relatively small, and the daily and annual hydrometeorological data from 1965 to 2010 was used to validate the model. The *NSE* was 0.742 and 0.68 between the simulated streamflow and observed streamflow in the calibration and verification periods, respectively (Table 2). The correlation coefficient *R* is greater than 0.85, and the water balance coefficient was 0.972 for the calibration period. These demonstrate that the hydrological model has sufficient accuracy for long-term simulation of streamflow without considering the influence of human activity. The water balance coefficient is greater than 1.0 for the verification period.

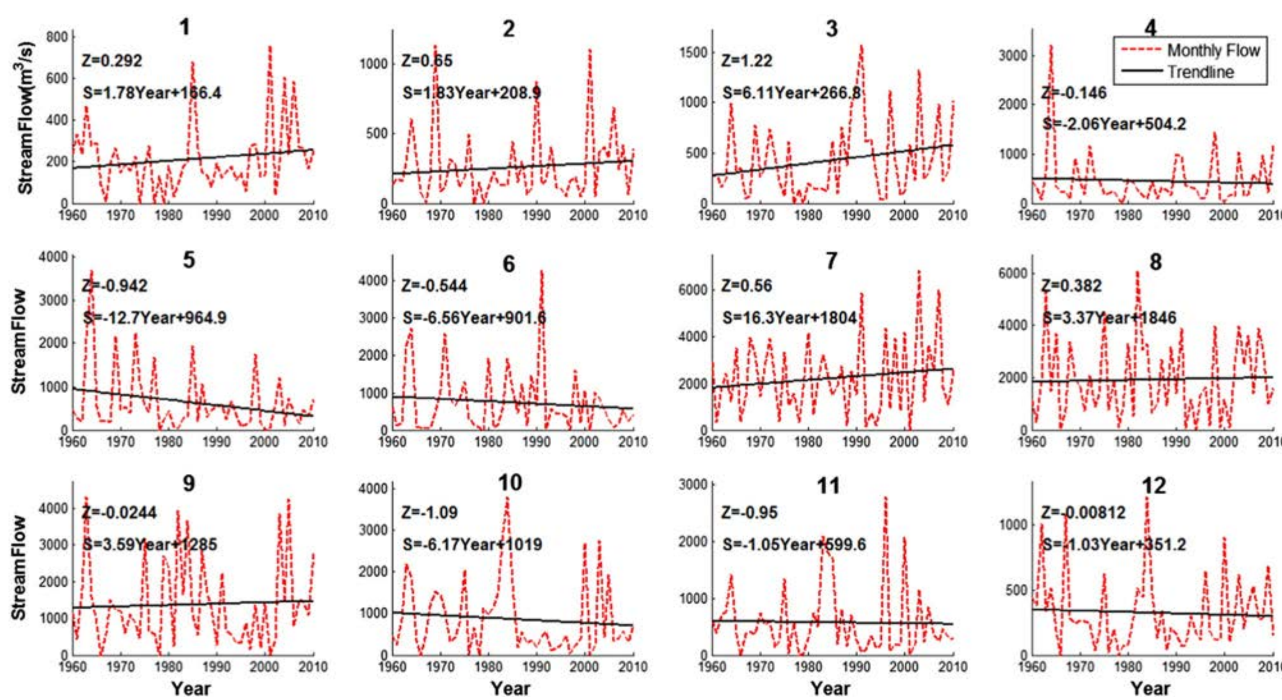

Fig. 8. The monthly streamflow during 1960–2010 in Bengbu station. *S* is streamflow.

Table 2
Performance indices calculated for discharge simulations at Bengbu Station.

	Calibration period, daily (1960–1964)	Verification period, daily (1965–2010)	Verification period, annual (1965–2010)
NSE	0.742	0.68	0.745
R	0.862	0.852	0.932
B	0.972	1.15	1.15

The main cause is human water use, without the model considering human activity.

Figs. 9 and 10 are the simulated and observed streamflow at Bengbu station for the calibration and validation periods. Figs. 9 and 10 show a good match between the simulated and observed streamflow.

Precipitation is the most important and sensitive input of hydrological model. If the model is too sensitive, then it will exaggerate the streamflow response. Kong et al. (2011) and Zhan et al. (2013) applied sensitivity analysis methods, including the RSMSobol, analyse the parameter sensitivity of distributed time-variant gain hydrological model (DTVGM) in Huai River Basin. The results revealed that the runoff parameters g_1 and g_2 (Eq. (8)) are the most sensitive for the water balance coefficient and Nash–Sutcliffe coefficient. When we got the optimal parameters in the calibration period, the model would be stable and reliable in the verification period. In order to know the model sensitive for precipitation, we changed the precipitation and compared the simulated streamflow in 1960–2009. We found that the variation is similar to streamflow by precipitation. The simulated streamflow decreased 18.37% if the precipitation decreased 10%. The simulated streamflow decreased 9.40% if the precipitation decreased 5%. The simulated streamflow increased 9.79% if the precipitation increased 5%. The simulated streamflow increased 19.97% if the precipitation increased 10%. The relation was stable between streamflow and precipitation, which demonstrated that the DTVGM can be used to analyse the impact of climate change and human activity on changes in flooding.

4.2.3. Comparison of changes between observed and simulated streamflow

In this study, we set the simulated streamflow to the natural streamflow, which was only affected by climate change from 1960 to 2009. The observed streamflow reflects the combined effects of human activity and climate change.

Fig. 11 shows the annual maximum daily simulated and observed streamflow for 1960–2010 at Bengbu station. The observed streamflow is the black dashed line. The simulated streamflow is the red dashed line. Both observed streamflow and simulated streamflow show insignificantly increasing trends. The simulated peak streamflow is apparently greater than the observed peak streamflow. In the other words, the natural flood peak must be greater than the actual (observed) flood peak.

Frequency analysis curve can be used to analyse daily streamflow at Bengbu station. Fig. 12 presents the frequency curves of the simulated and observed daily streamflow from 1960 to 2009 at Bengbu station. The low frequency simulated streamflow is significantly greater than the observed streamflow. These results indicate that human activity plays a more important role in the heavier floods.

The flood days are almost in agreement between the simulated and observed values (Fig. 13). The simulated and observed flood days increased. However, there were more simulated flood days in some years than observed ones. These results further confirm that climate change and human activity jointly trigger altered flooding across the Huai River Basin.

4.3. Quantitative evaluation

An analysis of quantitative impacts on flooding due to human activity and climate change was performed in the Huai River Basin. The streamflow change due to climate change was obtained from the simulated streamflow using the DTVGM model for 1960–2010. The quantitative impacts of climate change and human activities were identified by the method presented in Section 3.5, and the results are shown in Table 3. It can be seen from Table 3 that the annual maximum daily observed streamflow increased by 7.29 $m^3/s\ year^{-1}$, whereas streamflow due to climate change increased by 40.8 $m^3/s\ year^{-1}$, and human activities decreased streamflow by 33.51 $m^3/s\ year^{-1}$. A 45% decrease of annual maximum daily streamflow was contributed to by human activity. On the contrary, climate change contributed the 55% increase to annual maximum daily streamflow, which was greater than the decrease due to human activity. The effect on streamflow is dominated by the precipitation system, and human activity also changes the natural geographical conditions of the basin and causes changes in the hydrological circle system.

4.4. Discussion

Climate change can have profound effects on flooding through alterations in precipitation, evapotranspiration and temperature. As shown in IPCC, precipitation generally exhibits large natural variability, and El Niño and changes in atmospheric circulation patterns have a substantial influence. Seasonal variations of precipitation are primarily associated with water vapour in the atmosphere arising from the oceans, with more precipitation in monsoon season and less precipitation in other seasons. Flooding will be intensified with greater precipitation. However, the extra precipitation is unequally distributed around the Huai River

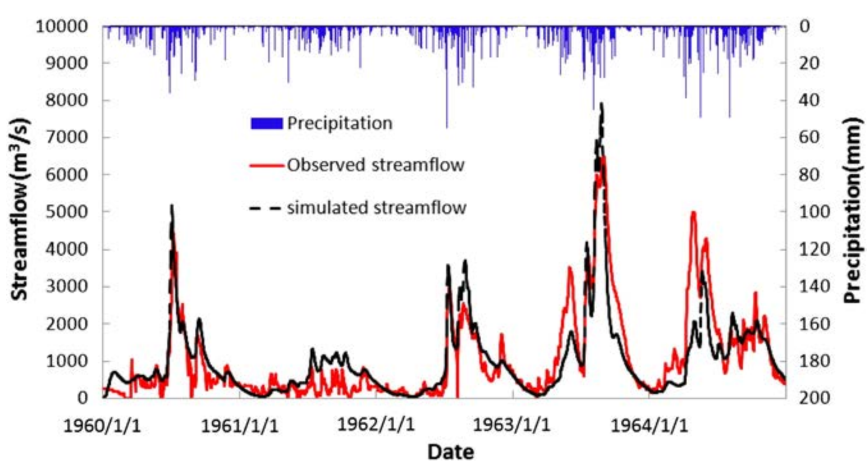

Fig. 9. Long-term daily hydrographs for the calibration period (1960–1964) at Bengbu station.

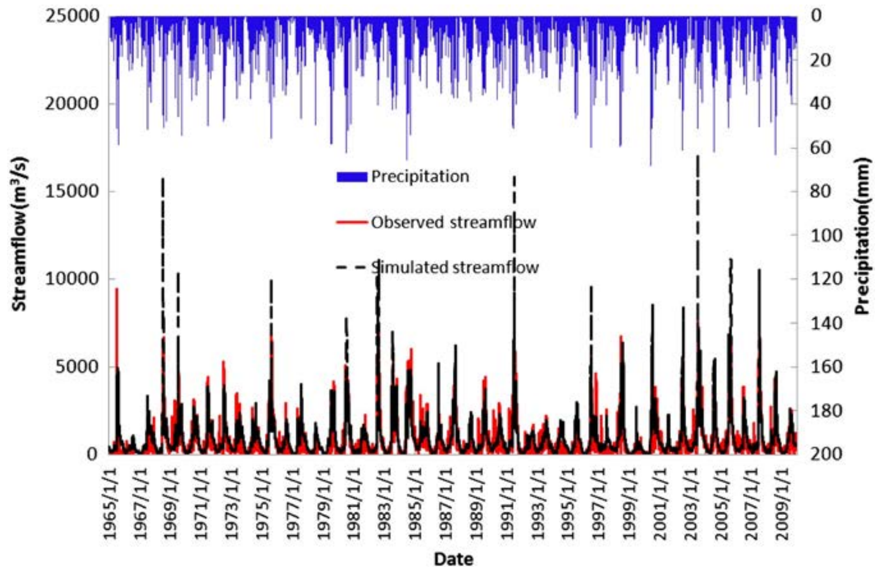

Fig. 10. Long-term daily hydrographs for the verification period (1965–2010) at Bengbu station.

Basin, leading to an increased probability of extreme events of the hydrological regime. Previous studies have identified climate change (mainly precipitation) as a main causative factor that impacts the hydrological cycle (Zhang et al., 2011a; Liu et al., 2013). However, human activities, such as water resource management, hydropower engineering, agricultural irrigation and urbanisation, may also affect the frequency and intensity of some extreme events. As Xia et al. (2008) indicated, dam and floodgate operation tend to reduce streamflow, decrease peak value and shift peak time. After the founding of the People's Republic of China, in 1949, the Chinese government strengthened the environmental comprehensive treatment of key river basins, including the Huai River Basin. By the year 2000, 5741 small and large-sized water reservoirs and embankments had been built in the Huai River Basin, for a total volume amounting to 30.3 billion m^3, accounting for 51% of the mean annual runoff (Zhang et al., 2010). In addition, large projects have a considerable storage capacity, accounting for 63% of the total water projects in Huai River Basin. These reservoirs are capable of absorbing water during the rainy seasons and releasing it slowly during the dry seasons, consequently leading to a decrease in intra-annual variation of the streamflow (Huang et al., 2012). They can be used to balance the flow in highly managed systems, reduce the risk and intensity of flooding and guarantee water supply for irrigation effectively in the Huai River Basin. As human-established crops used more water, streamflow in the watercourse decreased in the basin. The dominant land use types of the Huai River Basin are dry land and paddy fields, accounting for 55% and 15% of land, respectively. In addition, rural residence, woodland, grassland and other areas account for 10%, 7%, 5% and 8% of land, respectively. As can be observed from the collected land use data, due to economic growth and urbanisation, there has been a 1% reduction in areas of dry land and paddy fields and a slight increase in areas of urban and rural residences. In conclusion, the altered streamflow in the Huai River Basin is due to climate change (such as precipitation change) and human activity (such as the construction of reservoirs, decreasing of the dry land and paddy fields, and enlarged water surface areas).

5. Conclusions

Climate change and human activity have significantly affected the streamflow in the Huai River Basin. In this study, the annual and seasonal trends of streamflow were analysed for one hydrological station (Bengbu) during the period of 1960 to 2010. Spatial and temporal variations of annual precipitation from 172 stations in Huai River Basin were also determined. To accomplish this analysis, a non-parametric Mann–Kendall statistical method and linear regression method were successfully used. This study defined a conceptual framework and

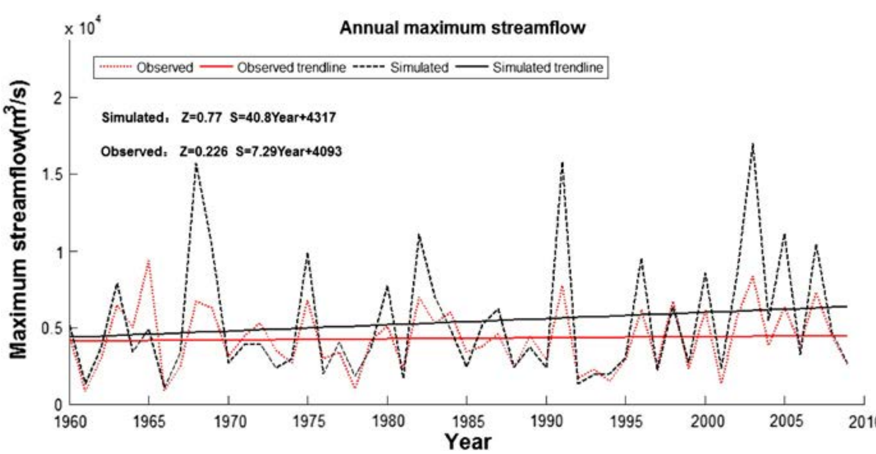

Fig. 11. Annual maximum daily streamflow for the 1960–2010 at Bengbu station. *S* is streamflow. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

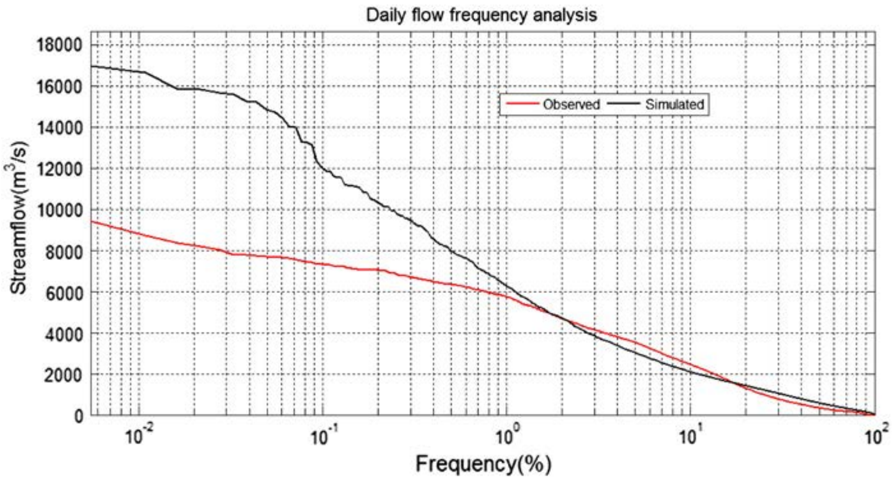

Fig. 12. The frequency curves of daily streamflow during 1960–2009 at Bengbu station.

applied a hydrological model (DTVGM) to quantify the effects of climate change and human activity on streamflow. The model was first calibrated for the period 1960 to 1964 using daily hydro-meteorological data and then was used to reconstruct the natural streamflow without considering local human activities for the entire period. In this study, the conclusions can be drawn as follows:

(1) Variations of spatial and temporal precipitation during 1960–2010 illustrate the uneven distribution in the Huai River Basin. No significant trend was revealed for total annual precipitation within the study period. There are strong increasing trends in both the summer and winter precipitation data series, whereas there are decreasing trends for both spring and autumn precipitation, and the decreasing trend is more remarkable in autumn. The mountain regions receive relatively more precipitation during the flood season, whereas they become drier in the dry season. The increase of precipitation in summer may lead to a greater risk of flooding in the Huai River Basin.
(2) The highly uneven spatial and temporal distribution of seasonal precipitation produces similar uneven seasonal streamflow. The annual streamflow from the Huai River Basin has an insignificant increasing trend during the period of 1960–2010. Extreme flood events in the Huai River Basin are increasing.
(3) Quantitative assessment revealed that climate change resulted in an increase in streamflow of 40.8 $m^3/s\ year^{-1}$ in 1960–2010 for the whole catchment, accounting for 55% of streamflow change. However, human activity may be responsible for a decrease in streamflow of 33.51 $m^3/s\ year^{-1}$ in 1960–2010, which accounts for 45% of streamflow change. It is suggested that the increase in streamflow in 1960–2010 can mainly be attributed to climate change, and human activity produced a negative effect on streamflow increase.
(4) Quantifying the effects of climate change and human activity on streamflow will contribute to regional water resource assessment and management. For the basin, human activities such as farmland irrigation, river regulation and construction of reservoirs and dams are the main anthropogenic stresses altering hydrological processes and decreasing flood risk.

However, the exact quantification of each individual impact is difficult. The effects of specific human activities on the streamflow require further study.

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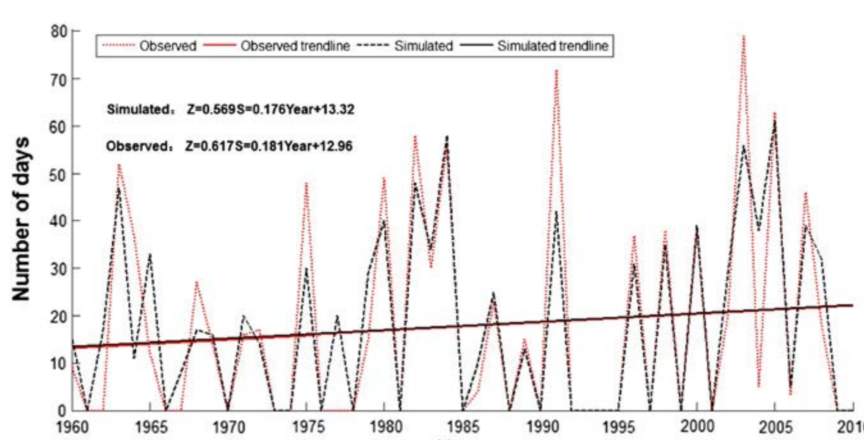

Fig. 13. The annual flood days at 5% frequency during 1960–2009 at Bengbu station.

Table 3
Impacts of climate change and human activities on the annual maximum daily streamflow.

Annual maximum daily Streamflow	Linear regress function	Change ΔQ (m^3/s)	Rate of contribution (P)
Observed	$S = 7.29$ yr $+ 4093$	7.29	100%
Simulated (nature)	$S = 40.8$ yr $+ 4317$	40.8 (ΔQ_c)	55% (P_c)
Human activities		−33.51 (ΔQ_h)	45% (P_h)

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