Detecting evolution trends in the recorded runoffs from the major rivers in China during 1950–2010
G. Q. Wang, X. L. Yan, J. Y. Zhang, C. S. Liu, J. L. Jin, Y. L. Liu and Z. X. Bao

ABSTRACT
Evolution trends as well as abrupt changes in recorded runoffs from the major rivers in China during 1950–2010 were investigated using the Mann–Kendall test and ordered clustering analysis. Results show that the recorded runoff series at ten key hydrometric stations on the major rivers in China are characterized by a general decreasing trend. A significant decrease has occurred at six stations: Yichang, Huayuankou, Guantai, Shixiali, Tieling and Haerbin stations, which are located on the northern major rivers. Abrupt changes in runoff series are detectable for the Yellow River (1986), the Hai River (1965 at Guantai station, 1970 at Shixiali station) and the Liao River (1965). The relationship between runoff and precipitation at these stations is different before and after the abrupt change. Intensive human activities, such as land use change, water conservation projects, water diversion projects and rapid increases in agricultural irrigation, are likely to be among the main causes of the abrupt changes in runoff. Effective strategies for water conservation and adaptation to climate change will be needed to ensure sustainable use of water resources and safeguard economic growth under China’s 12th 5-year plan.

Key words | abrupt change, major rivers, runoff, trends

INTRODUCTION
Water is arguably China’s most valuable resource. The continued economic and social development of China is critically dependent on water resources. A growing population and higher living standards, together with expanding industrial and agricultural production, place increasing demands on water resources.

River flow in the lower reaches of rivers is of crucial importance in ecological, social and economic contexts (Cui 2002). Due to climate change and intensive human activities, the discharge of many rivers is changing (Zhang & Wang 2007). About 22% of the world’s rivers were shown to have had a significant decrease in annual runoff over recent decades because of water consumption, diversion and reservoir construction; on the other hand, about 9% of the world’s rivers showed significant increasing trends in annual runoff as a result of more frequent extreme rainstorms, as well as human activities including urbanization (Walling & Fang 2003). In China, for example, the Yellow River ran dry in its lower reaches for 226 days in 1997. This dramatic decrease in discharge has had great impacts on the economy of the delta and on the ecology of the adjacent sea (Cui 2002).

Although the total amount of water resources in China is approximately 2,800 billion m³, the amount per capita is only about 2,185 m³, less than 30% of the world average (MWR 1992). Furthermore, the spatial and temporal distribution of water resources is uneven. Thus, water resources are becoming one of the key limiting factors for the socioeconomic development of China, and changes in runoff from major rivers in China will probably bring considerable challenges for security of water supply.

There have been many studies aimed at detecting trends in long time series of runoff data. Xu et al. (2005) analyzed trends in water resource use from the Trim River using linear regression and the Mann–Kendall rank test, and found a relationship between change in water resources
and global warming. Cao et al. (2007) detected the variation trend of runoff in the watershed that feeds the Yangtze River, and found that a temperature rise and a slight decrease in precipitation during 1956–2000 resulted in a decrease in runoff. Zhang et al. (2009) investigated characteristics of runoff variation from the Yellow River using the Mann–Kendall rank test and Spearman’s rank test, and concluded that the significant reduction in runoff mainly resulted from human activities. Zbigniew et al. (2005) used the Mann–Kendall test to detect trends in annual maximum flow for 197 gauging stations around the world, and found that for European series the maximum discharge occurred more frequently in the period 1981-2000 compared with 1961–1980. Other methods frequently used in trend detection include rescaled-range (R/S) analysis (Wang et al. 2002), the Rank Sum Test (Pettitt 1979, 1980), the Run Test, the Brown-Forsythe test (Zhang 2005) and Bayesian methods (Lee & Heghinian 1977; Xiong et al. 2003). Although some studies have detected trends in annual runoff for individual rivers in China, the time span of the data series is generally less than 50 years, and to our knowledge there are no published analyses of abrupt changes in runoff from all major Chinese rivers using longer runoff series.

The main purposes of this paper are: (1) to detect trends in runoff series from 1951 to 2010 for major rivers in China and examine their significance; (2) to identify years with abrupt changes in mean runoff that may have anthropogenic causes; and (3) to investigate the likely reasons for the abrupt changes identified.

DATA AND METHODOLOGY

Study area and data source

China, one of the largest countries in the world, spans about 62 degrees in longitude and 50 degrees in latitude, with a total area of 9,600,000 km², about one-fifteenth of the global land surface. The climatic conditions of China are complex and diverse because of its vast territory and complicated topography. The monsoon climate is a predominant feature. About 60–80% of the country’s annual precipitation falls during the rainy season, which normally lasts four months. The spatial distribution of precipitation is highly uneven, ranging from over 2,000 mm annually in the southeast coast region to less than 200 mm in northwest China. China has a large number of rivers, including more than 50,000 with drainage areas over 100 km². Owing to the varied topography and climate, the geographic distribution of river systems is very uneven; the majority of rivers are located in the eastern part of China, where the monsoon climate produces abundant rainfall, while fewer are located in the arid northwest inner region, where precipitation is limited owing to the continental climatic conditions.

There are seven major river systems in China in terms of drainage area, namely the Yangtze River, Yellow River, Huai River, Hai River, Liao River, Songhua River and Pearl River. We collected recorded runoff series from 1950 to 2010 at ten hydrometric stations on these seven rivers from the Hydrology Bureau of the Ministry of Water Resources. The areal average precipitation series corresponding to runoff observations were calculated based on data from 765 rain gauges collected from the China Meteorology Administration. The major river systems in China and the locations of the ten hydrometric stations are shown in Figure 1.

The selected hydrometric stations monitor most of the drainage area for each river system, except the hydrometric stations on the Hai River. For example, Datong station on the Yangtze River has a drainage area of 1,705,383 km², approximately 94% of the total drainage area of the Yangtze River basin. The Hai River basin consists of over ten sub-river systems, including the Luanhe River, Chaobaihe...
River and Tuhaimajiahe River, with a total drainage area of approximately 318,161 km². Although the selected hydrometric stations from the Hai River have drainage areas of 17,800 and 23,627 km², respectively, which are much smaller than the areas monitored by other hydrometric stations in this study, these two stations still control the majority of the area of each sub-river system.

**Methodology**

The Mann–Kendall rank test and ordered clustering analysis were used to detect trends in runoff series and to identify abrupt change points. The Mann–Kendall rank test is a non-parametric, distribution-free method to detect trends in series with minimal assumptions (Mann 1945). It has been widely used in trend detection for time series (Zhang et al. 2006; Kundzewicz & Robson 2004; Zhang & Wang 2007). The Mann–Kendall rank test statistic is calculated as follows:

\[ k = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_i - x_j) \]  

(1)

\[ \text{sgn}(x_i - x_j) = \begin{cases} 0 & \text{if } x_i - x_j \geq 0 \\ 1 & \text{if } x_i - x_j < 0 \end{cases} \]  

(2)

where \( x_i \) and \( x_j \) are the sequential measurements of annual runoff and \( n \) is the length of the data set.

Statistic \( U \) is called the Mann–Kendall rank test index, or M–K value. Under the null hypothesis of no trend, when \( n \) increases, \( U \) follows the standard normal distribution and is mathematically expressed as follows:

\[ U = \frac{\tau}{\sqrt{\text{var}(\tau)}} \]  

(3)

\[ \tau = \frac{4k}{n(n-1)} - 1 \]  

(4)

\[ \text{var}(\tau) = \frac{2(2n+5)}{9n(n-1)} \]  

(5)

A positive or negative M–K value represents an upward or downward trend, respectively. The null hypothesis is rejected at the significance level of \( \alpha \) if \(|U| \geq U_{\alpha/2}\), where \( U_{\alpha/2} \) is the critical value of the standard normal distribution with a probability exceeding \( \alpha/2 \). If \(|U| < U_{\alpha/2}\), the null hypothesis is accepted and the trend is deemed not significant. When the significance level \( \alpha = 5\% \), then \( U_{\alpha/2} = 1.96 \).

Hydrological series may be significantly altered by intensive human activities in a river basin. Abrupt changes in hydrological series have attracted attention from river basin managers as well as local government officials who want to better understand the impacts of human activities such as water diversion and hydraulic engineering construction. There are many methods available in the literature for detection of abrupt changes in a time series, such as ordered clustering analysis (Ding & Deng 1988; Wang et al. 2001; Wang et al. 2009). Bayesian methods (Xiong et al. 2003) and Brown–Forsythe-based methods (Zhang et al. 2005). Of these methods, ordered clustering analysis is a simple yet effective way to detect a critical year of abrupt change by examining the minimum sum of squared deviations for the data series before and after the possible critical year, as follows:

\[ V_\tau = \sum_{i=1}^{\tau} (a_i - \bar{a})^2 \]  

(6)

\[ V_{n-\tau} = \sum_{i=\tau+1}^{n} (a_i - \bar{a}_{n-\tau})^2 \]  

(7)

\[ \text{SumK}(\tau) = V_\tau + V_{n-\tau} \]  

(8)

where \( \bar{a}_\tau \) and \( \bar{a}_{n-\tau} \) are mean values of hydrological series before and after the possible critical year \( \tau \), respectively; \( a_i \) is the hydrological variable (i.e. runoff) for each year \( i \); \( V_\tau \) and \( V_{n-\tau} \) are the sum of the squared deviations of hydrological series before and after the possible critical year \( \tau \), respectively; \( \text{SumK}(\tau) \) is the total sum of squared deviations during the two periods; and \( n \) is the number of data samples. The critical year \( \tau_0 \) will produce the minimum value of \( \text{SumK}(\tau) \), namely:

\[ \text{SumK}(\tau_0) = \min\left\{\text{SumK}(\tau)\right\} \]  

(9)

In most cases, there is only one minimum value of \( \text{SumK}(\tau) \), and \( \tau_0 \) is unique.
The detected abrupt change year divides the hydrological series into two sets of data. We used the $F$ test to test the significance of the abrupt change year by comparing the variances of these two data sets from before and after the abrupt change year (pre-series and post-series). The $F$ statistic is defined as follows:

$$F = \frac{S^2_a}{S^2_b}$$

where $S^2_a$ is the variance of the pre-series data and $S^2_b$ is the variance of the post-series data.

Given a significance level of $\alpha = 5\%$, if $F > F_{a,N_1,N_2}$, the hypothesis that the two variances are equal is rejected, meaning that the abrupt change year is significant. Here $F_{a,N_1,N_2}$ represents the critical value of the $F$ distribution with $N_1$ and $N_2$ degrees of freedom (sample numbers of the two data sets) and a significance level of $\alpha$.

**RESULTS AND DISCUSSION**

**Changes in runoff during recent decades**

The Ministry of Water Resources (1992) organized the first assessment of national water resources in 1980. During recent decades, agriculture and industry have rapidly developed in China; substantial socio-economic changes have also occurred. Intensive human activities and climate change during the past 50 years may have resulted in changes in runoff in major rivers. To identify relevant trends and possible drivers of change over the period 1980–2010, we used runoff series from 1950 to 1979 as a baseline for comparison. Annual runoff at Datong station increased by 1.8% between these two periods, while runoff at the other nine stations decreased by 2.5–80.1%, with the greatest decrease occurring at Guantai station. In general, runoff in northern rivers has decreased more than in southern rivers; for example, runoff in the Hai River, located in northeast China, decreased by 79.6 and 80.1% at Shixiali station and Guantai station, respectively. In contrast, in central and southeast China, the changes are less, with a decrease of 2.5% in the Huai River (Wujiaodu station) and 4.9% in the Pearl River (Wuzhou station). The runoff has changed not only in terms of annual amount, but also in the seasonal distribution. Changes in mean monthly runoff at the ten stations between 1950–1979 and 1980–2010 are presented in Table 1.

Table 1 shows that for most months (grey boxes), in the rivers of northern China, including the Hai River, Yellow River and Liao River, recorded runoffs decreased, with the greatest decreases occurring in the Hai River. Increased water consumption due to rapid industry and agriculture development and population growth is one of the main drivers of the decrease in river runoff. Statistical results indicate that the total water usage in China has increased by 102.8% during 1965–1997, from 274.4 billion m$^3$ in 1965 to 556.6 billion m$^3$ in 1997, and nearly half of this increase has occurred in northern China (Qian & Zhang 2001). As mentioned above, China is characterized by water abundance in the south and scarcity in the north. Thus, dramatic increases in water consumption have led to decreasing runoff in most major rivers in China, with the greatest decreases occurring in already dry northern rivers such as the Hai River.

**Trend detection in runoff series**

We studied trends in annual and seasonal runoff series during 1950–2010. Four seasons were defined according to their climatic characteristics and hydrological features: March–April–May for spring (MAM), June–July–August for summer (JJA), September–October–November for autumn (SON) and December–January–February (the following year) for winter (DJF). Auto-correlation analysis of observational data series from the ten hydrometric stations showed that the runoff series are weakly auto-correlated, with the highest first-order auto-correlation coefficient of −0.236 occurring at Yichang station. This coefficient is lower than the critical value of 0.25 at the significance level of 0.05. Therefore, we examined trends in runoff series using the Mann–Kendall rank test and used linear regression to fit a regression line to each annual runoff series. The slope coefficient of the regression line indicates the magnitude of the upward or downward trend of the time series. The results of the linear regression and the Mann–Kendall test for all stations are summarized in Table 2.
Table 2 shows that $A$, the linear decline rate of annual runoff over 1950–2010, varied from 0.021 billion m$^3$/annum to 0.72 billion m$^3$/annum for all stations, with the highest value at Yichang station and the lowest at Shixiali station. Higher values of $A$ occur at Yichang, Huayuankou and Datong stations; Yichang and Datong stations are also characterized by high mean annual runoff. Conversely, Shixiali, Tangnaihai and Guantai stations have lower values of $A$ as well as lower mean annual runoff.

The Mann–Kendall test results in Table 2 indicate that six stations have a significant decrease ($\alpha = 5\%$) in annual runoff. These included Yichang station on the Yangtze River, Huayuankou station on the Yellow River, Guantai station and Shixiali station on the Hai River, Haerbin station on the Songhua River and Tieling station on the Liao River. The most significant decline (M–K value of $-8.86$) occurred at Shixiali station; however, this station has an $A$ of $-0.021$ billion m$^3$/annum, implying the lowest decline rate of this station among all ten stations, which does not match the result of the Mann–Kendall test. Further analysis indicates that the reason for this could be related to the different amounts of annual runoff at different stations. Although $A$ reflects the upward or downward trends of runoff series, it cannot properly reflect the overall strength of these trends owing to the differences in annual runoff.

$A/W$, the ratio of $A$ (rate of decline in annual runoff) to $W$ (mean annual runoff), could be more effective than $A$ in describing the strength of a runoff series trend. For example, $A/W$ and the M–K value at Shixiali station are approximately $-4.42\%/year$ and $-8.86$, respectively; both indicate that the greatest decline in annual runoff has occurred at this station. The values of these two indicators at Datong station are $-0.048\%/year$ and $-0.274$, respectively, both indicating that this station has had the least decline.

Owing to the effects of the Asian Monsoon climate and topography, seasonal runoffs in China are quite varied. Trend detection results for seasonal runoff series are given in Figure 2.

Figure 2 shows that the seasonal runoffs for most stations presented decreasing trends, except winter runoff at Yichang station and Datong station on the Yangtze River and at Wuzhou station on the Pearl River, and spring runoff at Yichang station. Significant decreasing trends are detectable at stations on the northern rivers, for
example the Hai River (Shixiali station and Guantai station) and the lower Yellow River (Huayuankou station). During recent decades, the population in the Hai River basin increased by approximately 24% from 1980 to 2008, and water consumption increased by about 36% (Ding et al. 2012). Human activities, including water conservation projects construction, as well as increased water consumption due to population growth and socio-economic development, are main drivers of the decreasing runoff, for example the Hai River.

In general, the Mann–Kendall test results shown in Figure 2 are in accordance with the annual runoff comparisons in Table 1. The exception was Datong station, where the annual runoff in 1980–2010 was 1.8% greater than in 1950–1979, but the Mann–Kendall test showed an insignificant decreasing trend in the annual runoff series over 1950–2010. The 1990s were a wet decade for Datong station, while 2001–2010 was a dry decade. Although the mean value of annual runoff during 1980–2010 was slightly higher than the baseline (1950–1979), the significant

### Table 2 | Results of trend detection analysis for the annual runoff series at ten key stations on the major rivers in China

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Station name</th>
<th>A (10⁶ m³/year)</th>
<th>W (10⁶ m³)</th>
<th>A/W (%)/year</th>
<th>M–K value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yichang</td>
<td>– 0.720</td>
<td>428.970</td>
<td>– 0.168</td>
<td>– 1.979</td>
</tr>
<tr>
<td>2</td>
<td>Datong</td>
<td>– 0.430</td>
<td>892.960</td>
<td>– 0.048</td>
<td>– 0.274</td>
</tr>
<tr>
<td>3</td>
<td>Huayuankou</td>
<td>– 0.528</td>
<td>37.464</td>
<td>– 1.408</td>
<td>– 5.75</td>
</tr>
<tr>
<td>4</td>
<td>Tangnaihai</td>
<td>– 0.036</td>
<td>19.889</td>
<td>– 0.179</td>
<td>– 1.282</td>
</tr>
<tr>
<td>5</td>
<td>Shixiali</td>
<td>– 0.021</td>
<td>0.464</td>
<td>– 4.418</td>
<td>– 8.861</td>
</tr>
<tr>
<td>6</td>
<td>Guantai</td>
<td>– 0.037</td>
<td>0.905</td>
<td>– 4.112</td>
<td>– 5.931</td>
</tr>
<tr>
<td>7</td>
<td>Haerbin</td>
<td>– 0.352</td>
<td>40.842</td>
<td>– 0.862</td>
<td>– 3.455</td>
</tr>
<tr>
<td>8</td>
<td>Tieling</td>
<td>– 0.053</td>
<td>3.070</td>
<td>– 1.710</td>
<td>– 3.684</td>
</tr>
<tr>
<td>9</td>
<td>Wujiadu</td>
<td>– 0.078</td>
<td>28.213</td>
<td>– 0.278</td>
<td>– 0.734</td>
</tr>
<tr>
<td>10</td>
<td>Wuzhou</td>
<td>– 0.302</td>
<td>205.314</td>
<td>– 0.147</td>
<td>– 1.431</td>
</tr>
</tbody>
</table>

Note: A, slope coefficient of the regression line for runoff series; W, mean of annual runoff.

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continuous decline in annual runoff during 1998–2010 may be the main reason for the decreasing trend of annual runoff over the period of 1950–2010. Reservoir regulation for flood control purposes – storing water in the flood season and releasing it in the dry season – is believed to be one of main drivers altering the seasonal distribution pattern of downstream runoff. We detected a significant increasing trend in winter runoff at Yichang and Datong stations on the Yangtze River, probably resulting from the Three Gorges Reservoir, which has been in operation since 2003.

Trend detection results indicated there have been significant decreases in annual runoff as well as in seasonal runoff in China’s northern rivers. Rainfall is a prominent factor in runoff yield, and because the ten selected basins are large, the monthly discharge at a given time may come partly from precipitation in the previous months. We therefore analyzed the correspondence between trends in annual precipitation series and runoff series, and examined the lag correlation between precipitation and runoff at monthly scale (Table 3).

Table 3 shows that annual precipitation decreased in nine basins. In the upper Yellow River (above Tangnaihai station), no significant trend was detected. Annual precipitation decreased most in the Liao River, Songhua River, Hai River and middle Yellow River basins, with M–K values above 1.0. Monthly runoff was highly correlated with precipitation in the same month for humid basins, but poorly correlated for arid basins. For example, the correlation coefficient for Wuzhou station on the Pearl River, the wettest basin in the study, is 0.86, much higher than those in drier basins (0.54 at Shixial station on the Hai River, 0.55 at Tieling station on the Liao River). Runoff is positively correlated with precipitation in the same month and previous months, but correlation coefficients between runoff and previous precipitation are lower than those between runoff and precipitation in the same month, implying that precipitation in previous months may contribute partly to runoff, but precipitation in the same month plays a dominant role. For dry basins, the correlation between annual runoff and annual precipitation is not as great as that between monthly runoff and monthly precipitation, but for humid basins they are almost identical.

### Abrupt change years in runoff series

Runoff results from precipitation, but is greatly affected by environmental changes including land use change, water conservation infrastructure construction and urbanization. Once intensive human activities have been implemented in the upper reaches of a river basin, mean runoff changes substantially at downstream stations and the change is maintained until another anthropogenic disturbance occurs. We define this pattern as an abrupt change in runoff series. The Mann–Kendall test indicated significant evolution trends in annual runoff at six of the ten stations we examined: Shixial, Guantai, Huayuankou, Tieling, Haerbin and Yichang stations. To visualize the changes, the annual runoff data at the six stations are plotted in Figure 3.

### Table 3 | Trend test of annual precipitation and correlation analysis for precipitation and runoff at monthly scale and yearly scale for series from 1951 to 2010

<table>
<thead>
<tr>
<th>Basin name</th>
<th>Station name</th>
<th>Precipitation (mm)</th>
<th>M–K value</th>
<th>Ra</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Yangtze River</td>
<td>Yichang</td>
<td>813</td>
<td>–0.98</td>
<td>0.81</td>
<td>0.82</td>
<td>0.71</td>
<td>0.43</td>
</tr>
<tr>
<td>Yangtze River</td>
<td>Datong</td>
<td>1,100</td>
<td>–0.62</td>
<td>0.79</td>
<td>0.78</td>
<td>0.63</td>
<td>0.37</td>
</tr>
<tr>
<td>Yellow River</td>
<td>Huayuankou</td>
<td>452</td>
<td>–1.46</td>
<td>0.46</td>
<td>0.63</td>
<td>0.54</td>
<td>0.45</td>
</tr>
<tr>
<td>Upper Yellow River</td>
<td>Tangnaihai</td>
<td>505</td>
<td>–0.23</td>
<td>0.77</td>
<td>0.72</td>
<td>0.64</td>
<td>0.52</td>
</tr>
<tr>
<td>Hai River</td>
<td>Shixial</td>
<td>432</td>
<td>–1.33</td>
<td>0.26</td>
<td>0.54</td>
<td>0.46</td>
<td>0.38</td>
</tr>
<tr>
<td>Hai River</td>
<td>Guantai</td>
<td>558</td>
<td>–1.64</td>
<td>0.42</td>
<td>0.61</td>
<td>0.45</td>
<td>0.42</td>
</tr>
<tr>
<td>Songhua River</td>
<td>Haerbin</td>
<td>578</td>
<td>–1.59</td>
<td>0.67</td>
<td>0.65</td>
<td>0.56</td>
<td>0.25</td>
</tr>
<tr>
<td>Liao River</td>
<td>Tieling</td>
<td>420</td>
<td>–1.82</td>
<td>0.43</td>
<td>0.55</td>
<td>0.46</td>
<td>0.27</td>
</tr>
<tr>
<td>Huai River</td>
<td>Wujiaodu</td>
<td>965</td>
<td>–0.19</td>
<td>0.70</td>
<td>0.72</td>
<td>0.60</td>
<td>0.54</td>
</tr>
<tr>
<td>Pearl River</td>
<td>Wuzhou</td>
<td>1,723</td>
<td>–0.56</td>
<td>0.89</td>
<td>0.86</td>
<td>0.78</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Note: R_a, R_1, R_2 are correlation coefficients between monthly runoff R_i and monthly precipitation P_i. R_1, R_2, R_3, R_4 is a correlation coefficient between annual runoff and annual precipitation.
Figure 3 shows that the runoff series at Guantai, Shixiali, Huayuankou and Tieling stations have clear declining trends. Most data in the first decades of data series are above the multi-year average while most data in the recent decades are below the multi-year average. Moreover, almost all runoff data in the recent period fall outside of the variation range of annual runoff from the first decades, which imply a true abrupt change at these four stations. For the runoff series at Yichang and Haerbin stations, although most of the annual runoffs in the later period are less than the multi-year average, they still fall within the variation range of annual runoffs in the prior period, from which we can conclude that there was no year of abrupt change for these two stations.

Ordered clustering analysis was carried out with the series from Guantai, Shixiali, Huayuankou and Tieling stations in order to identify the year in which an abrupt change occurred. In Figure 4, the total sum of squared deviations, \( \text{Sum} K(\tau) \), is plotted against time for the four stations.
Figure 4 shows that the curves of SumK against time at Huayuankou, Tieling and Shixiali stations each have a clear bottom peak occurring in 1986, 1965 and 1970, respectively, which indicates that the annual runoff series at the three stations changed significantly after the critical year. The curve of SumK at Guantai station has a flat bottom without a clear peak, implying that there are two possible abrupt changes, at the starting year (1965) and ending year (1977) of the bottom of the curve.

In order to test the significance of these detected abrupt change years, we used the F test to compare the data before and after the abrupt change year of each runoff series (Table 4).

Table 4 shows that all of the abrupt change years detected in Figure 4 are significant at the significance level of 0.05. The runoff series at Guantai station significantly changed from 1965 onward, with the greatest change starting in 1977. In order to identify the possible drivers of abrupt changes in the runoff series, we took the abrupt change year detected in the annual runoff series as a break year in the annual precipitation series and used the F test to determine whether precipitation differed significantly before and after the break year (Table 4). All F statistics for the precipitation series are less than the critical values of the F distribution at the significance level of 0.05, indicating that the precipitation series do not show abrupt changes.
in the years with abrupt changes in the runoff series. This implies that variation in precipitation is not the main driver of abrupt changes in the runoff series, although it may contribute to runoff decline trends to some extent.

Figure 5 shows differences in precipitation and runoff before and after the abrupt change points that were detected in four river basins (for Guantai station, the abrupt change year of 1965 was adopted in the analysis). Precipitation following the abrupt change year was 4.9–8.5% less than in the prior period, whereas the recorded runoff at the four stations decreased by 42.9–86.0%, with the greatest decreases occurring in the Hai River basin (Guantai station and Shixiali station). The finding that changes in runoff were in the same direction but much greater than changes in precipitation implies that precipitation changes have some effect in decreasing runoff, but that human activities are the dominant driver.

Effects of human activities on variability of runoff

In the eastern Asian Monsoon climate zone, variation in runoff is affected by many factors including precipitation, temperature, potential evaporation, land use change, water conservation and diversion projects, as well as other human activities. The above analyses show that evolution trends in precipitation are qualitatively similar to trends in runoff series for all river basins except the upper Yellow River, but that these precipitation trends are less pronounced. This indicates that climate change plays a certain role in declining runoffs, but the main driver may be human activities, such as increased withdrawals of stream water, especially in dry areas. During recent decades, China has undergone rapid population growth as well as economic development, which both require more water resources. Per capita water use, as an integrated index reflecting water use in all sectors, sharply increased from about 350 m³ in the 1970s to approximately 450 m³ in the 1980s. As important water sources for northern China, where the climate is very dry, the Hai River, Yellow River and Liao River have provided more than 50% of the total water available to meet the rapidly growing demands of agriculture and industry, as well as domestic water usage. This has resulted in significantly decreasing river runoffs; indeed, some northern Chinese rivers have frequently run dry during the dry season (Zhang 2005).

In contrast to intensively anthropogenically influenced basins, in catchments characterized by less intense human activity, rainfall is the most important factor driving variability of runoff at different scales (Zhang & Wang 2007). Intensive human activities, such as large-scale soil and water conservation measures and water diversion projects, can change the relationship between runoff and precipitation, resulting in a substantial modification of the hydrology and water resources (Wang et al. 2011). The above analysis indicated that six of the ten stations we studied had significant declining trends in annual runoff. Huayuankou, Tieling, Shixiali and Guantai stations each had an abrupt change in the runoff series, occurring in different years. In order to reveal possible reasons for the declining trends and abrupt changes in runoff series, we plotted annual runoffs against the corresponding catchment-mean precipitations for the periods before and after the abrupt change years at each of the four stations (Figure 6).

Figure 6 shows that the data are dispersed in plots of runoff against precipitation. The relationships between runoff and precipitation are not linear, although higher precipitations generally correspond to higher runoff, indicating that the variability of runoff is to some extent influenced by rainfall variability. The correlative coefficients between runoff and precipitation for the series before the abrupt change year are 0.58 (Huayuankou station), 0.54 (Guantai station), 0.43 (Shixiali station) and 0.42 (Tieling station), which are all higher than the corresponding coefficients after the abrupt change year, except for Tieling station, which has a coefficient of 0.46 for the post-abrupt change series. The analysis above (Table 3) also indicates that
basins with less anthropogenic influence, such as Tangnaihai station and Wuzhou station, have higher correlative coefficients between runoff and precipitation (0.77 and 0.89, respectively), while basins subject to intensive anthropogenic influence, such as Shixiali station and Tieling station, have lower correlative coefficients (0.26 and 0.43, respectively).

In Figure 6, for each of the four stations, most data from the post-abrupt change period fall in the lower zones, while those in the pre-abrupt change period fall in the upper zones, indicating that the runoff yield after abrupt change is less than that before, even when precipitation is similar. Theoretically, if there were no significant effects of human activities, plots of runoff against precipitation in periods before or after the abrupt change year would fall in the same area, not in different strip zones. The strip scatter of the plots could be explained by the influence of human activities on catchment hydrology.

Human activities could affect river runoff by changing runoff yield mechanisms, which would alter the relationship between runoff and precipitation. Large-scale water conservation measures and water diversion projects have been implemented in these catchments since the 1970s. For example, the Yellow River basin, where the Huayuankou station is located, has experienced soil and water conservation measures, including terrace construction, reforestation and construction of water conservation infrastructure. As of 1999, up to 140,600 km² of this basin had been retreated, and 520 check dams with cumulative storage capacity of 6.7 billion m³ had been built (Xu & Niu 2000). The average rainfall harvesting via soil and water conservation measures in the 1990s was 32 mm greater than in the 1950s and 1960s (Qian & Zhang 2001), which undoubtedly led to a certain decrease in river runoff. Wang et al. (2006) investigated attribution of runoff change in the Fen River catchment, a first-order tributary of the Yellow River, and concluded that approximately 62% of total runoff reduction was induced by soil and water conservation measures. Thus, human activities play a principal role in runoff reduction in typical tributaries of the Yellow River basin. While more research is required to investigate the complex relationship between human activities and changes in the hydrology of

![Figure 6](https://iwaponline.com/jwcc/article-pdf/4/3/252/374889/252.pdf)
major rivers, our results suggest that human activities are the main drivers of abrupt changes in runoff series, even for large-scale catchments such as the Yellow River.

**SUMMARY AND CONCLUSIONS**

China has scarce water resources, especially in the northern regions. The amount of water per capita in China is less than 30% of the world average. Climate change and increased variability in precipitation in particular, are likely to alter timing and magnitude of runoff; meanwhile, more intensive human activities have increased the tension between water supply and demand. A better understanding of evolution trends as well as variability of runoff series for major rivers in China is essential for better current management of the water resources as well as for future planning.

Here the Mann–Kendall test was used to detect evolution trends of runoff series. Recorded runoff series over 1950–2010 at ten selected hydrometric stations on the major rivers in China have all presented decreasing trends, with significant decreases occurring at six stations: Yichang station on the Yangtze River, Huayuankou station on the Yellow River, Guantai and Shixiali stations on the Hai River, Tieling station on the Liao River, and Haerbin station on the Songhua River.

Ordered clustering analysis was employed to identify years when abrupt change occurred in runoff series. Abrupt change in runoff series was detected at only four stations: Huayuankou station (1986), Guantai station (1965), Shixiali station (1970) and Tieling station (1965). For the other stations, although runoff series presented decreasing trends, there was no significant abrupt change.

The relationship between mean annual precipitation and runoff was found to differ before and after the abrupt change year. In general, with similar precipitation, runoff yields in the post-abrupt change period are substantially lower than in the pre-abrupt change period. Intensive human activities in the catchments are likely to be the main reason for abrupt changes in runoff series.

Variability in runoff series, along with the decreasing trend, has brought huge challenges for utilization of water resources and sustainable development. Global warming will worsen the situation, as water resources are highly sensitive to climate change. A water-saving society and effective adaptation strategies need to be developed to deal with these trends and safeguard economic growth and poverty reduction efforts under China’s 12th 5-year plan.

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