Contributions of climate change and human activities to the changes in runoff increment in different sections of the Yellow River

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Abstract
The runoff of many rivers in arid and semi-arid regions around the world has decreased remarkably with climate change and enhanced human activities, causing severe challenges in water resources utilization and ecological development. The runoff change in the Yellow River, a typical large river in the arid to semi-arid region, has been studied extensively. However, the spatial and temporal pattern of the runoff variations along the river is still not clear and the contributions of climate change (precipitation and evapotranspiration) and human activities to the runoff changes are not quantified. The purpose of this study is to identify the turning years of the changes in runoff increment for seven sections (above Tangnaihai, Tangnaihai-Lanzhou, Lanzhou-Toudaoguai, Toudaoguai-Longmen, Longmen-Tongguan, Tongguan-Huayuankou and Huayuankou-Lijin) in the Yellow River based on the annual observed data in 1950–2009. These turning years were used to divide the entire period into the baseline period and the measurement period, and calculate the contributions of climate change and human activities to the runoff increment changes in the measurement period. The methods used in this study include cumulative anomaly, linear regression, and the improved method of slope change ratio of cumulative quantity (SCRCQ). Results indicated that the turning years of the runoff increment change were 1989 for the section above Tangnaihai, 1985 for the sections of Tangnaihai-Lanzhou and Lanzhou-Toudaoguai, 1979 for the section of Toudaoguai-Longmen, 1985 for the sections of Longmen-Tongguan and Tongguan-Huayuankou, and 1971 for the section of Huayuankou-Lijin. The contributions to the runoff increment changes in the measurement period from precipitation were 11.98%, 10.02%, 16.60%, 28.49%, 19.24%, 9.45%, and 0.83%, from potential evapotranspiration were 1.32%, 1.61%, 7.37%, 7.74%, 5.82%, 0.96%, and 3.17%, and from human activities were 89.34%, 91.59%, 90.77%, 79.25%, 86.58%, 91.59% and 102.34%, respectively for these seven sections. For the entire runoff change of the whole Yellow River, the total contributions from precipitation were 11.76%, from potential evapotranspiration were 3.83%, and from human activities were 92.07%. These results suggest that human activities have been a dominant influencing factor in the runoff changes not only for each section, but also for the whole river basin since the 1980s.

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1. Introduction

The annual runoff of many rivers in arid and semi-arid regions around the world decreased remarkably in the last decades. The decrease in precipitation and/or the increase in evapotranspiration are regarded as direct influencing factors on the runoff decrease. However, as an indirect influencing factor, human activities (such as water diversion for agriculture irrigation, land utilization change, water and soil conservation, hydropower engineering, and so on) have caused hydrological process changes in many river basins globally, resulting in a series of water resources problems (Zhang et al., 2001; Li et al., 2007).

In recent decades, the global human demand for renewable water resources has increased rapidly due to the increased population and the rapid development of the global economy, and many regions in the world have experienced water stress (Vörösmarty et al., 2000). For example, although one third of the world’s freshwater are concentrated in Asia (Shiklomanov, 2001), water availability per capita has decreased more than seven times (from 77,000 to <1000 m³/a per capita) because of the freshwater decrease and the population growth in the continent during the last decades (McCarthy et al., 2001). In China, the shortage of...
renewable water resources has gradually become a severe problem with the rapid development of economy, population growth, and urbanization for the past three decades (Wang et al., 2006a).

Understanding runoff generation and variation in a changing environment is of critical importance to effectively manage water resources (Askew, 1987; Burn, 1994; Arnell, 1999; Drogue et al., 2004; Xu, 2011). Environmental changes can be categorized into two categories: climate-driven and human-driven changes (Xu, 2011). The runoff changes are usually affected by the combination of climate change and human activities in many regions in the world. Therefore, quantifying the contributions of climate change and human activities to the runoff changes is an important issue in hydrology.

The Yellow River provides freshwater for about 107 million people (Fig. 1), about 8.7% of the total population in China (Wang et al., 2006a). Many studies indicated that the runoff of the Yellow River has evidently decreased since the 1950s (Yang et al., 1998; Wang et al., 2006a, 2006b; Wang and Li, 2011), whereas population and economic development in the river basin have grown rapidly (Wang et al., 2006a). Therefore, the shortage of water resources in the Yellow River basin is very severe. Some studies suggested that the runoff decrease of the Yellow River was resulted from the decrease in precipitation and enhanced human activities (mainly water diversion, soil and water conservation measures) (Zhu, 1999; Wang and Fan, 2002; Miao et al., 2011; Wang and Li, 2011; Xu, 2011). However, few studies quantified the contributions of precipitation and human activities to the runoff change in the different sub-basins of the Yellow River except Miao et al. (2011). The study of Miao et al. (2011) indicated that the impact of climate and human activities to the runoff change in the Sanmenxia-Huayuankou section in the 1990s were 1812% and 1712%, respectively. However, such magnitude of the impacts is problematic. Thus, the contributions of climate and human activities to the runoff changes need more study. Xu (2011) suggested that a method for quantifying the contributions of climate and human activities to the runoff change is still an unsolved issue.

This study focuses on the variation trend of the runoff increments in seven different sections of the Yellow River in different periods. The objectives are: 1) to identify the turning years based on the annual data in 1950–2009 for each section and divide the whole period into the baseline period and the measurement period in terms of the runoff increment changes; 2) to introduce an improved method in the slope change ratio of cumulative quantity (SCRCQ) to quantify the impacts of different factors on the runoff change based on the SCRAQ method reported by Wang et al. (2012); and 3) to assess the contributions of precipitation, precipitation, and human activities.

Table 1
Features of the different sections in the Yellow River basin.

<table>
<thead>
<tr>
<th>Sections</th>
<th>Channel length (km)</th>
<th>Relief (m)</th>
<th>Drainage area ($10^4$ km$^2$)</th>
<th>Mean annual export runoff ($10^8$ m$^3$/a)</th>
<th>Mean annual precipitation during 1951–2010 (mm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Tangnaihai</td>
<td>1192</td>
<td>2168</td>
<td>12.197</td>
<td>200.025</td>
<td>503.65</td>
</tr>
<tr>
<td>Tangnaihai-Lanzhou</td>
<td>482</td>
<td>1169</td>
<td>10.058</td>
<td>308.673</td>
<td>429.77</td>
</tr>
<tr>
<td>Lanzhou-Toudaoguai</td>
<td>1239</td>
<td>527</td>
<td>14.535</td>
<td>215.043</td>
<td>277.97</td>
</tr>
<tr>
<td>Toudaoguai-Longmen</td>
<td>638</td>
<td>605</td>
<td>12.965</td>
<td>261.967</td>
<td>440.36</td>
</tr>
<tr>
<td>Longmen-Tongguan</td>
<td>164</td>
<td>55</td>
<td>18.459</td>
<td>344.275</td>
<td>539.38</td>
</tr>
<tr>
<td>Tongguan-Huayuankou</td>
<td>622</td>
<td>234</td>
<td>4.790</td>
<td>378.900</td>
<td>628.95</td>
</tr>
<tr>
<td>Huayuankou-Lijin</td>
<td>303</td>
<td>85</td>
<td>2.199</td>
<td>310.084</td>
<td>687.73</td>
</tr>
</tbody>
</table>
evapotranspiration, and human activities to the runoff increment changes in the seven sections of the Yellow River by comparing the values in the measurement period to the baseline period. This work will provide important insight into water resources management and planning to assess human impacts on runoff changes.

2. Environment setting

The Yellow River originates on the Tibetan Plateau, traverses the Loess Plateau and the North China Plain, and flows into the Bohai Sea (Fig. 1). The river has a total length of 5464 km, a drainage area of 752,443 km$^2$, an annual runoff of 46.4 billion m$^3$, and a mean annual discharge of 1822 m$^3$/s. Most areas of the drainage basin are located in arid and semi-arid climate regions with a mean annual precipitation of 478 mm (Wang et al., 2006b). It is commonly divided into the upper, middle, and lower reaches according to its geological and geographical settings. The upper reach (above Toudaoguai) is 3472 km long with a drainage area of about 0.39 million km$^2$ and a relief of 3496 m. The middle reach (from Toudaoguai to Tiexie) is 1206 km long with a drainage area of about 0.02 million km$^2$ and a relief of 120 m (Qian et al., 1992). The whole catchment contains 12.6 million ha of farmland and 40% of the farmland is irrigated using the water from the Yellow River (Xia et al., 2002).

The whole river was divided into seven sections using seven major hydrological stations to compare the runoff increment changes in different sections: above the Tangnaihai, Tangnaihai-Lanzhou, Lanzhou-Toudaoguai, Toudaoguai-Longmen, Longmen-Tongguan, Tongguan-Huayuankou, and Huayuankou-Lijin downstream the river (Fig. 1). All hydrological stations are located in the transition zones in terms of landforms, climate zones, and land utilizations. The upper three sections (above Tangnaihai, Tangnaihai-Lanzhou and Lanzhou-Toudaoguai) belong to the upper reach of the Yellow River. The upper section is located in the Tibetan Plateau (>3000 m above sea level (a.s.l.)) mainly with grassland and a cold semi-arid climate. The Tangnaihai-Lanzhou section is located in a transitional zone from the Tibetan Plateau to the Loess Plateau (>1500 m a.s.l.) with sloping farmland and a semi-arid climate. The Lanzhou-Toudaoguai section is located in

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Fig. 2. Spatial distribution of the annual precipitation determined using the Kriging interpolation of precipitation data (a) In 1951 based on 118 meteorological stations (77 stations are within and 41 stations around the river basin) and (b) In 2009 based on 118 meteorological stations (74 stations are within and 44 stations around the river basin) in the Yellow River basin.
the northwestern margin of the Loess Plateau and a marginal zone of deserts with arid climate and partial irrigated farmland (>1000 m a.s.l.). Three sections of Toudaoguai-Longmen, Longmen-Tongguan and Tongguan-Huayuankou belong to the middle reach and are located in the Loess Plateau, and with dry farmland and semi-arid climate, partial irrigated farmland and semi-arid climate, and semi-humid climate, respectively. The Huayuankou-Lijin section belongs to the lower reach and is located in an alluvial plain with a humid climate. The detailed information about these sections is listed in Table 1.

3. Dataset and methodology

3.1. Dataset

This study utilizes annual hydrological data from the Tangnaihai, Lanzhou, Toudaoguai, Longmen, Tongguan, Huayuankou and Lijin gauging stations (Fig. 1). The observed series cover the period from 1950 to 2009. The annual runoff data of the stations were obtained from the Yellow River Water Conservancy Commission (YRCC) before 2000 and were extracted from the China Water Resources Bulletin (Ministry of Water Resources, MWR) after 2000. The annual runoff increment (i.e. the net annual runoff yield) in each section was calculated by deducting the runoff input from the runoff output. It represents the total runoff generation (including tributaries) minus the total consumed water in each section.

The annual precipitation data were provided by China Meteorological Administration (http://www.cma.gov.cn/english/). The annual mean precipitation in each section can be calculated by the arithmetical average of the all data in the meteorological stations within the section. However, it does not account for the spatial distribution of the stations. In this study, the annual mean precipitation was determined using the Kriging interpolation of annual precipitation data from about 120 meteorological stations in certain year (total 140 meteorological stations were referred, in which 89 stations are within and 51 stations around the Yellow River basin) in ArcGIS (Fig. 1). In total, 60 precipitation maps were interpolated (1950–2009). For example, Fig. 2 illustrated the annual precipitation map in the river basin in 1951 based on 118 meteorological stations (77 stations are within and 41 stations around the river basin) (Fig. 2a) and in 2009 based on 118 meteorological stations (74 stations are within and 44 stations around the river basin) (Fig. 2b). The annual mean precipitation for each section was derived using the precipitation distribution map within the corresponding drainage area of each section.
To calculate the mean annual potential evapotranspiration before and after the turning year, the forest coverage for each section of the Yellow River basin in the early 1980s and the late 1990s were calculated based on the survey data (Survey Team of the Loess Plateau of CAS, 1992; Chen, 1994; Management Bureau of the Upper and Middle Yellow River, 2001). The forest coverage in the early 1980s was considered as the average forest coverage during the baseline period (before a turning year in the runoff increment changes for each section) because the increase of the man-made forest coverage was limited in this period. In the measurement period (after a turning year in the runoff increment changes for each section), with the continuous increase of the man-made forest in the basin, the forest coverage in the late 1990s was considered as the average forest coverage in this period because the survey years are in the middle of the period.

3.2. Methodology

The main methods used in this study are the cumulative anomaly and the slope change ratio of cumulative quantity (SCRCQ). The former is used to identify the turning year in the changes of the runoff increments for each section in 1950–2009 (e.g., Fig. 3a). The latter is used to quantify the contributions of climate change and human activities to the runoff increment changes in each station.

3.2.1. Cumulative anomaly

Cumulative anomaly is used to identify the changing tendency of discrete data, such as sequential precipitation, evapotranspiration and runoff data (Ran et al., 2010). For a discrete series $x_t$, the cumulative anomaly ($X_t$) for data point $x_t$ can be expressed as:

$$ X_t = \sum_{i=1}^{t} (x_i - x_m), \quad t = 1, 2, \ldots, n, \quad x_m = \frac{1}{n} \sum_{i=1}^{n} x_i \quad (1) $$

Where $x_m$ is the mean value of the series $x_t$, and $n$ is the number of discrete points. As the equation indicated, cumulative anomaly can be used to analyze the fluctuation magnitude and potential inflection point of a series of discrete data. Specifically, a positive or negative cumulative anomaly indicates that the corresponding data point is higher or lower than the average, respectively (Wang and Li, 2011). In this study, the variable $x$ represents runoff increment or precipitation in each section.

3.2.2. SCRCQ

The SCRCQ method was revised from the SCRAQ method proposed by Wang et al. (2012) to account for the potential negative runoff increment in a certain section/period. The elements are the same as the SCRCQ method but the expression formulas are different. The influence factors on the runoff change in a river basin include climate (precipitation, evapotranspiration), groundwater recharge and human activities. The precipitation and evapotranspiration directly affect the runoff change, while the groundwater recharge partly affects the runoff change especially in rainy season. The contribution (unit: %) of precipitation to the runoff change could be expressed as the proportion of the change ratio of the precipitation to the runoff change ratio in a river catchment or section during a period (Wang et al., 2012).
Similarly, the contribution (unit: %) of evapotranspiration to the runoff change could be expressed as the proportion of the change ratio of the evapotranspiration to the runoff change ratio in a river catchment or section during a period. Consequently, based on water balance the contribution (unit: %) of human activities to the runoff change could be expressed as 100% minus the sum of contributions of precipitation, evapotranspiration and ground-water recharge.

Assuming that the slope of the linear relationship between year and cumulative runoff before and after a turning year (e.g., Fig. 3b) is \( S_{R_b} \) and \( S_{R_a} \) (10^3 m^3/a), respectively, and the slope of the linear relationship between year and cumulative precipitation before and after the turning year (e.g., Fig. 3c) is \( S_{P_b} \) and \( S_{P_a} \) (mm/a), respectively, the runoff change ratio and the precipitation change ratio can be expressed as 
\[
\left( \frac{S_{R_a}}{C_0} \right) / \left( \frac{S_{R_b}}{C_0} \right) = \left( \frac{S_{R_a}}{S_{R_b}} \right)
\]
and 
\[
\left( \frac{S_{P_a}}{C_0} \right) / \left( \frac{S_{P_b}}{C_0} \right) = \left( \frac{S_{P_a}}{S_{P_b}} \right)
\], respectively. For the runoff increment in each section, \( S_{R_b} \) and \( S_{R_a} \) could be obtained from the linear relationship between year and cumulative runoff increment. Therefore, the contribution of the precipitation (\( C_P \), unit: %) to the runoff change after the turning year comparing to that before the turning year can be expressed as:
\[
C_P = 100 \times \left( \frac{(S_{P_a} - S_{P_b})}{(S_{R_a} - S_{R_b})} \right) / \left( \frac{(S_{R_a} - S_{R_b})}{S_{R_b}} \right)
\]  

Similarly, assuming that the slope of the linear relationship between year and cumulative potential evapotranspiration in a river basin before and after a turning year is \( S_{E_b} \) and \( S_{E_a} \) (mm/a), respectively, the change ratio of the potential evapotranspiration can be expressed as 
\[
\left( \frac{S_{E_a}}{C_0} \right) / \left( \frac{S_{E_b}}{C_0} \right) = \left( \frac{S_{E_a}}{S_{E_b}} \right)
\]. Thus, the contribution of the potential evapotranspiration (\( C_E \), unit: %) to the runoff change after the turning year comparing to that before the turning year can be expressed as:

\[C_E = 100 \times \left( \frac{(S_{E_a} - S_{E_b})}{(S_{R_a} - S_{R_b})} \right) / \left( \frac{(S_{R_a} - S_{R_b})}{S_{R_b}} \right)\]

Fig. 7. Relationships between year and cumulative runoff increment for the six sections of the Yellow River basin: Tangnaihai-Lanzhou, Lanzhou-Toudaoguai, Toudaoguai-Longmen, Longmen-Tongguan, Tongguan-Huayuankou and Huayuankou-Lijin.
Based on water balance, the contribution of human activities ($C_H$, unit: %) to the runoff change can be expressed as:

$$C_H = 100 \times (S_{Ea} - S_{Eb})/(S_{Eb})$$

(3)

where $C_H$ is the contribution of groundwater to the runoff change.

In the Yellow River basin, the groundwater recharge does not remarkably affect annual runoff changes because of distinct dry season (from Nov. to May) and wet season (from Jun. to Oct.) within a year. On the other hand, extracting groundwater could lead to the negative annual potential evapotranspiration after and before a turning year, respectively. The function of the potential evapotranspiration to the runoff change because it is difficult to obtain the annual potential evapotranspiration data.

$$C_E = 100 \times (E_a - E_b)/E_b$$

(5)

where $E_a$ and $E_b$ are the mean annual potential evapotranspiration after and before a turning year, respectively. The function of $(E_a - E_b)/E$ represents the change ratio of the mean annual potential evapotranspiration after a turning year comparing to that before the turning year. $E_a$ and $E_b$ calculated based on the ET model (Formula (6)) proposed by Zhang et al. (2001), under the condition that $p$ and $f$ are replaced by mean annual precipitation and average forest coverage during the baseline period and measurement period, respectively.

$$ET = \left( \frac{1 + 2 \frac{1410}{p + F_p}}{1 + 2 \frac{1410}{p + 0.5}} + (1 - f) \frac{1 + 0.5 \frac{1100}{p + 0.5}}{1 + 0.5 \frac{1100}{p + 1100}} \right) F$$

(6)

4. Results

4.1. Changes in annual runoff and annual runoff increment

The annual runoff in 1950–2009 was examined at all these seven stations in the Yellow River (Fig. 4). A decreasing trend with time was apparent after the 1980s in all these stations, especially the three stations below the Longmen station. The minimum annual runoff of all these stations occurred in 1997–2002.

Fig. 5 illustrated the runoff increment changes in the seven sections. Negative annual runoff increments in the sections of Lanzhou-Toudaoguai and Huayuankou-Lijin indicate that the export runoff always less than the import runoff in these two sections. Positive annual runoff increments in other sections showed that the export runoff always greater than the import runoff in these sections. A decreasing tendency of the annual runoff increment can be observed in all sections except the section above Tangnaihai. The maximum amount of runoff decrease was in the Lanzhou-Toudaoguai section during 1950–1975 and after 2003 and in the Huayuankou-Lijin section during 1976–2002 (Fig. 5). The mean annual runoff increments were 308.67, 108.65, –93.27, 46.56, 82.31, 34.63 and –68.82 m³/a for the seven sections downstream in 1950–2009.

4.2. Relations between year and cumulative quantities

The cumulative anomalies of the runoff increment are presented in Fig. 3a for the above Tangnaihai section and Fig. 6 for all other sections. The year of 1985 is the turning year in the runoff increment for most sections. The years of 1989, 1979, and 1971 are the turning points in the runoff increment changes in the sections of above Tangnaihai, Toudaoguai-Longmen and Huayuankou-Lijin, respectively.

The scatter distributions, fitted beelines, and fitted best linear relationships between year and cumulative runoff increment before and after the turning year are illustrated in Fig. 3b for the above Tangnaihai section and Fig. 7 for all other sections. All relationships have high correlation coefficients of >0.98. The parameters of $S_{Ra}$ and $S_{Rb}$ extracted for each section in Figs. 3b and 7 are listed in Table 2.

Figs. 3c and 8 illustrated the scatter distributions, fitted beelines, and fitted best linear relationships between year and cumulative precipitation before and after the turning year for the above Tangnaihai section and all other sections, respectively. All relationships also have high correlation coefficients of >0.98. The parameters of $S_{Pa}$ and $S_{Pb}$ extracted for each section in Figs. 3c and 8 are listed in Table 2.

Because of the lack of the annual potential evapotranspiration in each section, similar relationships cannot be obtained. The mean annual potential evapotranspiration in each section could be calculated based on the Formula (6). The forest coverage for each

### Table 2

Extracted slopes from the relationships between year and cumulative runoff increment as well as between year and cumulative precipitation in different periods for the different sections of the Yellow River.

<table>
<thead>
<tr>
<th>Sections</th>
<th>Drainage area ($10^4$ km²)</th>
<th>Time period</th>
<th>$S_{Ra}$ ($10^4$ m³/a)</th>
<th>$S_{Rb}$ ($10^4$ m³/a)</th>
<th>$S_{Pa}$ (mm/a)</th>
<th>$S_{Pb}$ (mm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Tangnaihai</td>
<td>12.197</td>
<td>1950–1989</td>
<td>211.36</td>
<td>170.12</td>
<td>507.12</td>
<td>495.27</td>
</tr>
<tr>
<td></td>
<td>10.058</td>
<td>1990–2009</td>
<td>125.45</td>
<td>85.14</td>
<td>435.82</td>
<td>421.79</td>
</tr>
<tr>
<td></td>
<td>12.965</td>
<td>1950–1979</td>
<td>63.69</td>
<td>472.52</td>
<td>415.59</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18.459</td>
<td>1950–1985</td>
<td>99.23</td>
<td>563.02</td>
<td>505.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.79</td>
<td>1950–1985</td>
<td>44.56</td>
<td>646.14</td>
<td></td>
<td>602.48</td>
</tr>
<tr>
<td></td>
<td>2.199</td>
<td>1950–1971</td>
<td>–9.53</td>
<td>732.10</td>
<td></td>
<td>665.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1972–2009</td>
<td>–113.26</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The time period of precipitation is 1951–2010.
section in the early 1980s and late 1990s was used as the average forest cover for the baseline period and measurement period, respectively. The forest coverage in the early 1980s for the seven sections is 0.05, 0.1196, 0.0028, 0.0537, 0.1127, 0.0593, and 0.043, respectively, while that in the late 1990s is 0.049, 0.148, 0.017, 0.193, 0.216, 0.313, and 0.082, respectively (Table 3). The obtained mean annual potential evapotranspiration in the measurement period and the baseline period for each section is listed in Table 3.

4.3. Contributions of climate change and human activities to the runoff change

The contributions of precipitation, potential evapotranspiration, and human activities to the runoff increment changes in each section were calculated based on the parameters listed in Table 2 and Table 3 and results were listed in Table 4. The impacts of precipitation and potential evapotranspiration on the runoff increment changes in all sections after the turning year were positive and negative, respectively (Table 4). The contributions of the precipitation ($C_P$) in the seven sections range from 0.83% to 28.49% with an increasing and a decreasing trend downstream above and below the Toudaoguai-Longmen section, respectively. The contributions of potential evapotranspiration ($C_E$) range from $-0.96\%$ to $-7.74\%$ with a decreasing and an increasing tendency downstream above and below the same section, except for the Huayuankou-Lijin section. Both the maximum contribution of precipitation and the minimum contribution of potential evapotranspiration are in the Toudaoguai-Longmen section. The contributions of the human activities to the runoff increment changes in the seven sections range from 79.25% to 102.34%, with the

Fig. 8. Relationships between year and cumulative precipitation for the six sections of the Yellow River basin: Tangnaihai-Lanzhou, Lanzhou-Toudaoguai, Toudaoguai-Longmen, Longmen-Tongguan, Tongguan-Huayuankou and Huayuankou-Lijin.
maximum and the minimum values in the Huayuankou-Lijin section and the Toudaoguai-Longmen section, respectively.

The contributions of each influencing factor in a section to the total runoff change in the whole Yellow River could be determined by multiplying the contributions from each influencing factor on the runoff increment change with the proportion of the runoff increment change in the section to the total runoff change in the river basin. The total contributions from each influencing factor to the entire runoff change in the whole basin are determined by summing the contributions in the seven sections for the corresponding factor. Table 4 listed that the contributions to the runoff change in the whole Yellow River after the turning year range from 0.22% to 3.90% for precipitation, −1.18% to −0.10% for potential evapotranspiration, and 6.14%–26.53% for human activities in the sections. The total contributions in all sections to the entire runoff change in the Yellow River basin were 11.76%, −3.83% and 92.07% from precipitation, potential evapotranspiration and human activities, respectively.

5. Discussion

5.1. Runoff change in a gauging station does not affect the runoff increment change in a section

Some studies have investigated the runoff changes at different gauging stations rather than the runoff increment changes in sections of the Yellow River in annual or decadal scales and discussed their influencing factors (Li et al., 2009; Zhang et al., 2009). However, the runoff change at a given station did not reflect the actual change in the runoff increment in a section. The runoff change observed in a station reflects the total runoff increment change in the corresponding basin above the station, not the change of runoff increment between two stations. This study used the runoff increment at each section to detect their change trends and quantify their influence factors. It is more efficient and accurate.

5.2. Different turning years in runoff increment changes among different sections

Miao et al. (2011) used the 1950s–1960s as the baseline period in different sub-basins of the Yellow River. The establishment of this baseline period is subjective. Other studies in different tributaries of the middle Yellow River suggested different turning years in runoff changes, such as 1971 for Wuding River (Xu, 2011), 1973 for Kuye River (Zhao et al., 2010), and 1992 for Weihe River (Wang et al., 2008). Therefore, the baseline periods in different sub-basins are different because the inflexion points in climate change and human activities are not the same among different sub-basins. Li et al. (2009) showed that the turning years in runoff changes at six major gauging stations of the Yellow River range from 1985 to 1994, indicating that the baseline periods in different sections are different.

This study shows that the turning years of the runoff increment changes in different sections of the Yellow River are not the same (Figs. 3 and 6). The turning years in the sections of Tangnaihai-Lanzhou, Lanzhou-Toudaoguai, Longmen-Tongguan and Tongguan-Huayuankou are 1985 (Fig. 6), suggesting simultaneous inflexion points in the changes of the runoff increments in these four sections. The turning years in the sections of above Tangnaihai, Toudaoguai-Longmen and Huayuankou-Lijin are 1989, 1979 and 1971, respectively. They are different from each other, and also different from the turning year of the other four sections. The turning years reflect the shift in the relative intensity of influencing factors, and separate the runoff increment changes into the early climate-driven (limited human activities) and late human-driven (dominated by human activities) changes. The turning years in runoff increment changes were the earliest in the Huayuankou-Lijin section and the latest in the above Tangnaihai section. The Huayuankou-Lijin section is located in the lower reach of the Yellow River with more intensified and earlier human influences than other sections. In contrast, the above Tangnaihai section is located in the headwater region with limited human influences and relatively late turning year.

5.3. Impacts of precipitation on the runoff increment changes

The impacts of precipitation on the runoff increment changes were different in different sections. It was inappreciable (0.83%) for the Huayuankou-Lijin section because the precipitation was relatively stable in this section. It was similar (ranged from 9.45% to 11.98%) in the sections of above Tangnaihai, Tangnaihai-Lanzhou, and Tongguan-Huayuankou because of the similar precipitation decrease percentage in these sections. The decrease percentage of the precipitation in the sections of Lanzhou-Toudaoguai and Longmen-Tongguan was apparent after the turning year. As a result, the contributions of precipitation to the runoff increment changes reached to 16.6% and 19.24%, respectively in these two sections. The most decrease percentage of the precipitation after the turning year occurred in the Toudaoguai-Longmen section in the northern Loess Plateau, and the contribution of precipitation to the runoff

Table 3

<table>
<thead>
<tr>
<th>Sections</th>
<th>Time period</th>
<th>Forest coverage</th>
<th>Mean annual precipitation (mm/a)</th>
<th>$E_a$ (mm/a)</th>
<th>$E_b$ (mm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Tangnaihai</td>
<td>1951–1989</td>
<td>0.050</td>
<td>506.78</td>
<td>418.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1990–2010</td>
<td>0.049</td>
<td>497.85</td>
<td>412.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1995–1997</td>
<td>0.120</td>
<td>434.20</td>
<td>375.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1986–2010</td>
<td>0.148</td>
<td>423.56</td>
<td>369.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1995–1997</td>
<td>0.003</td>
<td>288.17</td>
<td>264.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1986–2010</td>
<td>0.017</td>
<td>263.68</td>
<td>244.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1980–2010</td>
<td>0.193</td>
<td>413.71</td>
<td>364.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1986–2010</td>
<td>0.113</td>
<td>562.41</td>
<td>455.99</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1986–2010</td>
<td>0.216</td>
<td>507.13</td>
<td>429.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1985–1985</td>
<td>0.059</td>
<td>651.07</td>
<td>499.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1986–2010</td>
<td>0.313</td>
<td>597.98</td>
<td>494.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1985–1985</td>
<td>0.043</td>
<td>716.68</td>
<td>529.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1972–2010</td>
<td>0.082</td>
<td>672.14</td>
<td>512.31</td>
<td></td>
</tr>
</tbody>
</table>

Note: The forest coverage in the baseline period (first period) for each section was calculated according to the basic survey data in the early 1980s by the Survey Team of the Loess Plateau of CAS (1992) and Chen (1994), and that in the measure period (second period) was after Management Bureau of the Upper and Middle Yellow River (2001).
increment change reached to 28.49%. Spatially, the contributions of precipitation on the runoff increment change were the highest in the middle section (Toudaoguai-Longmen) and decreased upward and downward. The contribution of precipitation to the runoff increment change in the whole Yellow River was 11.76%, not the dominant factor to cause the runoff increment changes.

Miao et al. (2011) suggested that the contribution of climate change to the reduction in water discharge of the upper, middle, and lower reaches of the Yellow River in 1970–2008 is 17%, 71%, and 72%, respectively. The value in the upper reach is similar to this study’s results in this reach. However, the values for other reaches are significantly higher than these results. One potential reason is that the contributions of precipitation in Miao et al. (2011) were calculated based on the runoff changes at the gauging stations that may not reflect the runoff increment change in a section. In addition, the baseline period in Miao et al. (2011) was not derived based on the turning year. This assessment of the contributions of precipitation to the runoff increment changes is more reasonable because all relations obtained by SCRCQ have very high correlation coefficients.

### 5.4. Impacts of potential evapotranspiration on the runoff increment changes

The potential evapotranspiration in arid to semi-arid climate regions is mainly influenced by precipitation and forest coverage (Zhang et al., 2001) with positive relations between the potential evapotranspiration and precipitation and between the potential evapotranspiration and forest coverage. The mean annual precipitation at almost all sections of the Yellow River decreased, whereas the forest coverage increased to 13% for the whole basin in the measurement period (the forest coverage in the baseline period is 8.9%). This led to relatively small changes in the change ratio of the annual potential evapotranspiration after the turning year in each section. Consequently, the contribution of the potential evapotranspiration change to the runoff change in each section was minor (−7.74% to −0.96%).

### 5.5. Impacts of human activities on the runoff increment changes

The impacts of human activities on the runoff change were about 90% in most sections, and that the impacts of human activities in the whole Yellow River basin was 92.07%. This indicates that human activities have become the dominant influencing factor on the runoff increment changes for each section and for the whole Yellow River basin. The contributions of human activities in the seven sections were also represented as an increasing trend upward and downward from the Toudaoguai-Longmen section except the above Tangnaihai section. The contribution of human activities to the runoff increment change in the Huayuankou-Lijin section even exceeded 100% (102.34%), indicating that the negative contribution of the potential evapotranspiration exceeded the positive contribution of the precipitation in the section.

The modes of human activities influencing on the runoff increment changes in the different sections are different. In the area above Tangnaihai, the population is small (Miao et al., 2010) and the direct water wasting by human diversion and utilization are relatively weak. The decrease in runoff increment in this section was mainly influenced by the overloading of grasslands with the rapid development of stockbreeding after 1989. The overloading of grasslands resulted in desertification of partial grassland and reduced water conservation function, thus enhanced the actual evapotranspiration and reduced the runoff in the section. Moreover, because the economic development in this section started later than others, the turning year (1989) in this section was also later than others. The decrease in the runoff increments at four sections of Tangnaihai-Lanzhou, Lanzhou-Toudaoguai, Tongguan-Huayuankou, and Huayuankou-Lijin was affected by increasing water diversion from the main stream for irrigation and industry utilization. In the Tangnaihai-Lanzhou section, the runoff increment decrease was mainly affected by the industry utilization, and local water and soil conservation in tributaries. In the Lanzhou-Toudaoguai section, the runoff increment decrease was mainly influenced by water use from the Yellow River for the irrigation purpose after the construction of the Qingtongxia and Liujiaxia reservoirs in 1968 and especially the Longyangxia reservoir in 1986 (Wang et al., 2011). In the Huayuankou-Lijin section, the irrigation areas were extended outside the basin in the 1970s and 1980s (Yang et al., 2004). The water diversion for irrigation resulted in remarkable decrease of the runoff increment in this section and the turning year (1971) is the earliest among all sections.

The decrease of runoff increments in two sections of Toudaoguai-Longmen and Longmen-Tongguan was mainly influenced by water soil conservation measures. These two sections are located in the Loess Plateau with severe soil erosion. To
improve the environment, local soil conservation practices have been started since 1949 (Liu, 2005). However, a series of regional soil conservation practices with general planning (such as afforestation, grass-planting, creation of level terraces, and building check dams, etc.) were developed in the 1970s and 1980s. These human activities changed the local micro-topography, increased the ability of intercepting precipitation, and consequently delayed and reduced the runoff in these two sections (Miao et al., 2011). In addition, the intercepted water by check dams, diverted water resources for irrigation, and others will participate in the atmospheric cycle by evapotranspiration. This means that human activities also altered part of the water cycle in each section of the Yellow River basin.

6. Conclusions

Using the observed records of runoff in seven major gauging stations along the Yellow River in 1950–2009 and of the precipitation from about 140 meteorological stations in and around the Yellow River basin in 1951–2010, this study identified the turning years in runoff increment changes for seven sections, quantified the contributions of the precipitation, potential evapotranspiration and human activities to the runoff increment change for each section.

(1) The turning years in runoff increment changes for the seven sections are different. For the sections of above Tangnaihai, Toudaoguai-Longmen, and Huayuankou-Lijin, the turning years are 1989, 1979 and 1971, respectively, while for the other four sections it is 1985. The turning year was used to divide the whole period into the climate-driven period (baseline period) and human-driven period (measurement period) in each section.

(2) The contributions to the runoff increment changes in the seven sections of the Yellow River basin (above Tangnaihai, Tangnaihai-Lanzhou, Lanzhou-Toudaoguai, Toudaoguai-Longmen, Longmen-Tongguan, Tongguan-Huayuankou and Huayuankou-Lijin, downstream the Yellow River) from precipitation were 11.98%, 10.02%, 16.60%, 28.49%, 19.24%, 9.45% and 0.83%, from potential evapotranspiration were –1.32%, –1.61%, –7.37%, –7.74%, –5.82%, –0.96% and –3.17%, and from human activities were 89.34%, 91.59%, 90.77%, 79.25%, 86.58%, 91.59% and 102.34%, respectively. The contributions in the whole Yellow River from precipitation were 11.76%, from potential evapotranspiration were –3.83%, and from human activities were 92.07%.

(3) Human activities have become a dominant influencing factor on the runoff increment changes in the Yellow River since the 1980s. The modes and intensity of human activities must be changed to sustainably utilize water resources in the Yellow River basin.

Acknowledgments

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