Precipitation and runoff variations in the Yellow River Basin of China

Jianxia Chang, Jie Wei, Yimin Wang, Meng Yuan and Jiacheng Guo

ABSTRACT

Runoff in the Yellow River (YR) of China is steadily declining due to climate change and human activities. In this study, the basic trend and abrupt changes of precipitation at 63 meteorological stations and runoff as measured at six hydrological stations from 1956 to 2010 are analyzed. Results indicate that 38 stations exhibit negative precipitation trends. These stations are mainly located in the lower reaches. All six hydrological stations exhibit declining runoff trends. Abrupt runoff changes were mainly noted in the downstream portion of the basin. These variations then expanded to the middle and upper reaches. A precipitation–runoff double cumulative curve was used to detect the breakpoint of the precipitation–runoff relationship and to identify the impacts of human activities on runoff in the YR. Results show that the relatively uniform precipitation–runoff relationship has changed since 1993 in the upstream reaches and since 1970 in the middle and downstream reaches. Additionally, the relationship was more sensitive in the Lanzhou section. Human activities have become the dominant influencing factor on runoff variation since the 1970s. After the 1990s, the percentages of runoff variations due to human activities were 74.87%, 82.2%, 80.63%, and 88.71% at the Lanzhou, Toudaoguai, Huayuankou, and Lijin stations, respectively.

Key words | abrupt change, precipitation, precipitation–runoff relationship, runoff, Yellow River Basin

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INTRODUCTION

Recent climate research suggests that the world is warming and the climate is changing. These changes will impact water resources. Therefore, runoff generation and environmental variations have become important hydrologic issues over the past 20 years. Environmental changes can be grouped into two categories: climate-driven changes and human activities (Franczyk & Heejun 2009; Zhang *et al.* 2010, 2014a, 2014b; Raghavan *et al.* 2014). The former includes temperature and precipitation changes. The latter includes population, water use, fertilizer consumption, river damming, domestic water consumption and industrial water consumption increases. In semi-arid and arid regions, water resources, primarily runoff, are highly sensitive to climate change. Changes in temperature and precipitation can affect evapotranspiration rates, soil moisture, and runoff regimes. Small changes in climate variables may result in significant variations in hydrological cycles and subsequent changes to regional water resources (Lioubimtseva & Henebry 2009; Siliverstovs *et al.* 2009; Wang & Hejazi 2011; Istanbulluoglu *et al.* 2012; Van Vliet *et al.* 2013). Runoff, as an important hydrological variable, is a combination of precipitation, evaporation, and other hydrological cycle processes on a large basin scale ($\geq$100,000 km^2). As such, runoff can be used as an indicator of the hydrological response to climate change (Hao *et al.* 2008; Yu *et al.* 2014; Zhang *et al.* 2014a, 2014b).

The Yellow River (YR) is a major source of freshwater for approximately 8.7% of the total population in China. Originating from the high Qinghai-Tibet Plateau in the far west of China, the YR flows north, turns south, and then bends

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east for a total of 5,464 km before debouching into the Bohai Sea, draining a basin area of approximately 752,000 km^2 (Figure 1). The headstream of the YR is covered by snow and frozen soil for the whole year, and the area from upstream to Lanzhou is the main source of water resources, and approximately 54% of the river runoff is from this area. From the Lanzhou to Toudaoguai station, the river runs through the influx region in the Loess Plateau, and little flow runs into the river. From Toudaoguai to Huayuankou station, runoff increases with the inflow of several tributaries. Except for the water supply from the melted ice cover on the Qinghai-Tibet Plateau, precipitation is the major source for river runoff and controls the drought–flood cycles of the river. As a result, the precipitation distribution and trends could affect the water resources to a large extent. Due to global climate change, the mean values of temperature, precipitation, and runoff are not constant in the Yellow River Basin (YRB). The YR runoff has decreased by over 80% from 1950 to 2005 (Wang *et al.* 2007; Miao *et al.* 2011), and the average annual precipitation has decreased over the past 50 years (Xue 1993; Liu & Xia 2004; Peng & Xu 2010; Wang *et al.* 2012). Additionally, large-scale human activities, including water diversion for human use and erosion control practices, have been conducted since the 1970s. The main type of water resource utilization in the YR is irrigation. Consumption of irrigation water in the area surrounding HuaYuanKou station was 134×10^8 m^3 in 1971, representing a 181% increase from 74×10^8 m^3 in 1949.

Precipitation and runoff are two critical processes in the hydrological cycle. The main objectives of this study are as follows: (1) to explore the temporal and spatial patterns of precipitation and runoff in the YR; (2) to determine abrupt runoff changes via the sequential Mann–Kendall test; (3) to analyze the relationships between runoff and precipitation in different sections of the YR basin; and (4) to explore the effects of human activities and precipitation variations on runoff change.

YRB

The YR crosses 'the three major stairs' of the macroscopic landform structure of China, i.e., the Qinghai-Tibet Plateau, the Loess Plateau, and the North China Plain, and empties into the Pacific Ocean. It drains a wide basin and exhibits a variety of geological and climatic features. In terms of physical geography, the YRB is located in the transitional zone between arid and sub-humid climates. Much of the

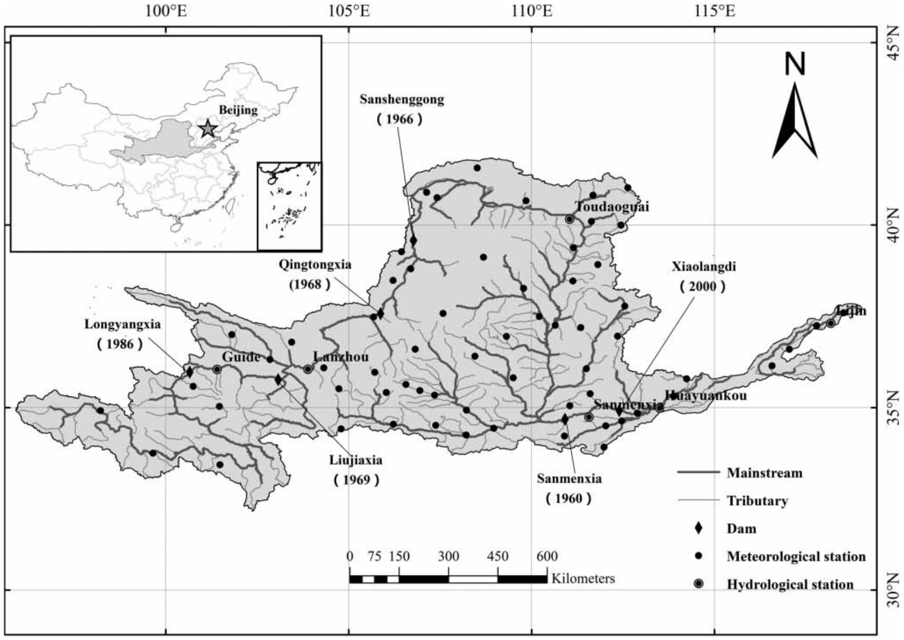

Figure 1 | Map of the YR.

region is mantled by thick loess. According to the geographical settings, the river can be divided into three sections. The upper reaches extend from the river source to Toudaoguai, covering a length of 3,471 km and draining an area of 385,996 km^2. Most of the river water in the YR originates from the upper reaches, where ice melt and snowfall are the main contributors. The middle reaches extend from Toudaoguai to Huayuankou, spanning 1,206 km and draining an area of 343,751 km^2. A considerable number of tributaries join the main stream in the middle reaches. The lower reaches extend from Huayuankou to the river delta, encompassing a length of 786 km and draining an area of 22,726 km^2 (Figure 2).

The mean annual precipitation and temperature of the YR are highly variable across the river basin and correspond with changes to the geology of the river. The upper reaches are located in arid regions with low annual precipitation (368 mm/year). The semi-arid middle reaches have an annual precipitation of 562 mm/year, while the lower reaches are more humid, with an annual precipitation of more than 600 mm/year. The annual mean temperature varies from 1 to 4 °C in the upper reaches, 8 to 14 °C in the middle reaches, and 12 to 14 °C in the lower reaches, with the highest temperatures occurring in July and the lowest in January. Table 1 lists the mean precipitation and runoff values in different

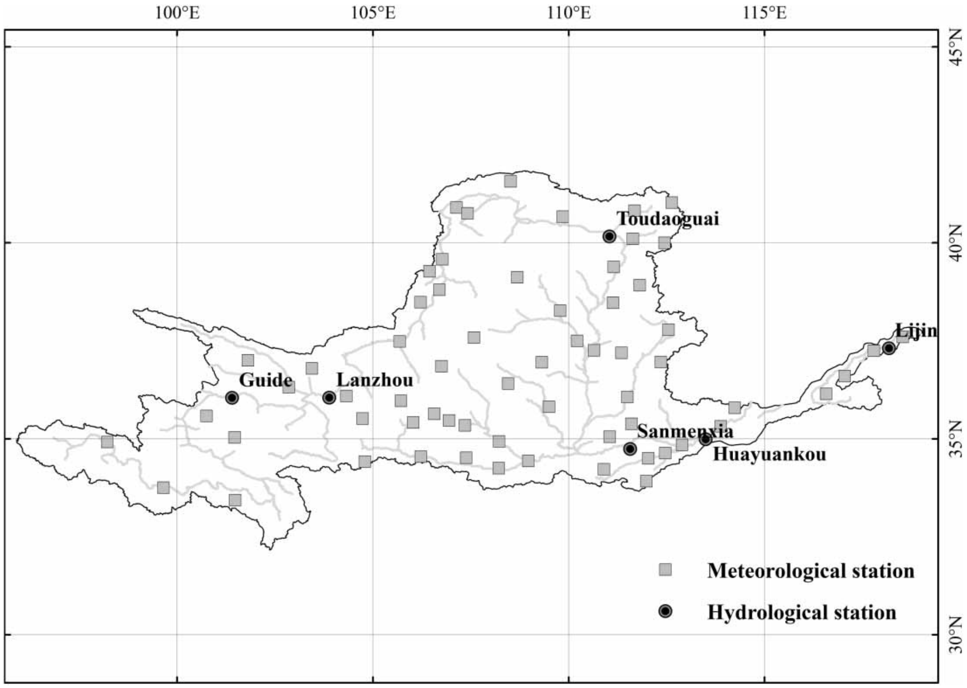

Figure 2 | Meteorological and hydrological stations.

Table 1 | Summary of major variables for different reaches of the YRB

Reach	Precipitation mean (mm/yr)	Length km	Area km^2	Streamflow mean (10^6 m^3)	Temperature mean (°C)
Upper reaches	368	3,471	385,996	33,896.6	1–4
Middle reaches	562	1,206	343,751	56,166.22	8–14
Lower reaches	648	786	22,726	56,429.22	12–14

reaches of the YRB. These variables display large variabilities between reaches.

DATA AND METHODS

Data preparation

Daily precipitation data in the YRB were collected from January 1956 to December 2010 by the China Meteorological Administration. Monthly and annual precipitation were established from the collected data. Monthly precipitation data sets from 63 meteorological stations are used in this study. These stations are shown in Figure 2. The observed runoff is used to investigate stream flow changes at the Guide, Lanzhou, Toudaoguai, Sanmenxia, Huayuankou, and Lijin hydrological stations (Figure 2). Furthermore, to analyze the sensitivity of runoff to precipitation, the 'naturalized runoff' was used instead of the observed runoff, reducing the influence of human activities, such as domestic, industrial, irrigation, and dam-control water use. These data were provided by the Yellow River Conservancy Commission (YRCC).

To explore the runoff response to precipitation in different sections of the YRB, the basin has been divided into four sections: (1) the region above Lanzhou station, denoted the Lanzhou section, includes 11 meteorological stations, which were used to analyze the precipitation variation in this section; (2) the region from Lanzhou to Toudaoguai station, called the Toudaoguai section, has 19 meteorological stations; (3) the region from Toudaoguai to Huayuankou, denoted the Huayuankou section, encompasses several tributaries that flow into the YR as well as 23 meteorological stations; and (4) the region from Huayuankou to Lijin station, denoted the Lijin section, has eight meteorological stations. The annual mean precipitation for each section was derived using the Thiessen polygon method. The annual runoff for each section refers to the interval runoff. For instance, the runoff in the Toudaoguai section equals the measured runoff at Toudaoguai station minus that at Lanzhou station. The upper two sections (the Lanzhou and Toudaoguai sections) belong to the upper reaches of the YR, which are located in the Tibetan Plateau (>3,000 m above sea level (a.s.l.)) and in a transitional zone from the Tibetan Plateau to the Loess Plateau (>1,500 m a.s.l.), which is mainly characterized by grassland and a cold, semi-arid climate. The Toudaoguai section is located in the northwestern margin of the Loess Plateau, which is characterized by a marginal, arid climate zone with portions of irrigated farmland (>1,000 m a.s.l.). The Huayuankou section belongs to the middle reaches and is located in the Loess Plateau. This section is characterized by dry farmland with both semi-arid and semi-humid climates. The Lijin section belongs to the lower reaches and is located in an alluvial plain with a humid climate.

Methodology

The Mann–Kendall trend test and regression analysis methods were used to detect the time-series trends for precipitation and runoff and to identify periods of abrupt precipitation and runoff changes in the YRB. A double mass curve (DMC) is used to assess the effects of precipitation and human activities on runoff change.

The Mann–Kendall trend test is a non-parametric assessment of the significance of monotonic trends (Mann 1945; Taxak *et al.* 2014). This test has the advantage of not assuming any special form for the distribution function of the data, while having predictive power nearly as high as parametric competitors. Thus, the test has been widely used and tested as an effective method to evaluate the presence of a statistically significant trend in hydrological and climatological time series (Novotny & Stefan 2007; Jones *et al.* 2015).

In this study, the Mann–Kendall test procedure follows Gerstengarbe & Werner (1999), who used the method to test an assumption about the beginning of the development of trend within a sample ($x_1, x_2, \ldots, x_n$) of the random variable x, based on the rank series r of the progressive and retrograde rows of this sample. The assumption (null hypothesis) is formulated as follows: the sample under investigation shows no beginning of a developing trend. The following test is performed to prove or to disprove the assumption, and first, a Mann–Kendall test statistic, d_k is calculated:

$$d_k = \sum_{i=1}^{k} r_i \quad (2 \le k \le n) \tag{1}$$

$$r_i = \begin{cases} 1 & \text{if } x_i > x_j \\ 0 & \text{otherwise} \end{cases} \quad (2 \le k \le n) \tag{2}$$

Under the null hypothesis of no trend, the statistic d_k is distributed as a normal distribution with the expected value of $E(d_k)$ and the variance $\mathrm{Var}(d_k)$ as follows:

$$E(d_k) = \frac{n(n-1)}{4} \tag{3}$$

$$Var(d_k) = \frac{n(n-1)(2n+5)}{72} \tag{4}$$

We defined the following:

$$UF_k = \frac{d_k - E(d_k)}{\sqrt{Var(d_k)}} \quad k = 1, 2, 3, \ldots, n \tag{5}$$

UF_k follows the standard normal distribution. In a two-sided test for trend, the null hypothesis is rejected at the significance level of α if $|UF| > UF_{(1-a/2)}$, where $UF_{(1-a/2)}$ is the critical value of the standard normal distribution with a probability exceeding $a/2$. A positive UF value denotes a positive trend, and a negative UF value denotes a negative trend. In this paper, a significance level of $a = 5\%$ is used.

The terms of the $UF_k (1 \leq k \leq n)$ constitute curve C_1, which represents the forward trend of the series. Applying the method to the inverse series, we could obtain the series of UB_k as follows:

$$\begin{cases} UB_k = -UF_{k1} \\ k1 = n + 1 - k \end{cases} \quad k = 1, 2, 3, \ldots, n \tag{6}$$

The terms of UB_k constitute another curve C_2, which represents the backward trend of the series. If the intersection point of the C_1 and C_2 is between the two confidence lines, we can consider that abrupt breakpoint occurred at that point.

To analyze the precipitation–runoff relationship and address the impacts of precipitation and human activities on runoff, DMCs and linear regression relationships were used to show the correlation between cumulative annual runoff and precipitation. Regression analyses can effectively analyze the relationship between precipitation and runoff. The least-squares linear model is the most common method used to detect trends. In addition, the method is commonly used for statistical diagnoses and forecasting in modern climatology (Hameed *et al.* 1997; DaSilva 2004). The linear trend of the annual precipitation series, which was calculated using the least-squares regression, was chosen in this paper because it provides the simplest model of the unknown trend. The estimated slopes were tested against the null slope hypothesis using a two-tailed T-test at a confidence level of 95%.

The DMC is a method to check the consistency and long-term trend of many kinds of hydro-meteorological data. The theory behind DMCs is that the graph of the accumulation of two variables will plot as a straight line if two variables are proportional, and the slope of this line will represent the constant of proportionality between the two variables (Searcy & Hardison 1960). The precipitation–runoff DMC can be applied to investigate the correlation between cumulative annual runoff and precipitation. In general, the precipitation–runoff DMC is a straight line that denotes the relationship of cumulative precipitation and runoff is proportional (Zhang & Lu 2009). However, in most cases, an abrupt breakpoint can be identified in the DMCs, indicating an obvious change in the precipitation–runoff relationship, which was mainly due to human activities (Jiang *et al.* 2015). In this study, based on the annual precipitation and runoff, the DMC of precipitation and runoff was first plotted to investigate the abrupt breakpoint and the proportional relationship between cumulative precipitation and annual runoff. For the N-year observation period, two discrete variables P_i (annual precipitation) and R_i (annual runoff) are used to calculate the corresponding annual cumulative values. New accumulated sequences of P'_i and R'_i are obtained and can be expressed as follows:

$$P'_i = \sum_{i=1}^{t} P_i \quad i = 1, 2, 3, \ldots, t \tag{7}$$

$$R'_i = \sum_{i=1}^{t} R_i \quad i = 1, 2, 3, \ldots, t \tag{8}$$

where t is the length of the observation sequence.

The breakpoint of the cumulative precipitation and runoff curve divided the time series into a reference period (before the breakpoint) and affected period (after the breakpoint). Based on the least-squares regression, a linear regression analysis was performed to explore the relationship between cumulative precipitation and cumulative runoff in the reference period. According to the linear regression equation, the calculated runoff ($Q_{\text{calculated}}$) in the affected period can be obtained by substituting the precipitation value of the affected period into the equation. By subtracting the mean observed annual runoff in the referenced period ($Q_{\text{referenced}}$) from the calculated values ($Q_{\text{calculated}}$), the runoff change caused by precipitation can be estimated (ΔQ_p). The total change of the observed runoff (ΔQ_o) compared with that in the referenced period ($Q_{\text{referenced}}$) can be expressed as follows:

$$\Delta Q_o = \Delta Q_p + \Delta Q_h \tag{9}$$

Then, the runoff change caused by human activities (ΔQ_h) can be estimated by Equation (9). Thus, the effects of precipitation and human activities on runoff change can be calculated using the following equation:

$$C_p = \frac{\Delta Q_p}{\Delta Q_o} = \frac{Q_{\text{calculated}} - Q_{\text{referenced}}}{Q_{\text{observed}} - Q_{\text{referenced}}} \times 100\% \tag{10}$$

$$C_h = 1 - C_p \tag{11}$$

where Q_{observed} is the mean annual observed runoff during the affected period and C_p and C_h are the percentages of runoff change caused by precipitation and human activities, respectively.

RESULTS

Annual precipitation trend

The annual precipitation for the Lanzhou section, Toudaoguai section, Huayuankou section, and Lijin section (from 1956 to 2010) is presented in Figure 3. The average annual precipitation is 483 mm, 261 mm, 559 mm, and 645 mm, respectively, for these sections.

The Mann–Kendall test was used to determine the annual precipitation trends of the 63 meteorological stations, and the results are presented in Figure 4. Only seven among the 63 stations display a significant trend ($P = 0.05$), and the remaining 56 stations display no significant trend. Among the seven stations with a significant trend ($P = 0.05$), one station (Linhe) has an upward trend, and six stations display a downward trend. Thirty-five stations present downward, non-significant trends. These stations are mainly located in the middle and lower regions of the basin.

In the region above Lanzhou station (Lanzhou section), the annual precipitation trends for all 11 meteorological stations are statistically insignificant. There are six stations (Maduo, Zeku, Guide, Xining, Minhe, and Lanzhou) with increasing trends (indicating precipitation increases). In the region from Lanzhou to Toudaoguai (Toudaoguai section), eight of the 19 stations exhibit increasing trends; however, most of the trends are not significant. Only the Linhe station has a significant increasing trend (Z-value of 2.23). There are

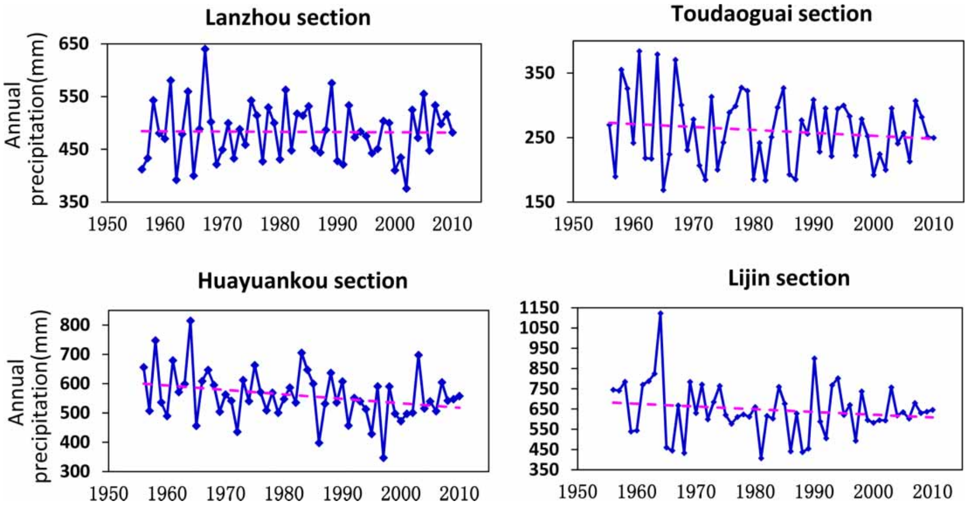

Figure 3 | Annual precipitation variations (1956–2010) in the YRB.

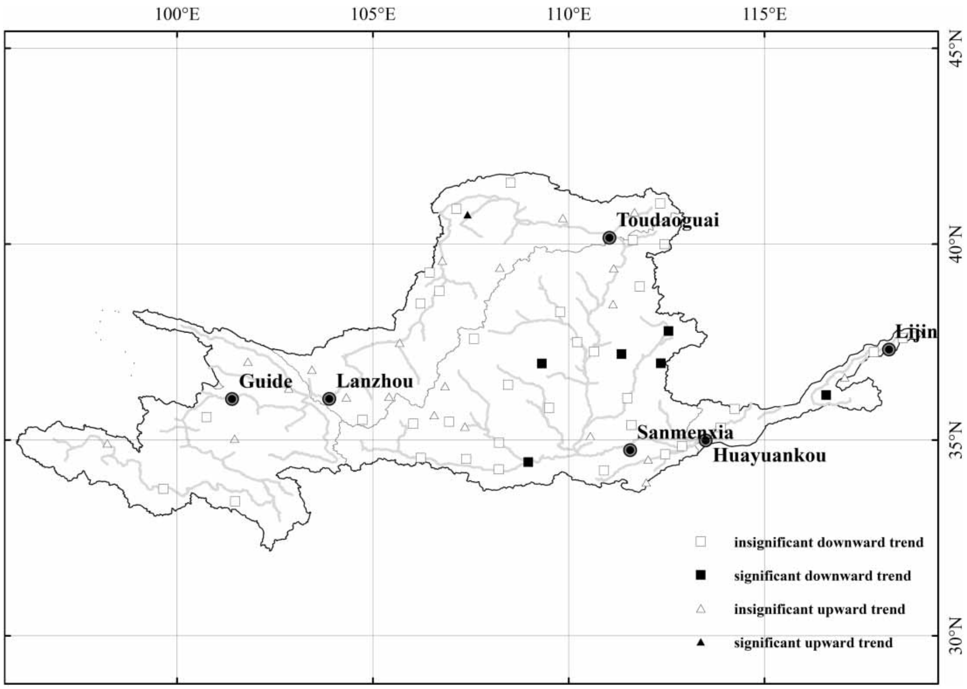

Figure 4 | The annual precipitation trend detected by the Mann–Kendall method.

11 stations with decreasing trends, but the trends are not significant. In the region from Toudaoguai to Huayuankou (Huayuankou section), 20 of the 27 stations exhibit decreasing trends in annual precipitation. Additionally, the Wu Zhai, Lishi, Jiexiu, and Hengshan stations display significant declines, with Z-values of −2.01, −2.34, −2.02, −2.35, and −2.10, respectively. In the region from Huayuankou to Lijin (Lijin section), five of the six stations exhibit decreasing trends. These trends are statistically insignificant except for the trend at Taian station (Z-value of −2.02).

The spatial distribution of precipitation indicates that the stations displaying increasing trends mainly lie in the upper region (Lanzhou section and Toudaoguai section), and most stations display insignificant trends. However, the stations that display decreasing trends for precipitation are mainly located in the middle and lower regions of the YRB (Huayuankou section and Lijin section). Moreover, only one significant increasing trend change occurred in the upward reaches of the YR, so climate in these regions has not significantly changed in the study period. Five significant downward trends were concentrated in the middle reaches.

These results indicate that the precipitation distributions are uneven in every section of the YRB due to varying geographic location, topography and physiognomy characteristics; thus, the degrees of precipitation response in

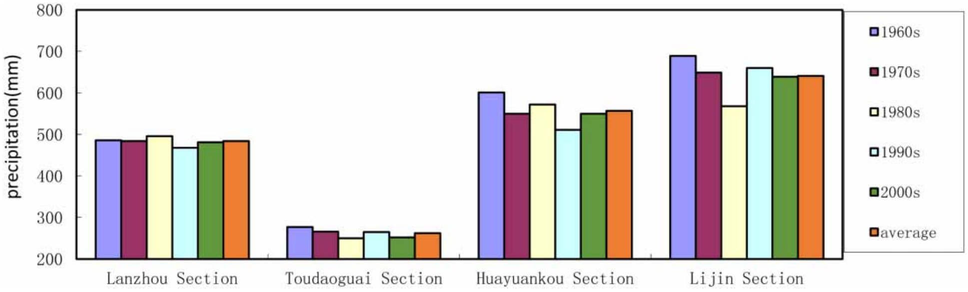

Figure 5 | Variations in the decadal mean precipitation in different sections of the YRB.

Table 2 | Precipitation characteristics in the YRB during different decades

	Lanzhou section		**Toudaoguai section**		**Huayuankou section**		**Lijin section**	
Year	**Average precipitation**	C_v	**Average precipitation**	C_v	**Average precipitation**	C_v	**Average precipitation**	C_v
1960s	486.00	0.15	276.87	0.26	601.07	0.16	689.29	0.27
1970s	484.39	0.08	266.40	0.19	550.65	0.11	649.40	0.10
1980s	496.47	0.10	239.59	0.20	572.65	0.14	568.30	0.21
1990s	471.27	0.07	268.52	0.12	512.51	0.15	668.07	0.19
2000s	477.31	0.11	246.59	0.15	543.83	0.11	634.24	0.12

every section of the region are different. The regional precipitation has decreased in the middle and lower sections, in which the annual precipitations in the 2000s have decreased by 60 mm and 44 mm, respectively, compared with annual precipitations from the 1960s (Figure 5). The decadal mean precipitations of different sections and the corresponding coefficients of variation (*Cv*) are calculated in Table 2. The precipitation variation in the upper regions of the basin is considerably smaller than in other regions. The average precipitations in the Lanzhou and Toudaoguai sections decreased by 5 mm and 2 mm, respectively, in the 2000s compared to observations in the 1960s. The value of *Cv* in the Lanzhou section is relatively small, and the variation is not significant. However, *Cv* variations in different decades are significant in the Lijin section. The middle and lower sections of the YRB are close to sea level; therefore, they are influenced by monsoons. Monsoon precipitation is sensitive to meteorological variables (e.g., air temperature, wind speed, and net radiation) and significantly impacts some of the stations in this region. A relatively small monsoon effect was observed in the upstream Tibetan Plateau area (average elevation is above 4,200 m), as the precipitation measurements at most of the stations displayed insignificant trends (Liu & Cui 2011).

Abrupt precipitation change

The number and frequency of abrupt changes identified using the Mann–Kendall test are shown in Figure 6 and Table 3.

The results indicate that abrupt precipitation changes occurred over the past 55 years. There were 38 stations with abrupt changes among the 63 meteorological stations. The stations with abrupt changes are mainly located in the middle Huayuankou section and downstream Lijin section of the YRB. For example, two or three abrupt changes took place at nine stations. Seven of these stations are located in the above-mentioned area, indicating that precipitation variations in this region are more frequent. Furthermore, abrupt changes in recent decades were different. There were 9, 13, 5, and 19 abrupt changes in the 1960s, 1970s, 1980s, and 1990s, respectively. The stations with abrupt changes in the 1960s and 1970s are mainly in the southeastern YRB, while the stations with abrupt changes in the 1980s and 1990s mainly lie in the central YRB and expand to the west in the upper reaches of the YRB. When comparing the El Niño–Southern Oscillation (ENSO) events to the regional precipitation from 1950 to 2000, it is clear that the ENSO events correspond to low precipitation in the YRB. Wang *et al.* (2006) confirmed that the regional precipitation was strongly affected by the global climate system; since the mid-1980s, global ENSO events have become stronger and more frequent, most of the low-level precipitation years in the YRB were closely associated with moderate and strong ENSO events. Other studies have also detected significant linkages between ENSO and hydro-climatic variables (Trenberth 1997; Chiew & McMahon 2002). Zhao *et al.* (2014a, 2014b) concluded that strong ENSO events and monsoon activities, which primarily affect regional precipitation, together with global climate change influence the hydrological cycle in the MRYRB.

Temperature variations

The temperature trend in the YRB has increased over the past 60 years. This trend was particularly significant after the

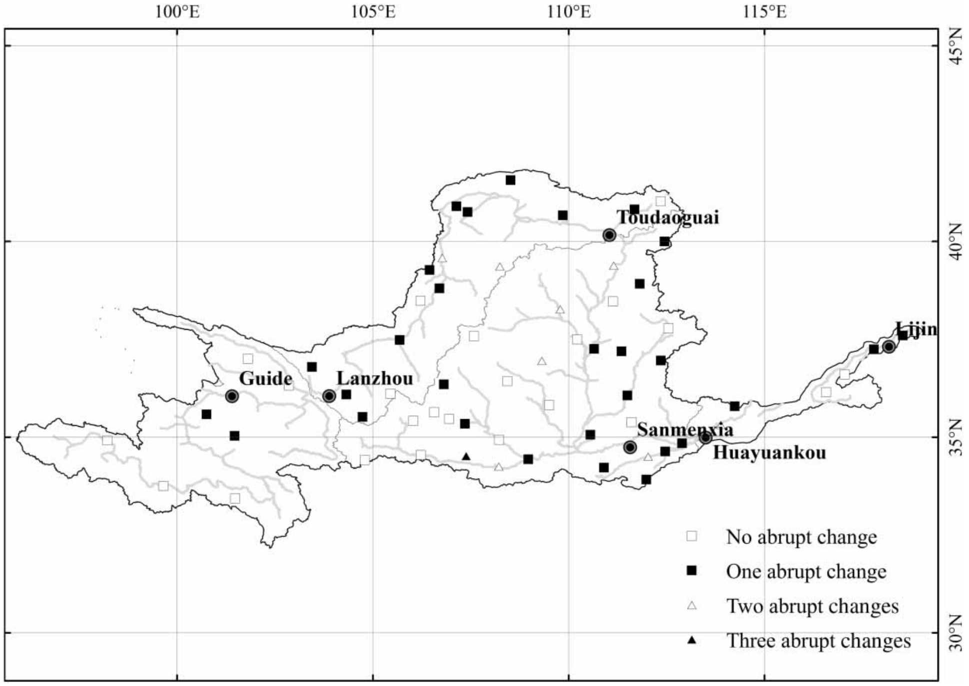

Figure 6 | Abrupt changes detected by the Mann–Kendall method at the YRB meteorological stations.

Table 3 | Abrupt precipitation changes in the YRB during different decades

Year	Lanzhou section	Toudaoguai section	Huayuankou section	Lijin section	Abrupt changes
1960–1969	1	–	6	2	9
1970–1979	–	3	8	2	13
1980–1989	1	3	1	–	5
1990–2000	2	6	9	2	19

1990s. Among the 63 stations, only two displayed decreasing temperature trends. The temperature increased at the other 61 meteorological stations, with an average increase of 0.6 °C. The increasing trend was most obvious during winter and weakest during summer. In addition, the increase was higher in the north than in the south, which is consistent with the zonal distribution of global warming. Overall, the annual average temperature increased by 0.6 °C. The correlation coefficients between the temperature and runoff and between the precipitation and runoff were −0.4 and 0.15 in the source region of the YR and −0.31 and 0.42 below the Lanzhou section, respectively. This result indicates that precipitation is the main factor that influences runoff variations in the majority of the YR.

Annual runoff trend

Figure 7 depicts the annual observed runoffs at the Guide, Lanzhou, Toudaoguai, Sanmenxia, Huayuankou, and Lijin hydrological stations from 1956 to 2010. Table 4 lists the mean runoff values of different decades and percent changes compared with the 1960s for all the stations. A decreasing trend was observed over time after the 1980s, especially at the three stations below Toudaoguai station. The minimum annual runoffs of all these stations occurred after 1990. The runoff trends at the Lanzhou and Lijin stations increased after 2000.

Based on the Mann–Kendall analysis, the annual runoff displays a decreasing trend at six stations (Figure 8). The trend is insignificant only for Guide station. The Lanzhou, Toudaoguai, Sanmenxia, Huayuankou and Lijin stations exhibit Z-values of −2.08, −3.71, −5.36, −5.29, and −5.71, respectively.

Abrupt runoff changes

The Mann–Kendall test was used to graphically illustrate the observed runoff trends before and after abrupt changes at

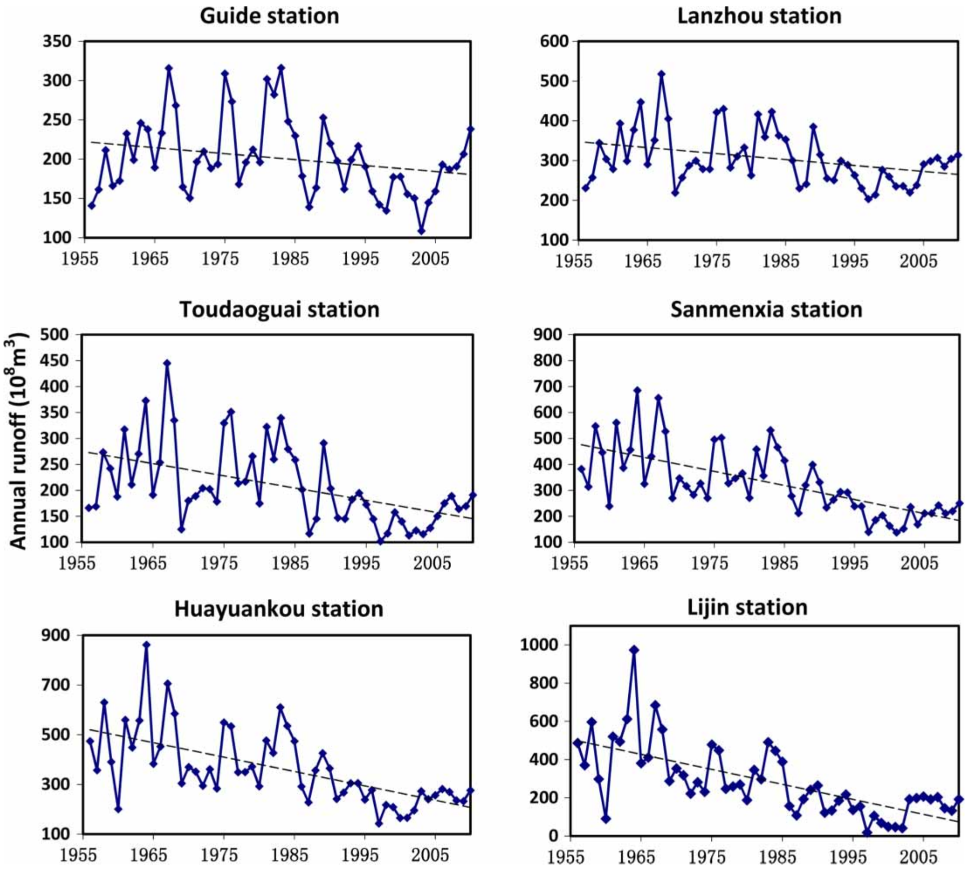

Figure 7 | Annual observed runoff variations (1956–2010) at six hydrological stations in the YRB.

Table 4 | Mean observed runoffs in different decades at the six stations

	Guide		**Lanzhou**		**Toudaoguai**		**Sanmenxia**		**Huayuankou**		**Lijin**	
Year	**10^8 m^3**	**%**	**10^8 m^3**	**%**	**10^8 m^3**	**%**	**10^8 m^3**	**%**	**10^8 m^3**	**%**	**10^8 m^3**	**%**
1956–1969	209.96		336.89		254.4		444.91		493.68		483.09	
1970–1979	209.76	0.10	317.96	5.62	233.12	8.36	358.16	19.50	381.57	22.71	311.05	35.61
1980–1989	230.86	−9.95	333.52	1.00	239.03	6.04	370.91	16.63	411.74	16.60	285.82	40.84
1990–1999	179.75	14.39	259.74	22.90	155.22	38.99	235.07	47.16	248.56	49.65	132.37	72.60
2000–2010	173.82	17.21	271.81	19.32	150.82	40.71	200.47	54.94	235.66	52.27	145.71	69.84

the six stations from 1956 to 2010. The separation point of the upward and downward curves indicates the starting point of an abrupt runoff change. An abrupt runoff change is significant ($P < 0.05$) at the point where the curves fall outside the dotted lines. There are abrupt and significant runoff declines at the Lanzhou, Toudaoguai, Sanmenxia, Huayuankou, and Lijin stations (Figure 9). In contrast, runoff decline is insignificant at Guide station.

In general, 1990–2010 is the period with abrupt runoff declines in the YRB. Lijin station exhibits the earliest runoff decline. This decrease starts as early as 1981 and accelerates drastically in 1986. At Huayuankou station and Sanmenxia station, abrupt changes began in 1989 and 1990, respectively, and became significant in 1993. Runoff declines at Toudaoguai station and Lanzhou station began in 1990 and accelerated drastically in 1993. At Guide

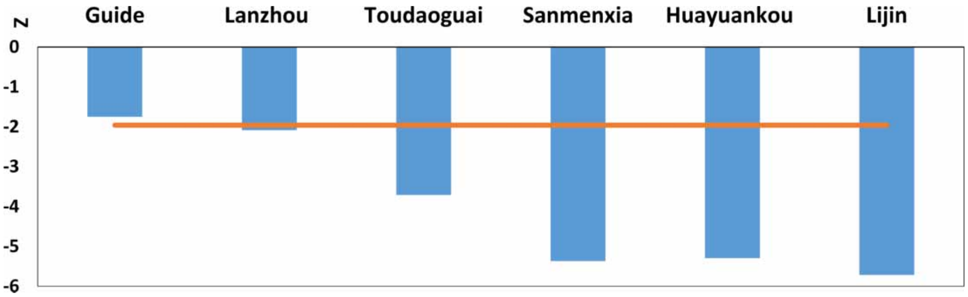

Figure 8 | Mann–Kendall test for annual runoff at six hydrological stations. Horizontal lines represent critical values (−1.96) corresponding to the 95% confidence interval.

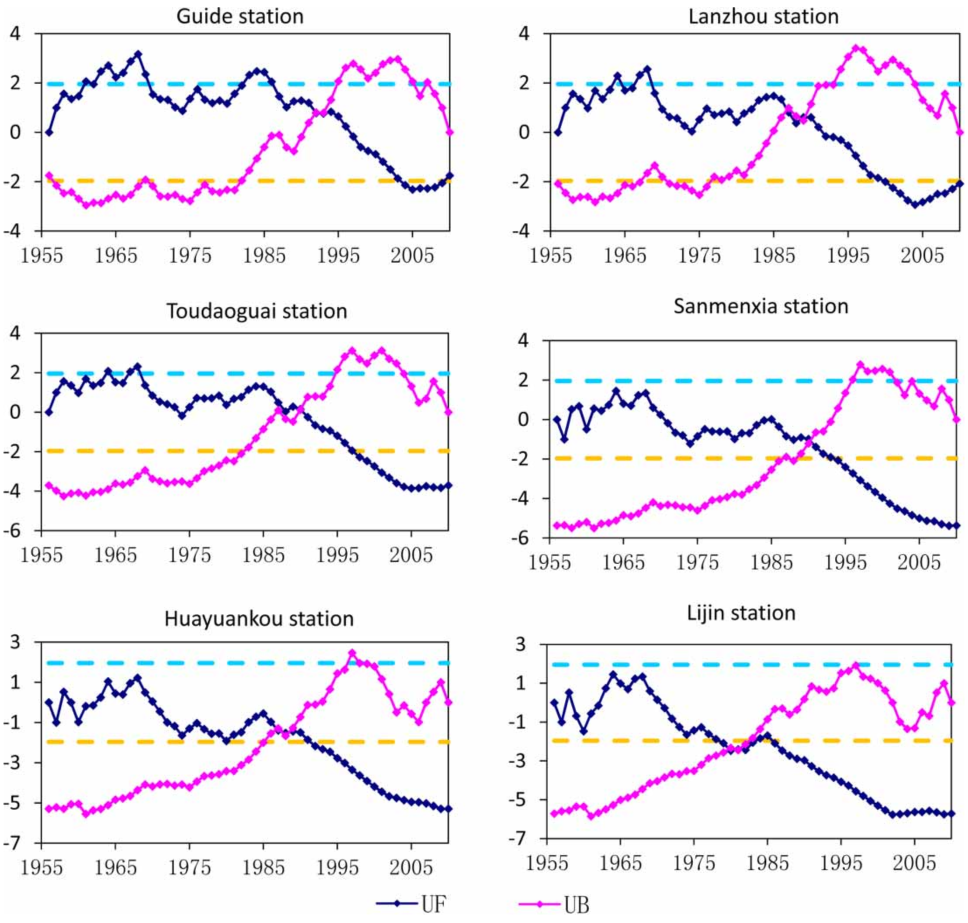

Figure 9 | Mann–Kendall test for annual observed runoff. Dotted horizontal lines represent critical values corresponding to the 95% confidence interval.

station, abrupt change occurred in 1993. Runoff decline there began later (starting in 1997), but the trend is not significant. Therefore, abrupt runoff changes initially occurred in the downstream portions of the YRB and then expanded to the middle and upper reaches of the basin.

Relationships between runoff and precipitation

A precipitation–runoff double cumulative curve was used to detect the breakpoints of the precipitation–runoff relationships in different sections from 1956 to 2010. As shown in Figure 10, some abrupt changes in the DMCs are evident. The relationships between cumulative observed runoff and precipitation are well represented by straight lines with different slopes before and after the abrupt changes. In the Lanzhou section, a breakpoint occurred in the DMC in 1990, which verifies the result of the Mann–Kendall test. The slope of the regression line is slightly lower after the transition year, indicating that runoff is decreasing. In the region from Lanzhou to Toudaoguai (Toudaoguai section), runoff accumulation is negative because the observed runoff at Toudaoguai station is lower than at Lanzhou station in most years. This suggests that the runoff in the Toudaoguai section is influenced by underlying surface and human activities. In the Huayuankou and Lijin sections, both of the DMCs show breakpoints in 1970 and 1990. The observed cumulative annual precipitation and runoff values in these sections demonstrate that precipitation and runoff were relatively uniform before 1970; however, the precipitation or runoff characteristics changed after 1970. A straight line was observed from 1956 to 1969, suggesting that the annual runoff consistently varied with annual precipitation. Thus, the period had no detectable runoff changes due to human activities. From 1970 to 1990, there was an obvious deviation between the extended regression line and current regression line. The deviation increased after 1990, indicating that the cumulative increasing effect on annual runoff was due to human activities.

Contributions of precipitation and human activities to the runoff change

The DMCs indicate that human activities clearly impact runoff change. The variations in hydrological processes were not only affected by precipitation, but also by human activities in the catchment. To quantitatively analyze the impacts of human activities and precipitation variations on runoff change, we use the period less affected by human activities (before the breakpoint) as a reference period based on the characteristics of the DMCs. The reference period of the Lanzhou and Toudaoguai sections is 1956 to 1992. The reference period is 1956 to 1970 for the Huayuankou and Lijin sections. The period after the breakpoint is the affected period, in which human activities impact runoff variations. The regression equations for the

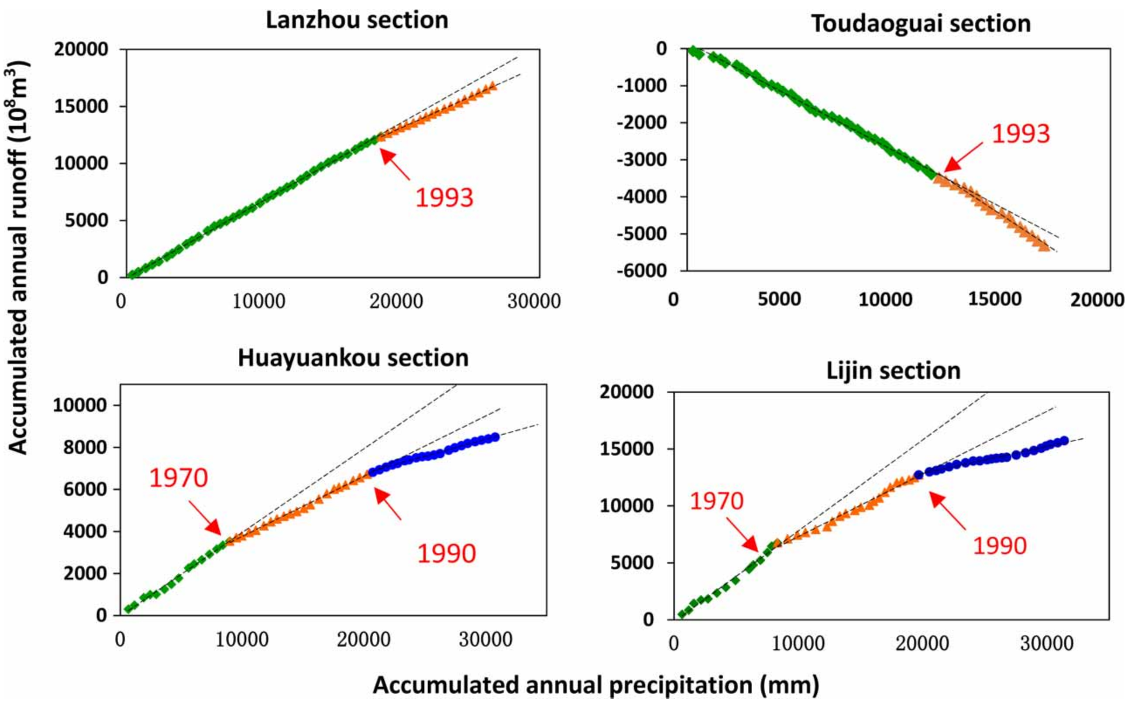

Figure 10 | DMCs of runoff and precipitation in different sections.

reference period were used to represent the effects of precipitation variations on the runoff variables. By extending the regression equations between observed runoff and precipitation during the reference period to the precipitation in the affected period, runoff variations due to precipitation variations can be estimated. By subtracting the observed values of runoff variables from estimated values based on precipitation, the changes caused by human activities can be further estimated. The estimated contributions of precipitation variations and human activities to runoff changes in different sections are summarized in Table 5 for the affected periods. Runoff in the Lanzhou section decreased by 18.70% compared with the reference period. Additionally, the contributions of human activities and precipitation variations are 74.87% and 25.13%, respectively. In the Toudaoguai section, the runoff is more negative compared with the reference period. The impacts of human activities and precipitation are 82.20% and 17.80%, respectively. In the middle reaches of the YRB (Huayuankou section), runoff consistently decreased throughout the entire period after 1969. Human activities played a role in decreasing runoff, with contributions of 80.36% and 80.63% in 1970–1989 and 1990–2010, respectively. In the lower reaches, the impact of human activities gradually increased, dominating the runoff change with contributions of 83.98% and 88.71% in the two affected periods. These results provide the quantitative contributions of human activities and precipitation to the runoff change based on the reference period. Generally, human activities increasingly contribute to temporal and spatial runoff change in the YRB.

DISCUSSION

Sensitivity of runoff to precipitation

In this section, the naturalized runoff was used to analyze the sensitivity of runoff to precipitation. The linear correlation between annual precipitation and naturalized runoff was calculated using the least squares regression. The estimated slopes were tested against the null slope hypothesis using a two-tailed T-test at a confidence level of 95% (DaSilva 2004). The slopes indicate that runoff is positively related to precipitation in the Lanzhou, Toudaoguai, Huayuankou, and Lijin sections. The sensitivity of the runoff response to precipitation change varies in different sections, with R^2 values of 0.73, 0.02, 0.67, and 0.59 in the Lanzhou, Toudaoguai, Huayuankou, and Lijin sections, respectively. Therefore, the relationship between runoff and precipitation is most sensitive in the Lanzhou section, followed by the Huayuankou, Lijin, and Toudaoguai sections. This result indicates that watershed characteristics, such as vegetation conditions, soil moisture, and saturated hydraulic conductivity, influence the response of runoff to precipitation. The YRB has a very broad range of climate and land surface conditions. Compared with other regions, the Lanzhou section has good vegetation cover and

Table 5 | Quantification of the impact of precipitation change and human activities on runoff

				Measured runoff change (ΔQ_o)		Effect of precipitation (ΔQ_p)		Effect of human activity (ΔQ_h)	
Section	**Period**	**Observed runoff**	**Calculated runoff**	10^8 m^3	%	10^8 m^3	%	10^8 m^3	%
Lanzhou	1956–1992	325.73	327.99						
	1993–2010	264.81	310.42	60.92	18.70	15.31	25.13	45.62	74.87
Toudaoguai	1956–1992	− 88.46	− 87.04						
	1993–2010	− 113.11	− 92.85	24.64	27.85	4.39	17.80	20.26	82.20
Huayuankou	1956–1969	239.27	237.70						
	1970–1989	160.58	223.82	78.69	32.89	15.45	19.64	63.24	80.36
	1990–2010	92.13	210.77	147.14	61.49	28.50	19.37	118.64	80.63
Lijin	1956–1969	483.09	462.87						
	1970–1989	298.44	453.50	184.65	38.22	29.59	16.02	155.07	83.98
	1990–2010	143.35	444.74	339.74	70.33	38.35	11.29	301.39	88.71

relatively less human activity. Thus, the area has relatively saturated soil conditions that promote runoff. Runoff is more sensitive to precipitation changes in the Lanzhou region than in other regions. Furthermore, the spatial precipitation distribution and trends reveal that no significant variations occurred in the upper reaches of the Lanzhou section. Additionally, the declining annual runoff trend in Lanzhou is insignificant because of the strong relationship between runoff and precipitation. In the Toudaoguai section, the river flows across the Loess Plateau and less water enters the river from fewer tributaries. As a result, more water is consumed in this region due to a high evaporation rate and drought soil conditions on the Loess Plateau. Therefore, runoff in the Toudaoguai section is less sensitive to precipitation than in the Lanzhou section.

To further investigate the sensitivity of runoff to precipitation, $\triangle Q\% - \triangle P\%$ was calculated as a function of $\triangle P\%$, as shown in Figure 11 (Risbey & Entekhabi 1996; Liu & Cui 2011). This value can be used to explain the nonlinearity between precipitation and runoff in different regions of the YRB. The results indicate that the runoff change increases with the precipitation change. When $\triangle P\% < 0$, the runoff response to the precipitation change was more sensitive in Lijin, Lanzhou, and Huayuankou than in Toudaoguai. When $0 < \triangle P\% < 10$, there was little runoff response to precipitation in different regions. When $\triangle P\% > 10$, the runoff response to precipitation change was more sensitive in the Lanzhou section, followed by the Lijin, Huayuankou, and Toudaoguai sections.

In addition to the significant impact of precipitation on the regional runoff in the YRB, other global climate changes also influence the hydrological cycle. In particular, global warming has increased air temperatures in the river basin, causing increased evapotranspiration (Zhang *et al.* 2004). Since 1970, the average annual air temperature over the river basin has increased from 16.5 °C to 17.5 °C (Xu 2005). As a result, the evapotranspiration from agriculture and reservoir evaporation have increased. Thus, the climate of the YRB has become warmer and drier, while the regional runoff has decreased.

Different abrupt runoff change years among different sections

This study demonstrates that the abrupt runoff change years vary in different sections of the YRB. The abrupt runoff changes in the upper reaches of the Lanzhou section and Toudaoguai section occur in 1993, suggesting simultaneous inflexion points in the runoff change of these two sections. The abrupt runoff changes in the middle and lower reaches of the Huayuankou and Lijin sections occurred in 1970 and 1990, respectively. The abrupt runoff change years reflect the shift in the relative intensities of influencing factors, including both climate-driven factors and human activities. The Huayuankou and Lijin sections are located in the middle and lower reaches of the YR, which experienced more intense and earlier human influences than other sections (Yang *et al.* 2004). In contrast, the Lanzhou section is located in the headwater region of the river, which is subject to only limited human influences. Thus, the abrupt runoff change years in the downstream reaches were earlier than those for the upstream reaches. Other studies of

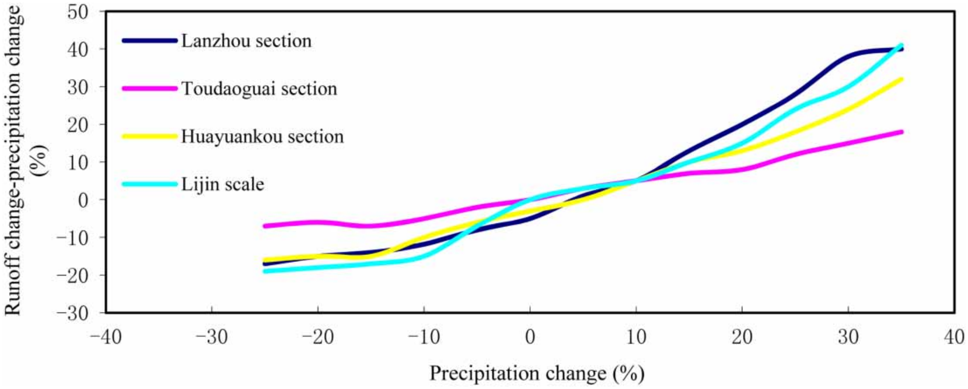

Figure 11 | Average runoff change minus precipitation change as a function of precipitation change for the Lanzhou, Toudaoguai, Huayuankou, and Lijin sections in the YRB.

different tributaries of the middle YR have suggested different abrupt runoff change years (Chang *et al.* 2015), such as 1971 for the Wuding River (Xu 2011) and 1992 for the Weihe River (Wang *et al.* 2008). However, the results in the tributaries correspond with the abrupt change points in the middle reaches of the YR.

Impacts of human activities on the runoff

According to the results of Table 5, human activities played a dominant role in runoff reduction in the YRB after each breakpoint year. Additionally, the impacts of human activities on the runoff changes vary in the different sections. The two most important aspects of human activities in the YRB are basin-wide erosion control practices and water diversion for irrigation and other human uses. Runoff has significantly decreased due to the effects of these factors.

In the upper reaches of the Lanzhou and Toudaoguai sections of the YRB, water resources are abundant; however, human activities have inevitably influenced the runoff. Large-scale human activities include hyper-irrigation and large hydroelectric projects. There are 24 reservoirs scattered throughout the YRB, with storage capacities exceeding 0.10×10^9 m^3. These reservoirs redistribute the seasonal and annual water discharges and sediment loads. Large hydroelectric projects (including reservoirs at Longyangxia, Liujiaxia, Qingtongxia, and Sanshenggong) are located in the upper reaches (Figure 1). The slope of the DMC in the Lanzhou section (Figure 10) decreases in 1993, indicating that the impact of human activities increased, reaching 74.87% (Table 5). This increase is mainly due to the Liujiaxia and Longyangxia reservoirs. The Liujiaxia and Longyangxia reservoirs were constructed above Lanzhou in 1968 and 1985, respectively. The Liujiaxia reservoir has a storage capacity of 5.7 km^3 and a 147 m high dam wall. The Longyangxia reservoir (27.6 km^3 storage capacity and a 178 m high dam wall) is a multi-year reservoir. The combined operation of these two reservoirs regulates the seasonal water discharge from the upper reaches to meet demands for agricultural irrigation; thus, these operations affect the middle and lower reaches (Chen 1997). Moreover, Figure 10 shows that the precipitation and runoff DMC in the Toudaoguai section is negatively correlated because runoff at Toudaoguai station is less than that at Lanzhou station. Human activities and underlying surface conditions directly reduce the runoff in this section. The hyper-irrigation area of the upper reaches of the YRB is approximately 1,230 km^2 according to statistical data from the Chinese Ministry of Water Resources. More than 94% of this area is located in the Toudaoguai section (Table 6). Hyper-irrigation directly reduces the regional water discharge due to water consumption by irrigation fields. The runoff decrease in the upper reaches has been affected by increasing water diversion from the main stream for irrigation and industrial utilization. Therefore, the impacts of human activities on runoff are most significant in the upper reaches. As a result, the runoff trends at three stations (Guide, Lanzhou, and Toudaoguai) in the upper reaches have declined. However, the annual precipitation trend at one station displayed a significant increase (Figure 4).

In the middle reaches of the YRB, soil conservation practices, including biological measures (e.g., trees and pasture) and structural projects (e.g., terraces and dams), were implemented in the 1970s and 1980s because of severe soil losses that contributed to >90% of the total river sediment load. Thus, the DMC exhibits breakpoints in 1970 and 1990 (Figure 10). The effects of human activities on runoff increased gradually, reaching 80.36% and 80.63% in the two affected periods. As shown in Table 7, the soil

Table 6 | Hyper-irrigation areas in the YRB

Section	Area (km^2)	Hyper-irrigation area (km^2)
Lanzhou	222,551	73
Toudaoguai	145,347	1,161
Huayuankou	362,138	2,316
Lijin	21,833	3,580

Source: Yang *et al.* (2004).

Table 7 | Area of soil conservation practices in the Hekou-Longmen sub-catchment

	Level terrace	Afforestation	Grass-planting	Check dam	Total
1959	331	1,513	357	28	2,229
1969	1,158	3,423	383	154	5,118
1979	2,305	8,818	1,045	395	12,563
1989	3,448	19,862	2,114	563	25,987
1996	4,859	25,373	2,408	682	33,322

conservation area has expanded with time. Human activities have changed the local micro-topography, increased the ability of intercepting precipitation, and consequently, delayed and reduced the runoff (Miao *et al.* 2011). Tang indicated that the surface runoff decrease in the upper and middle reaches due to soil conservation measures was approximately 0.63×10^9 m^3/year over the period of 1980–1997 (Tang 2004). In addition, the Sanmenxia reservoir, the first large reservoir built in the river basin, is located in the middle reaches (Figure 1). The Xiaolangdi reservoir, which has a storage capacity of 12.7 km^3 and a 160 m high dam wall, is also located in the middle reaches between the Sanmenxia reservoir and Huayuankou station. In 2002, the YRCC initiated the Water-Sediment Regulation Scheme, which uses the controlled release of floodwaters from the Xiaolangdi reservoir and other small reservoirs to distribute the sediment retained within the Xiaolangdi across the lower reaches (Wang *et al.* 2005). These major reservoirs are situated on the main stream, and make the largest contributions to water regulation and sediment retention (Wang *et al.* 2006).

In the lower reaches of the Lijin section, hydrological change results from the combination of contributory effects from the local region, and the upper and middle reaches of the YRB. Similar to the Huayuankou section, the DMC in this section occurs in the years 1970 and 1990, and human activities have an increasing influence on runoff change. Due to the flat topography of the lower YR subbasin, the irrigation areas were extended outside the basin in the 1970s and 1980s (Yang *et al.* 2004). The water diversion for irrigation resulted in a remarkable decrease in the runoff in this area, and the abrupt change year (1971) is the earliest among all the surveyed areas and stations.

CONCLUSIONS

Using the runoff records from six major hydrological stations and precipitation measurements from 63 meteorological stations in the YRB, this study identified the basic trends and abrupt changes associated with precipitation and runoff in four sections of the basin. DMCs were used to analyze the relationship between precipitation and runoff, and to detect the impact of human activities on runoff in the YRB.

Different trends and spatial patterns were obtained for precipitation and runoff in the YRB. Only seven of the 63 stations displayed a significant precipitation trend, with one station displaying an increasing trend and six stations displaying decreasing trends. Thirty-eight stations exhibited negative trends. These stations are mainly located in the Huayuankou and Lijin sections of the basin. Annual runoffs at the six hydrological stations all display declining trends, although the trend is insignificant at Guide station.

There were 49 abrupt precipitation changes at 63 meteorological stations. Most of these were located in the middle Huayuankou section and downstream Lijin section of the YRB. In addition, abrupt changes were more common from 1991 to 1998 than in other years due to the impacts of land use and human activities. The most abrupt runoff decline in the YRB was observed between 1990 and 2010. Additionally, abrupt runoff changes were mainly noted in the downstream reaches of the YRB. These changes then expanded to the middle and the upper reaches of the basin.

Precipitation–runoff double cumulative curves were used to detect the breakpoints of the precipitation–runoff relationships in different sections for the period of 1956–2010. In the upper reaches of the YRB, precipitation and runoff were relatively uniform. However, precipitation or runoff characteristics changed after 1993. In the middle and downstream reaches, the breakpoints were 1970 and 1990. Furthermore, the relationship between runoff and precipitation is most sensitive in the Lanzhou section, followed by the Huayuankou, Lijin, and Toudaoguai sections.

Human activities have become the dominant factors influencing runoff variations since the 1970s. After the 1990s, the percentages of runoff variations due to human activities were 74.87%, 82.2%, 80.63%, and 88.71% at the Lanzhou, Toudaoguai, Huayuankou, and Lijin stations, respectively. The two most important human activities in the YRB are erosion control practices and water diversion for irrigation and other human uses.

This study illustrated the runoff changes in the YRB and analyzed the influences of precipitation and human activities on runoff variations. The influences of evaporation, air temperature, and land use change on runoff are not considered due to data limitations. Future studies will consider these factors in an attempt to fully reveal the impacts of climate change and human activities on runoff variations in the YRB.

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