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ORIGINAL ARTICLE

Attribution assessment and projection of natural runoff change in the Yellow River Basin of China

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Abstract Climate variability and human activities are two driving factors in the hydrological cycle. The analysis of river basin hydrological response to this change in the past and future is scientifically essential for the improvement of water resource and land management. Using a water balance model based on Fu' equation, the attribution of climate variability and land-use/ land-cover change (LUCC) for natural runoff decrease was quantitatively assessed in the Yellow River Basin (YRB). With five general circulation model (GCM) s' output provided by The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), future runoff in the context of climate change was projected. The results show that (1) compared with other

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distributed hydrological models, the water balance model in this study has fewer parameters and simpler calculation methods, thus having advantages in hydrological simulation and projection in large scale; (2) during the last 50 years, the annual precipitation and runoff have decreased, while the mean temperature has increased in the YRB. The decrease of natural runoff between natural period (1961 to 1985) and impacted period (1986 to 2011) could be attributed to 27.1–49.8 and 50.2–72.9% from climate variability and LUCC, respectively. As the LUCC is the major driving factor of the decrease in the upper and middle reaches of the YRB, policymakers could focus on water resources management. While climate variability makes more contribution in the middle and lower reaches of the YRB, it is essential to study the impact of future climate change on water resources under different climate change scenarios, for planning and management agencies; (3) temperature and precipitation in the YRB were predicted to increase under RCP4.5. It means that the YRB will become warmer and wetter in the future. If we assume the land-use/land-cover condition during 2011 to 2050 is the same as that during 1986 to 2011, future annual average natural runoff in the YRB will increase by 14.4 to 16.8%. However, future runoff will still be lower than the average value during 1961 to 1985. In other words, although future climate change will cause the increase of natural runoff in the YRB, the negative effect of underlying surface condition variation is stronger. It is necessary to promote the sustainable development and utilization of water resources and to enhance adaptation capacity so as to reduce the vulnerability of the water resources system to climate change and human activities.

Keywords Climate variability · Land-use/land-cover change · Runoff decrease · Yellow River Basin

1 Introduction

Climate variability and human activities are considered to be the two driving factors for the change of temporal and spatial distribution of runoff. The former factor mainly includes the change of temperature and precipitation (Chen and Xia 1999). The rise of average surface air temperature and change in precipitation pattern may result in alteration to regional hydrological cycle (Xu 2000; Labat et al. 2004; Huntington 2006; Milliman et al. 2008; Déry et al. 2009). The later factor can be water withdrawal from river, groundwater pumping, dam construction, land-use/covers change (LUCC), etc., which can change the elements of the hydrological cycle in terms of quantity and quality, both in temporal and spatial scale (Wilk and Hughes 2002; Levashova et al. 2004; Hao et al. 2008). Therefore, assessment of the impacts of climate variability and human activities on runoff change can make an important contribution to water resources planning and management (Narsimlu et al. 2013). A number of studies have been carried out on the quantitative assessment of attribution for runoff or surface water resources change in river basins of China and other countries. Arnell (2004) found that runoff decreased because of climate change in Mediterranean, parts of Europe, central and southern America, and southern Africa. While in southern and eastern Asia, climate change causes the runoff increase. However, this increase tends to occur in the wet season and the extra water may not be available during the dry season. Menzel and Bürger (2002) projected that discharges of the Mulde catchment (Southern Elbe, Germany) would decrease because of temperature increase and precipitation decrease. Coe and Foley (2001) detected that climate variability controls the inter annual fluctuations of the water inflow but that human water use accounts for roughly 50% of the observed decrease in the Lake Chad Basin since the 1960s and 1970s. According to Twine et al. (2004) and Qian et al. (2007), annual runoff increased in the Mississippi River Basin from 1948 to 2004 due to precipitation increase and land-cover change. With global vegetation and hydrology model, the contributions of different drivers to worldwide trends of runoff in the twentieth century were quantified by Gerten et al. (2008); the results showed that precipitation was the most important factor, followed by land-use change, rising atmospheric carbon dioxide (CO_2) content, global warming, and irrigation. Study of Ren et al. (2002) showed that the impact of human activities on river runoff was more significant in arid or semi-arid area than that in humid area. Wang et al. (2009) reported that decrease in runoff can be attributed to 31 to 35% from climate variation and 68 to 70% from human activities in the Chaobai River Basin in northern China. Ma et al. (2010) found that climate impact and indirect impact of human activity were accountable for about 51~55 and 18%, respectively for the runoff decrease in the Miyun Reservoir catchment located in North China. Tao et al. (2011) revealed that the decrease of the water volume diverted into the main stream of the Tarim River Basin was caused by human activities since the 1970s. What is worse, this situation was worsened in the 2000s. There are two problems in previous research. (1) The methodology used in these studies is the distributed hydrological model. Driving a distributed hydrological model needs enormous data such as the land surface condition, soil, vegetation, and land use and the temporal-spatial variability of climatic inputs. The model is difficult to be built with limited data, especially in ungauged basins (Sivapalan 2003). A lot of parameters need to be calibrated during the modeling process which is one of the principal sources contributing to modeling uncertainty (Aronica et al. 1998). Due to the lack of data and being over-parameterized, the distributed hydrological model may not be suitable for application in catchment with large scope. In the study of assessing the impact of climate variability and human activities on runoff, we pay more attention to the overall basin response. So a simplified water balance model is better than complex distributed hydrological model. In this study, we built a water balance model based on Fu rational function equation. The performance of the model in simulating natural annual runoff in large-scale catchments can meet the requirements of accuracy. The model has a simple structure. Inputs of these models only include meteorological variables and there is only one parameter needs to be calibrated. So the model has advantages in hydrological simulation and projection at regional or global scale; (2) most of the studies only focused on the historical changes of runoff. In fact, with rising temperature in the future, spatial and temporal distribution of runoff is altered and water resources will be implicated consequently (IPCC 2008; IPCC 2014). It will result in the alteration of water availability for different uses, such as municipal use, irrigation, hydro-electric power generation, and aquatic wildlife (Milly et al. 2008). Therefore, assessment of potential effects of future climate change on runoff has great significance in sustainable utilization and basin-wide adaptive management (Boini et al. 2013). In addition, improvement of coupled climate models has given stronger foundation for research on assessing climate change potential effects on runoff in the future under different emission scenarios (Nakicenovic and Swart 2000). In this study, we used multiple climate change scenarios and Global Circulation Models (GCMs) to identify the impact of future climate variability on natural runoff.

Considering the Yellow River Basin (YRB) is one of the most important basins in China and it has been suffering from water shortage and related environmental problems, this research did a case study in the YRB. Attribution for decreasing natural runoff of the YRB was quantitatively assessed, and future runoff in the context of climate change was projected. The sections of this paper are organized as follows: the study area, dataset and methodologies (water balance model, attribution assessment, estimation of future natural runoff) are introduced in Section 2; Section 3 shows the hydro-meteorological trends, natural runoff simulation, the contribution of climate variability, and indirect impact of human activities (land-use/land-cover change, LUCC) to natural decrease in the Yellow River Basin and projection of future runoff; and the conclusions are summarized in Section 4.

2 Materials and methods

2.1 Study area

The Yellow River Basin (YRB, 95° 54′–119° 4′ E and 32° 10′–41° 50′ N) is located in north of Central China region, covering an area of 752,400 km^2 shared by nine provinces and autonomous regions (namely Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shannxi, Shanxi, Henan, and Shandong) (Fig. 1). The Yellow River, the second longest river in China, is about 5464 km in length and passes through a range of landscapes, originating in the eastern Qinghai-Tibet Plateau, cutting through Loess Plateau to North China Plain before joining the Bohai Sea (Yang et al. 2004). The climatic regions change from arid and semi-arid to semi-humid regions, with the arid zone in the upper reaches (UR), semi-arid zone in the middle reaches (MR), to semi-humid zone in the lower reaches (LR) (Cheng 1996). The average annual temperature varies between 4 and 14 °C. The annual average precipitation in UR, MR, and LR is 368, 530, and 670 mm, respectively (Wang et al. 2007). More than 60% of the total annual precipitation falls in the wet season (from June to September) (Yang et al. 2010). The average annual runoff is about 580 billion m^3, which mainly occurs from July to October (Liu et al. 2011).

The YRB is one of the most important basins in China. As the important source of water supply in the north-western China and northern China, the YRB has been suffering from water shortage and related environmental problems (Wang et al. 2001). Continuous zero-flow periods occurred more frequently in the lower reaches of Yellow River since the 1990s, when the channels of the lower reaches dried up every year (Liu and Xia 2004) (Fig. 2). The greater number of zero-flow days led to serious ecological hazards as well as economic losses (Liu and Zheng 2002). The increase of agricultural water use in the middle reaches is considered to be

Fig. 1 Topographical map of the Yellow River Basin

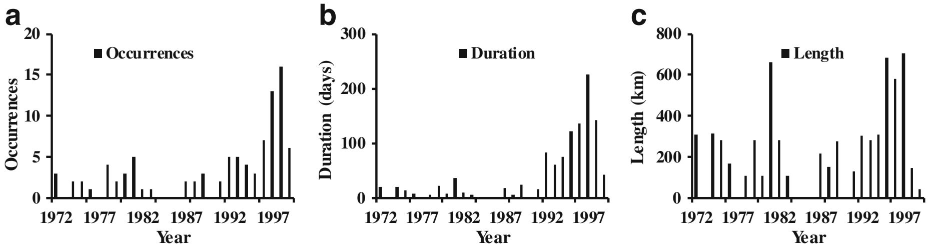

Fig. 2 Records of the dried-up channels in the lower reaches of the Yellow River at Lijin hydrological station. **a** Number of times when the channel dried up. **b** Duration of dried up period. **c** Length of dried up channel. Ps: the records come from the paper of Liu and Xia (2004)

the main cause to the flow reduction in lower reaches (Zheng et al. 2007). The climate change (eg., the decreases of precipitation) and the land-use change are also identified as the causes leading to the decrease of runoff (Yang et al. 2010).

2.2 Data

Observed daily meteorological data during 1961 to 2011 from 128 meteorology stations in and around the YRB were collected for this study (Fig. 3). The dataset, including precipitation (P), highest temperature (TH), lowest temperature (TL), average temperature (TA), sunshine hours (S), wind speed (WS), relative humidity (RH),longitude, latitude, and elevation, is provided by China Meteorological Data Sharing Service System (http://data.cma.gov.cn).

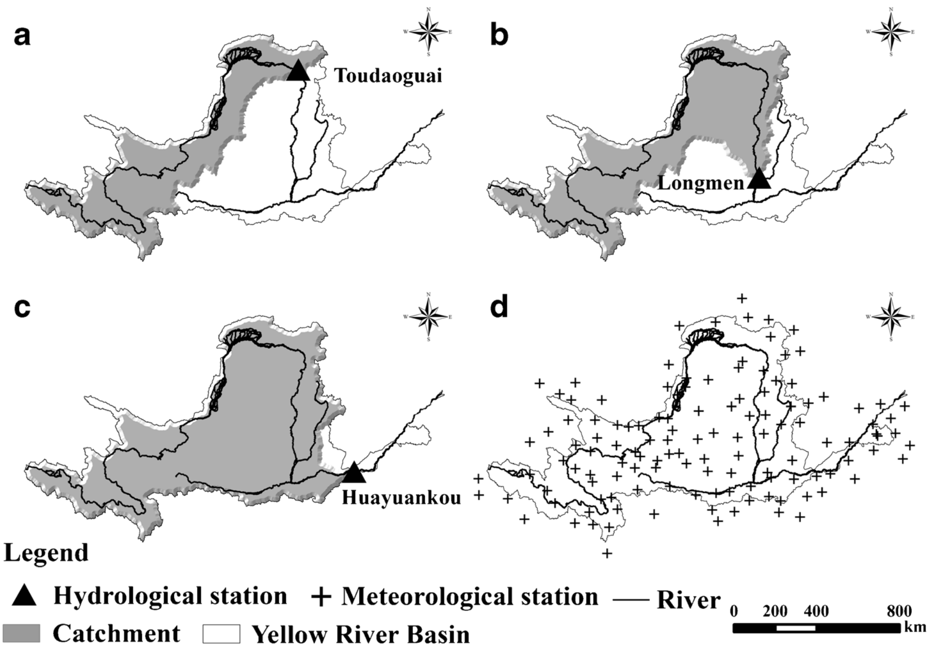

Fig. 3 Location of hydrological and meteorological stations. **a** Toudaoguai Station and its catchment. **b** Longmen Station and its catchment. **c** Huayuankou Station and its catchment.d Meteorology stations in and around the YRB

Natural discharge data was collected from three hydrological stations in different parts of the YRB during the period from 1961 to 2011. It was used to analyze the runoff trend and the change of the precipitation-runoff relationship, and to calibrate and validate the water balance model. The hydrological data is derived from National Integrated Water Resources Planning and Yellow River Conservancy Commission of the Ministry of Water Resources (http://www.yellowriver.gov.cn). The basic information of the three hydrological stations is listed in Table 1.

Climate change scenarios for this case study are obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, http://www.isi-mip.org). The ISI-MIP climate dataset includes five global climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) and covers the period from 1960 to 2099 on a horizontal grid with 0.5° × 0.5° resolution (Table 2) (Warszawski et al. 2014). In order to guarantee long-term statistical consistency between projected data and observational data (1960–1999), data was bias-corrected. Projected absolute trends in temperature and relative trends in precipitation have been retained by bias-correction method (Piani et al. 2010; Hagemann et al. 2011). In this study, we used the midrange mitigation emission scenario (RCP4.5) and the period 2011 to 2050 and selected 415 grids covering the YRB (Fig. 4).

2.3 Time series analysis method

1. Linear Regression Analysis and the Slope

In this study, we used the linear fitted model to estimate the magnitude of linear trend. This method tests against the null hypothesis slope by means of a two-tailed *t* test. It is a common method for climatic statistical diagnosis (Brunetti et al. 2000; Liang et al. 2011). The estimated trend of data sequence (k) can be calculated as follows:

$$k = \frac{n \times \sum_{i=1}^{n} (i \times x_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} x_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i \right)^2} \qquad (1)$$

where i is the number of whole study years and x_i is the value in the 푄th year.

2. Mann–Kendall test

Table 1 Description of hydrological stations used in this study

Hydrological station	Lon. (E°)	Lat. (N°)	Catchment area ($10^4 km^2$)
Toudaoguai	111.07	40.27	36.79
Longmen	110.6	35.67	49.76
Huayuankou	113.65	34.92	73.00

Table 2 List of general circulation models (GCMs) used in this study

Centre	Country	Name
Geophysical Fluid Dynamics Laboratory (GFDL)	USA	GFDL-ESM2M
Hadley Centre for Climate Prediction and Research, Met Office	UK	HADGEM2-ES
L'Institut Pierre-Simon Laplace (IPSL)	France	IPSL-CM5A-LR
Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies	Japan	MIROC-ESM-CHEM
Norwegian Climate Centre	Norway	NORESM1-M

The Mann–Kendall test was used to detect the break points of precipitation, temperature and natural runoff in the YRB. The time series were expressed as x_1, x_2,…, x_n and the test statistic (UF_i) can be calculated as follows:

$$UF_i = \frac{S_i - E(S_i)}{\sqrt{Var(S_i)}} \quad (i = 1, 2, ..., n)$$
$$S_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, ..., n) \tag{2}$$
$$ri = \begin{cases} +1 & x_i > x_j \\ 0 & x_i \leq x_j \end{cases} \quad (j = 1, 2, ..., i-1)$$

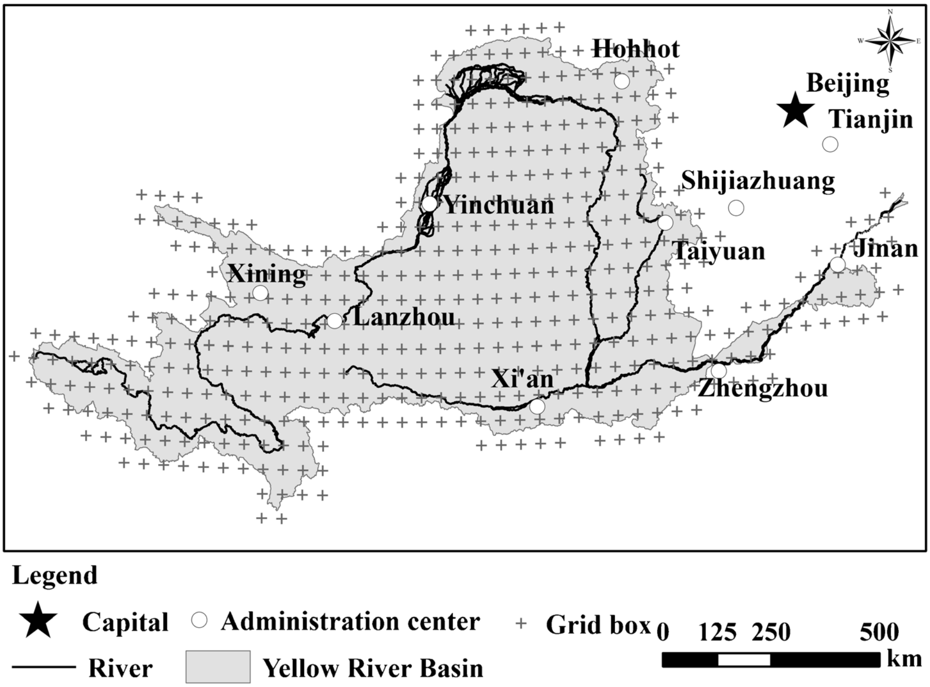

Fig. 4 Grid boxes distribution of Yellow River Basin

where, x_i is the variable with the sample of n. $E(S_k)$ and variance $Var(S_k)$ could be estimated as follows:

$$E(S_i) = \frac{i(i-1)}{4}$$
$$Var(S_i) = \frac{i(i-1)(2i+5)}{72} \tag{3}$$

Using the same equation but in the reverse data series (x_n, x_{n-1},…, x_1), UF_i could be calculated again. Defining $UB_i = UF_i$ ($i = n, n-1, \ldots, 1$), we can get the curve of UF_i and UB_i. If the intersection of the UF_i and UB_i curves occurs within the confidence interval, it indicates a change point (Demaree and Nicolis 1990; Moraes et al. 1998).

2.4 Water balance model based on Fu equation

For a basin, hydrological elements follow the water balance principle:

$$R = P - E + \Delta S \tag{4}$$

where P is precipitation; E is evaporation; R is runoff; ΔS is variation of water storage in a region (basin). In research for the ΔS with long time scale, ΔS approaches to zero.

Actual evaporation could be calculated by analytical expression based on Budyko assumption, which was carried out by Baopu Fu. This formula described the inter-relationship between precipitation, actual evaporation, evaporation capacity, and land-use (Fu 1981; Zhang et al. 2004).

$$\frac{E}{ET_0} = 1 + \frac{P}{ET_0} - \left[1 + \left(\frac{P}{ET_0}\right)^{\omega}\right]^{1/\omega} \tag{5}$$

where E is actual evaporation, mm; ET_0 is potential evaporation, mm. In this study, the Food and Agriculture Organization Penman-Monteith method (Allen et al. 1998) was used in calculating ET_0 (Eq. 6); P: annual precipitation, mm; ω: empirical parameter which is related to land-use type.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \tag{6}$$

where ET_0 is reference evapotranspiration, mm/day; R_n is the net radiation at the crop surface, MJ/(m day); G is the soil heat flux density, MJ/(m day); T is the air temperature at 2 m height, °C; u_2 is the wind speed at 2 m height, m/s; e_s is the saturation vapor pressure, kPa; e_a is the actual vapor pressure, kPa; Δ is the slope of the saturation vapor pressure-temperature curve, kPa/°C; γ is the psychometric constant, kPa/°C.

Based on Eqs. 4 and 5, water balance model based on Fu equation could be obtained:

$$R = ET_0\left\{\left[1 + \left(\frac{P}{ET_0}\right)^{\omega}\right]^{1/\omega} - 1\right\} \tag{4}$$

where R is annual runoff depth, mm. Other parameters are the same as those in the above case. Because the Budyko-curve is usually used to estimate the mean annual runoff, in this study, we use 5-year moving average precipitation, potential evaporation, and runoff depth to calibrate the model.

Correlation coefficient of linear regression equation (R^2), Nash-Sutcliffe values (Nash and Sutclife 1970), and relative error (*RE*) were chosen to quantify the performance of the model for simulating runoff, which were defined as follows:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(R_{\text{sim-}i}-\overline{R_{\text{sim}}}\right)\left(R_{\text{obs-}i}-\overline{R_{\text{obs}}}\right)\right]^2}{\sum_{i=1}^{n}\left(R_{\text{obs-}i}-\overline{R_{\text{obs}}}\right)^2\sum_{i=1}^{n}\left(R_{\text{sim-}i}-\overline{R_{\text{sim}}}\right)^2} \tag{5}$$

$$E_{NS} = 1-\frac{\sum_{i=1}^{n}\left(R_{\text{sim-}i}-R_{\text{obs-}i}\right)^2}{\sum_{i=1}^{n}\left(R_{\text{obs-}i}-\overline{R_{\text{obs}}}\right)^2} \tag{6}$$

$R_{\text{obs - }i}$is observed depth of runoff (mm); $R_{\text{sim - }i}$is simulated depth of runoff (mm); $\overline{R_{\text{obs}}}$ and $\overline{R_{\text{sim}}}$ are the mean value of observed and simulated depth of runoff, respectively(mm); n is number of observed value. Models perform better with higher R^2, greater E_{ns}, and smaller *RE*. When $E_{ns} \geq 0.75$, it means the simulation is good; when $0.36 < E_{ns} < 0.75$, the simulation is basically good; when $E_{ns} \leq 0.36$, the simulation is poor (Motovilov et al. 1999).

2.5 Quantitative assessment of the attribution for runoff decrease

In this study, we assumed that the change of natural runoff was driven by climate variability and land-use/land-cover change (LUCC). In order to assess the impact of climate variability and LUCC on natural runoff, the Mann–Kendall's test (Mann 1945; Kendall 1975) was used to detect the approximate time (break point) of the change in natural runoff. Then, the whole time series was divided into two periods (Fig. 5). The first period before the break point represents the baseline when climatic variability was not significant and land-use/land-cover was natural status, which is also defined as natural period. The second period after the break point represents the "impacted period" when the natural runoff is impacted by climate variability and/or LUCC.

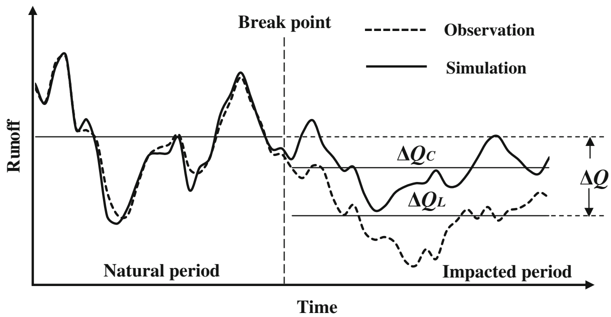

Fig. 5 The framework of the attribution for runoff decrease assessment

Figure 5 shows the framework of the assessment the attribution for runoff decrease assessment. A change in mean annual natural runoff (ΔQ) can be resulted from climate variability (ΔQ_C) and LUCC (ΔQ_L):

$$\Delta Q = Q_N - Q_I = \Delta Q_C + \Delta Q_L \quad (7)$$

where ΔQ is the change of annual natural runoff, Q_N is the average annual natural runoff in the "natural period," Q_I is the average annual natural runoff in the "impacted period," ΔQ_C is the runoff change caused by climate variability, and ΔQ_L is the runoff change caused by LUCC.

The parameter of water balance model calibrated by the hydrological data in the "natural period" can represent the characteristics of catchment in natural status. With the precipitation and potential evaporation data in the "impacted period" as input and the same model parameter as those in the "natural period," the simulated runoff (Q_{sim}) can be considered as the reconstructed natural runoff without the impact of LUCC. Then, the difference of reconstructed natural runoff in impacted period (Q_{sim}) and observed natural runoff in natural period (Q_N) can represent the impact of climate variability on runoff (ΔQ_C).

$$\Delta Q_C = Q_N - Q_{sim} \quad (8)$$

where Q_N is the average annual natural runoff in the "natural period"; Q_{sim} is the average annual simulated (reconstructed) natural runoff. Runoff change caused by LUCC could be estimated by

$$\Delta Q_L = \Delta Q - \Delta Q_C \quad (9)$$

with Eq. 2 and 3, the contribution of climate variability (η_C) and LUCC (η_L) to natural runoff change could be estimated using the following expression:

$$\eta_C = \frac{\Delta Q_C}{\Delta Q} \times 100\% \quad \eta_L = \frac{\Delta Q_L}{\Delta Q} \times 100\% \quad (10)$$

2.6 Estimation of climate change impact on annual runoff

Reorganizing daily precipitation and temperature output by five climate models in the RCP4.5 scenario, gridded monthly precipitation and temperature data could be calculated. On the basis of GRID function of ARC/INFO, monthly areal precipitation and areal temperature of each catchment could be got via ZONALSTATS. Then, based on the inter-statistical relationship between temperature and potential evaporation, future monthly potential evaporation could be projected. At last, yearly areal precipitation and potential evaporation in each catchment from 2011 to 2050 were calculated and put into water balance model as input data to project future natural runoff.

3 Results

3.1 Hydro-meteorological variability and trend in YRB

Figure 6a and b shows the time series of YRB areal precipitation and mean temperature. Figure 7a and b shows the distribution of slope across the YRB during 1961 to 2011. The

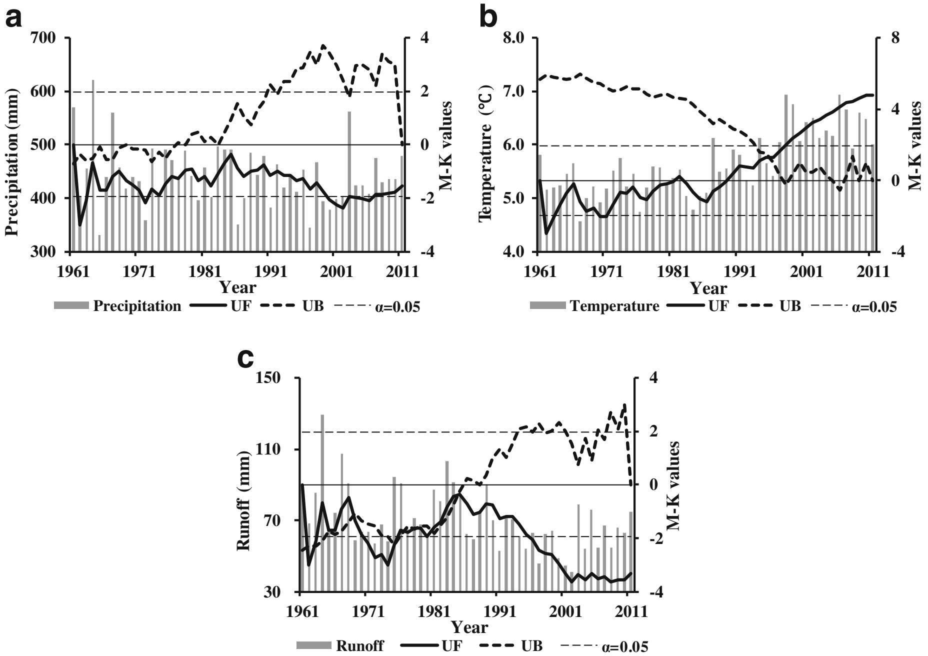

Fig. 6 Precipitation, mean temperature, and natural runoff during 1961 to 2011 and Mann–Kendall's testing statistical values. **a** YRB areal precipitation. **b** YRB mean temperature. **c** Natural runoff in the Huayuankou catchment

mean annual precipitation in YRB over the period 1961 to 2011 was 443.8 mm. It could be found that there was a negative trend in YRB during the last 50 years with the average annual decreasing rate of 7.6 mm/10a. But the trend did not pass the significance test through Mann–Kendall test (Fig. 6a). From the perspective of spatial variety, except the upper reaches of the YRB where precipitation showed an increasing trend, precipitation in most of the area showed a decreasing trend (Fig. 7a). The climate of the YRB has become warmer during the last 50 years. The annual mean temperature had increased by 0.29 °C per decade from 1961 to 2011, and the positive trend has been statistical significant at α = 0.01 level (Fig. 6b). The increasing extent of temperature is comparatively big in the middle and upper reaches of YRB,

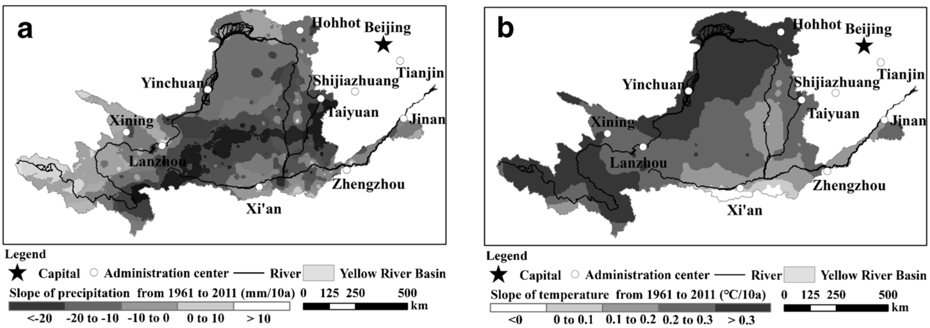

Fig. 7 Distribution of slope for the period 1961 to 2011 across the YRB. **a** Precipitation. **b** Temperature

especially in the reaches above Longyangxia and area between Xiaheyan and Hekouzhen where the increasing extent of temperature is more than 0.3 °C/10a (Fig. 7b).

Figure 6c is the variation of annual runoff depth of Huayuankou catchment. Since the controlling area of Huayuankou catchment is 7.3×10^5 km^2, which is 91.9% of the total area of HRB, the variation of its natural runoff depth can reflect the variation of the whole surface water resources of YRB. It can be seen from Fig. 6c that the natural runoff depth of YRB has obvious decreasing trend ($\alpha = 0.01$). The break point of the annual natural runoff depth tested by the Mann–Kendall method was 1985. Annual average natural runoff depth during 1986 to 2011 was 62.5 mm, which has decreased by 20.9% compared with the average value during 1961 to 1985 (79.0 mm). In this study, 1961 to 1985 was considered as the natural period and 1986 to 2011 was considered as the impacted period.

3.2 The change of the precipitation-runoff relationship

The runoff coefficient, expressed as the runoff divided by the precipitation, was a recapitulative way to examine the hydrological performance of a catchment (Chen et al. 2014). The average annual runoff coefficient of Toudaoguai (TDG), Longmen (LM), and Huayuankou (HYK) catchments were 0.23, 0.19, and 0.16, respectively. The runoff coefficient decreased by 0.012, 0.010, and 0.009 per decade in these catchments from 1961 to 2011(Fig. 8). The relationship between precipitation and runoff of the three catchments in the two periods divided by 1985 was shown in Fig. 9. Runoff coefficient after 1985 in each catchment was smaller than that before 1985. Compared with the runoff coefficient during the natural period, that during the impacted period had decreased by 15.0, 14.7, and 15.6%,

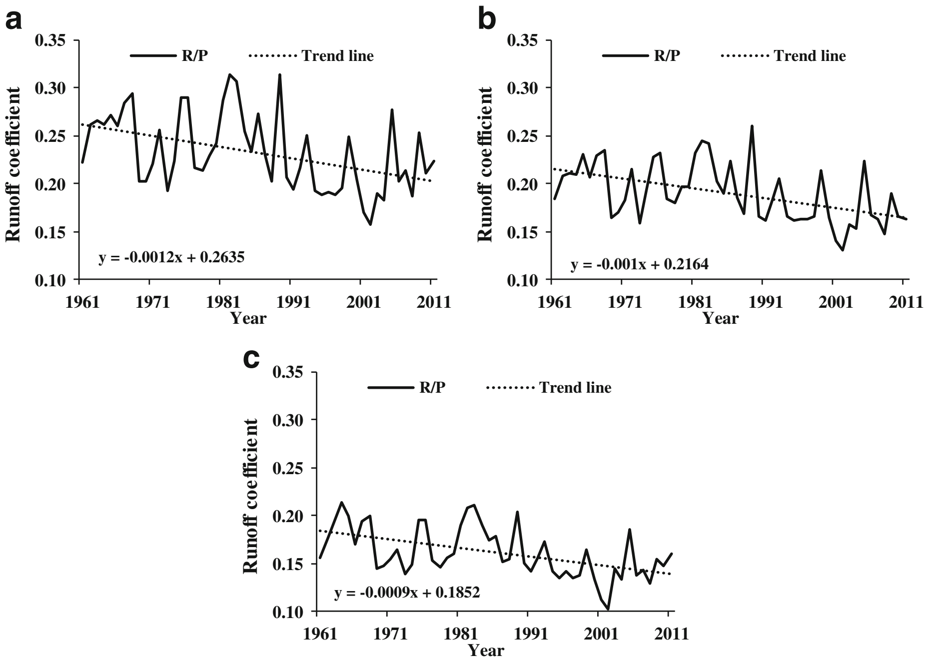

Fig. 8 Annual runoff coefficient during 1961 to 2011. **a** Toudaoguai catchment. **b** Longmen catchment. **c** Huayuankou catchment

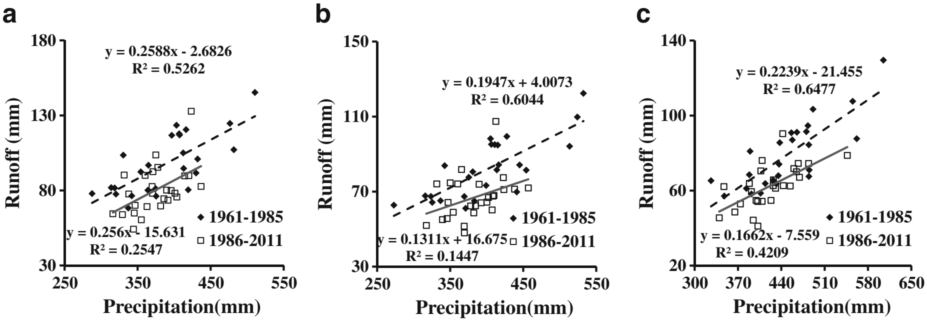

Fig. 9 The relationship between annual precipitation and runoff during the two periods divided by 1985. **a** Toudaoguai catchment **b** Longmen catchment. **c** Huayuankou catchment

respectively, in Toudaoguai, Longmen, and Huayuankou. This implied that with the same precipitation, the converted runoff in impacted period was less than that in natural period. It can also be seen that during the impacted period, underlying surface condition has changed obviously, thus changing the relationship between precipitation and runoff.

3.3 Assessment of the attribution for decreasing runoff

Since water balance model based on Fu' equation is good at simulating annual average runoff, the calibration and validation were completed using the 5-year moving average runoff records

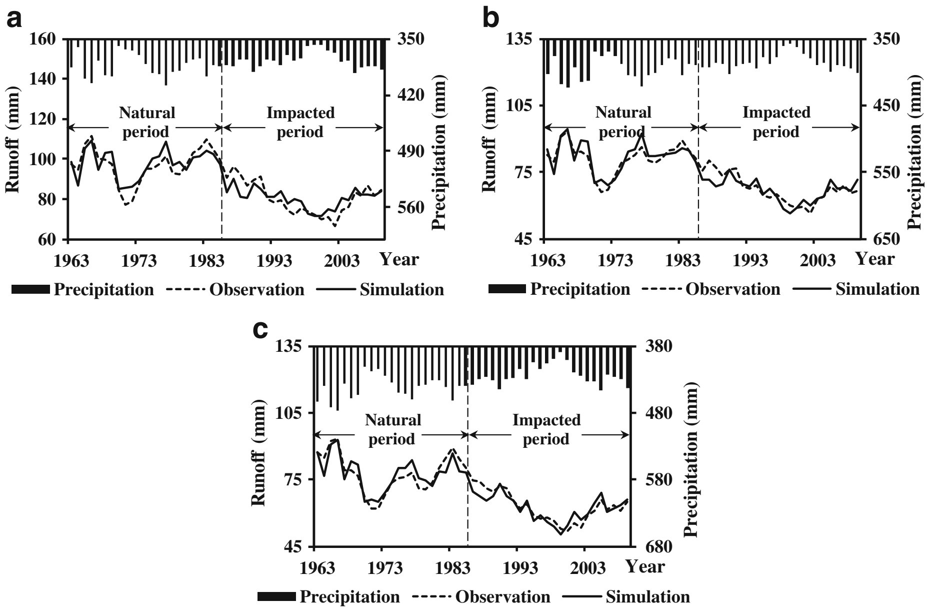

Fig. 10 Observed and simulated runoff in the calibration and verification period, which were smoothed with a 5-year moving average filter for the whole period. **a** Toudaoguai catchment. **b** Longmen catchment. **c** Huayuankou catchment

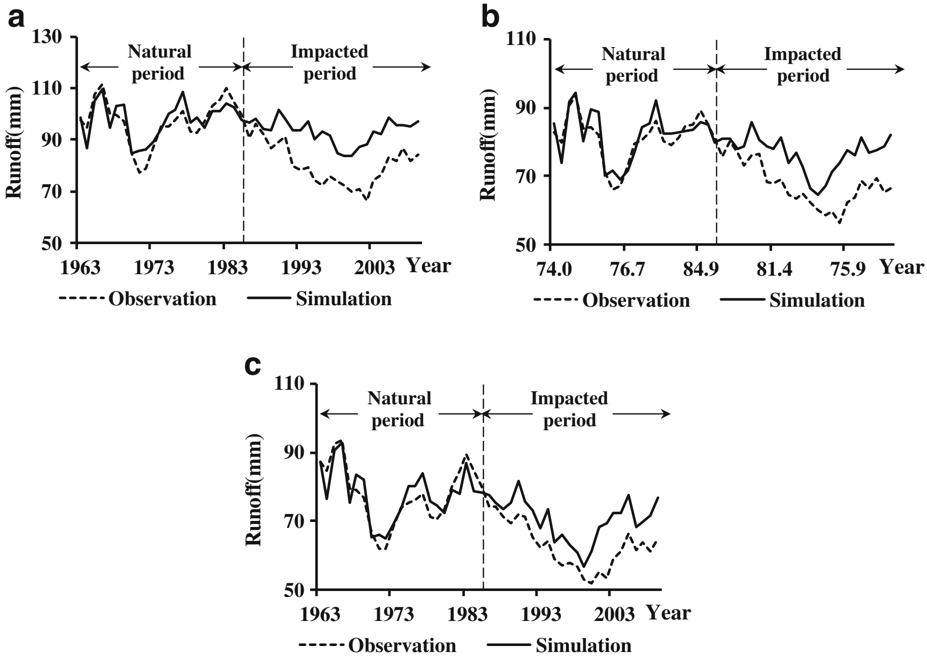

Fig. 11 Difference between simulated and observed annual runoff, which were smoothed with a 5-year moving average filter during the whole period. **a** Toudaoguai catchment. **b** Longmen catchment. **c** Huayuankou catchment

from 1963 through 2009 (eg., runoff depth of 1963 is actually the average value from 1961 to 1965.) The results were presented in Table 3. The values of E_{ns} and R^2 were greater than 0.5 for the calibration period and verification, which indicated close relationship between simulated runoff with observed values. The runoff simulation of Huayuankou has comparatively higher accuracy. Figure 10 compared the simulated and measured 5-year moving average runoff in Toudaoguai, Longmen, and Huayuankou catchments. It can be seen from the figure that the simulation curve fits well with the observation curve. It can be seen from Table 3 and Fig. 10 that the calibrated water balance model can describe the hydrological processes, although there were still some differences between simulation and observation.

Simulating the runoff of the whole study period with the water balance model established during the natural period, we can get the runoff when the underlying surface condition is natural. Comparing the simulated value (red curve in Fig. 11) and observed value (dotted blue curve in Fig. 11), it can be seen that simulated and observed natural runoff have big difference after 1985. The gap between the simulated and observed natural runoff can be assumed as the impact of LUCC on natural runoff. Analyzing the mean value of the natural runoff depth during two periods, it can be got that during the impacted period, observed natural runoff depth in Toudaoguai, Longmen, and Huayuankou catchments decreased by 16.6, 13.9, and 15.1 mm compared with those during the natural period, while the simulated natural runoff depth decreased by 4.5, 5.5, and 7.5 mm compared with those during the natural period (Table 4). Thus, it can be concluded that the contribution of LUCC accounted for 72.9, 60.6, and 50.2%, and climate variability accounted for 27.1, 39.4, and 49.8% to the natural runoff decrease in Toudaoguai, Longmen, and Huayuankou catchments, respectively (Fig. 12).

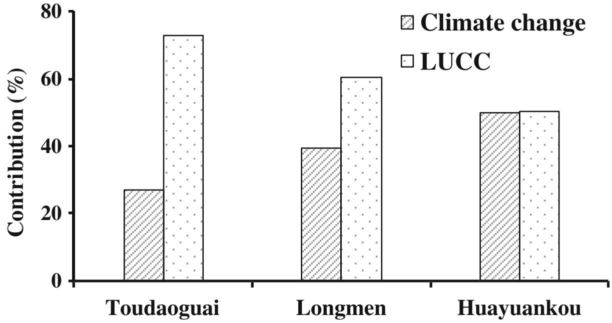

Fig. 12 Contribution of climate change and LUCC for decreasing annual runoff during the two periods divided by 1985

3.4 Projection of future runoff in the context of climate change

Figures 13 and 14 present the projection of annual average air temperature and annual precipitation for Toudaoguai, Longmen, and Huayuankou. To calculate the mean value of the five GCMs outputs (i.e., "MEAN" in the following passage), the RCP4.5 scenario projects a mean annual temperature increase between 1.44 and 1.56 °C (change between 1986 to 2010 and 2011 to 2050), depending on the catchment of interest. Despite a greater uncertainty regarding precipitation, the five GCMs project an increase of annual precipitation, with a multi-model average between 12.3 and 14.1% for RCP4.5 (change between 1986 to 2010 and 2011 to 2050), depending on the catchment of interest (Table 6).

Based on the monthly areal mean temperature (T_m) and areal potential evaporation (ET_0) in Toudaoguai, Longmen, and Huyuankou catchments during 1961 to 2011, correlation between potential evaporation and temperature was established. Based on this, future temperature can be projected via climate models so as to investigate the potential evaporation under different climate models. Monthly temperature and monthly potential evaporation of Toudaoguai, Longmen, and Huayuankou catchments have strong correlation. Temperature and potential evaporation from January to June approximately fit linear relationship and those from July to December approximately fit exponential relationship. R^2 of each regression equation is bigger than 0.97 (Eq. 11, Fig. 15, Table 5).

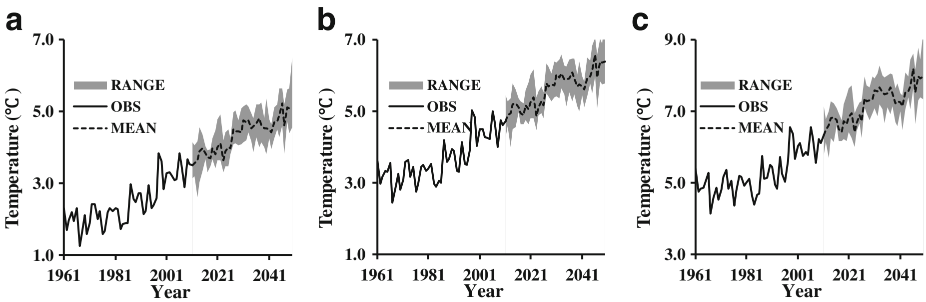

Fig. 13 Annual average air temperature during the period 1961 to 2050. Temperature during 1961 to 2010 is the observed temperature and that during 2011 to 2050 is the simulated temperature. **a** Toudaoguai catchment. **b** Longmen catchment. **c** Huayuankou catchment

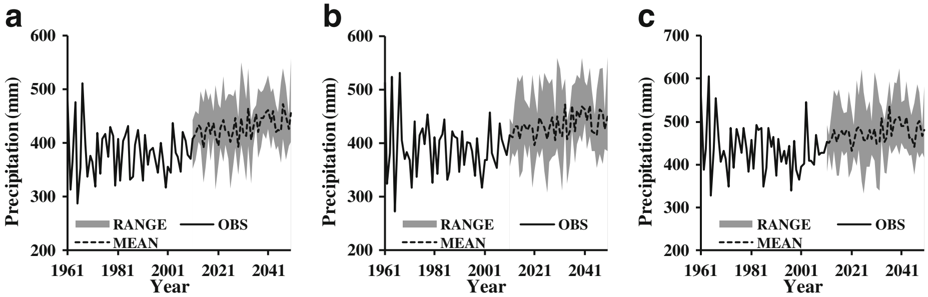

Fig. 14 Annual precipitation in the period 1961–2050. Precipitation during 1961 to 2010 is the observed precipitation and that during 2011 to 2050 is the simulated precipitation. **a** Toudaoguai catchment. **b** Longmen catchment. **c** Huayuankou catchment

$$ET_0 = \begin{cases} aT_m + b & \text{(From Jan.to Jun.)} \\ \alpha e^{\beta T_m} & \text{(From Jul.to Dec.)} \end{cases} \tag{11}$$

Based on Eq. 11, the future potential evaporation was projected from monthly temperature (T_m) which comes from the climate models. Besides, future annual depth of runoff in each catchment could be projected using the water balance model. Figure 16 shows the simulated runoff depth in Toudaoguai, Longmen, and Huayuankou catchments during 2011 to 2050. Table 6 lists the changes in mean annual runoff for the RCP4.5 scenario (change between 1986 to 2010 and 2011 to 2050). It can be concluded that mean annual runoff simulated by the RCP4.5 scenario has an increasing trend. Multi-model average results show the increase ranges from 14.4 to 16.8%, depending on the catchment of interest. Dispersion exists in the hydrological simulations. For instance, mean annual runoff is projected to increase between 8.3 and 9.3% by HadGEM2-ES while between 24.3 and 25.0% by MIROC-ESM-CHEM. On the contrary, all the five GCMs suggest an increase in future mean runoff compared with that during the 1986 to 2011. That is to say, if we assume the future underlying surface condition remains the same with that during 1986 to 2011, future climate change may lead to the increase of natural runoff of the YRB (Fig. 17a). The reason is that although temperature rise in the YRB can cause the increase of evaporation, the precipitation increase is much bigger (Table 6). However, even if the natural runoff in the YRB during 2011 to 2050 is bigger than that during 1986 to 2011, it is still smaller than the average value during 1961 to 1985. Multi-model

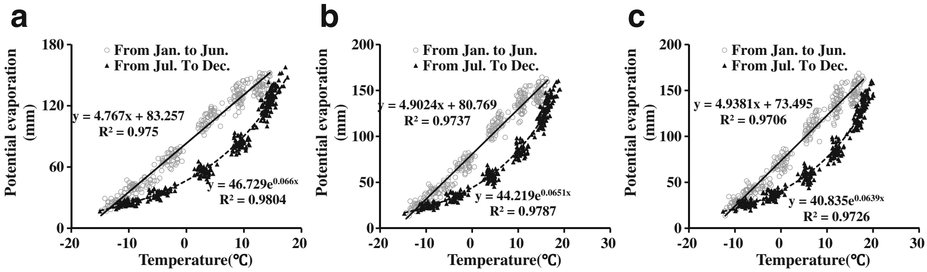

Fig. 15 Fitting curve of temperature–potential evaporation. **a** Toudaoguai catchment. **b** Longmen catchment. **c** Huayuankou catchment

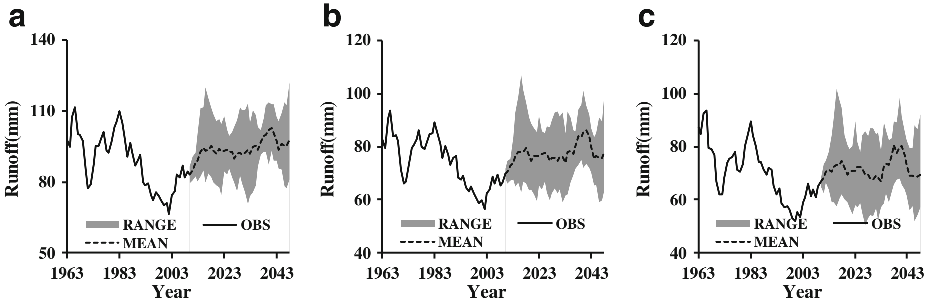

Fig. 16 Annual runoff during 1961 to 2050. Runoff depth during 1961 to 2010 is the observed runoff and that during 2011 to 2050 is the simulated runoff. **a** Toudaoguai catchment. **b** Longmen catchment. **c** Huayuankou catchment

average results show that the annual average natural runoff during 2011 to 2050 will decrease by 3.2~7.7% compared with that during 1961 to 1985 (Fig. 17b).

4 Conclusions and discussion

The water balance model based on Fu equation performed well at simulating annual runoff depth in the YRB. Compared with other distributed hydrological models, water balance model has fewer parameters and simpler calculation methods, thus having advantages in hydrological simulation and projection in large scale.

During the last 50 years, there were statistically significant increasing and non-significant decreasing trends for mean temperature and precipitation respectively in the Yellow River Basin (YRB). That is to say, the YRB had been becoming warmer and drier, particularly in the middle reaches. In the meantime, annual natural runoff was detected to have statistically significant decreasing trend in Huayuankou catchment. That was mainly attributed to two driving factors: climate variability and land-use/land-cover change (LUCC). Using the break point of the annual natural runoff in Huayuankou station, the whole period was divided into two periods: natural period (1961 to 1985) and impacted period (1986 to 2011). During the impacted period, annual average natural runoff in Huayuankou catchment decreased by 21.9% compared with that during the natural period. Since the Huayuankou catchment covers 91.9%

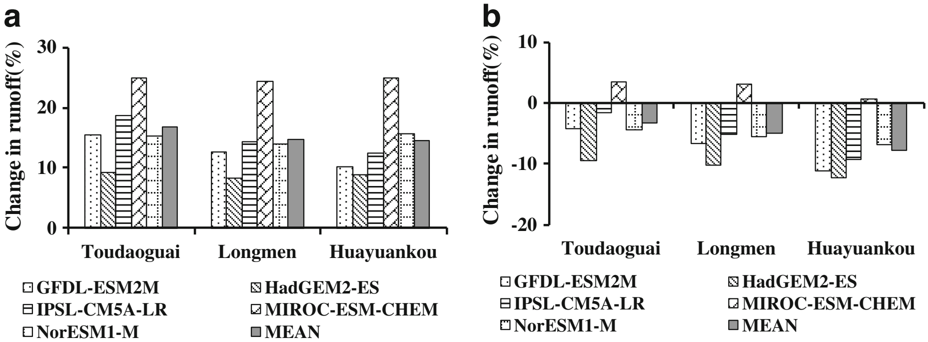

Fig. 17 Annual average natural runoff variation during 2011 to 2050. **a** Variation compared with that during 1986 to 2010. **b** Variation compared with that during 1961 to 1985

Table 3 Performance of the water balance model for annual natural runoff simulation in the Toudaoguai, Longmen, and Huayuankou catchments

Catchment	Period		Year	ω	E_{ns}	R^2
Toudaoguai	Natural period	Calibration	1963–1977	1.810	0.71	0.75
		Verification	1978–1985		0.57	0.70
	Impacted period	Calibration	1986–2001	1.911	0.64	0.69
		Verification	2002–2009		0.60	0.82
Longmen	Natural period	Calibration	1963–1977	1.953	0.74	0.82
		Verification	1978–1985		0.54	0.59
	Impacted period	Calibration	1986–2001	2.041	0.63	0.69
		Verification	2002–2009		0.54	0.76
Huayuankou	Natural period	Calibration	1963–1977	2.145	0.83	0.84
		Verification	1978–1985		0.62	0.71
	Impacted period	Calibration	1986–2001	2.233	0.80	0.84
		Verification	2002–2009		0.58	0.76

of the total area in the YRB, its natural runoff depth variation can reflect the variation of the whole surface water resources in YRB.

Three catchments located in different parts of the YRB were used as the case study area for the quantitative assessment of the attribution for natural runoff decrease. They are Toudaoguai catchment, Longmen catchment, and Huayuankou catchment. Using the water balance model, the natural runoff without the impact of LUCC was reconstructed for the whole period. The differences of the reconstructed natural runoff between the natural period and impacted period represent the impact of climate variability on runoff. The rest part of runoff decrease was caused by LUCC. The results indicated that the contribution of LUCC accounted for 50.2–72.9%, and climate variability accounted for 27.1–49.8% to the natural runoff decrease.

Temperature and precipitation in YRB both show an increase trend under RCP4.5, which means YRB will become warmer and wetter in the future. In the context of this climate condition, if we assume the underlying surface condition during 2011 to 2050 is the same as

Table 4 Changes of annual mean temperature, precipitation, and runoff during the two periods

Catchment	Period	T_{mean} (°C)	P (mm)	R_{obs} (mm)	R_{sim}(mm)
Toudaoguai	Natural period	2.01	383.4	97.1	97.8
	Impacted period	2.92	376.7	80.4	93.3
	Change	0.91	−6.7	−16.6	−4.5
Longmen	Natural period	3.21	394.8	81.3	82.2
	Impacted period	4.08	384.9	67.4	76.7
	Change	0.87	−9.9	−13.9	−5.5
Huayuankou	Natural period	4.87	442.3	77.8	78.0
	Impacted period	5.65	423.0	62.8	70.5
	Change	0.78	−19.3	−15.1	−7.5

Table 5 Values of the coefficients *a*, *b*, *α*, and *β* of Eq. 11 which was used to calculate the monthly potential evaporation

Catchment	From Jan. to Jun.			From Jul. to Dec.		
	a	*b*	R^2	*α*	*β*	R^2
Toudaoguai	4.767	83.257	0.975	45.729	0.066	0.980
Longmen	4.902	80.769	0.974	44.219	0.065	0.979
Huayuankou	4.938	73.495	0.971	40.835	0.064	0.973

that during 1986 to 2011, future annual average natural runoff in YRB will increase to some degree compared with that during 1986 to 2011. Climate change may have huge impact on runoff, but due to the uncertainty in the future projection of precipitation, uncertainties still exist in the runoff projection. Multi-model average results show that future natural runoff in Toudaoguai catchment, Longmen catchment, and Huayuankou catchment will increase by 16.8%(9.3–25.0%), 14.7%(16.0–24.3%), and 14.4%(16.0–24.9%) compared with that during 1986 to 2011, but still lower than the average value during 1961 to 1985. That is to say, although future climate change will cause the increase of natural runoff in YRB, the variation of underlying surface condition will have stronger negative effect on the natural runoff.

The study provides a valuable reference and opportunity to understand the change of hydrological cycle in arid and semi-arid region in the context of climate change and human activities. The hydrological cycle has been intensively changed by human activities, thus causing severe eco-environmental problems. It is not only a local problem in the YRB, but also a global issue. So the water resource managers, government, and researchers should pay more attention to promote the sustainable development and utilization of water resources, especially in arid or semi-arid region. Considering the potential water issues in the YRB or other arid and semi-arid region, the adaptation strategies and measures to climate change could include the following:

1. Enhance water use efficiency in irrigated agriculture

There are three pathways to enhance water use efficiency in irrigated agriculture. In the aspects of engineering and agronomic management, it is important to increase the output per unit of water and avoid over-irrigation use of water. In the aspects of environment, we should reduce the losses of water to unusable sinks and water degradation. In the aspects of society, reallocating water to higher priority uses can be considered as an adaptation option.

2. Increase supply through alternative water sources

With increasing population and rapid economic development, arid and semi-arid region is facing serious challenges. Climate change is adding another layer of complexity. One response to these challenges is increasing supply through alternative water sources. People can adapt new strategies to optimize the utility of available water by rainwater harvesting, gray-water reuse, flood water utilization, and seawater desalination.

3. Construct water conservancy or water transfer project reasonably

Table 6 annual average temperature, precipitation, potential evaporation, and runoff depth during 1986 to 2010 and 2011 to 2050

Catchment	Period	T_{mean}(°C)	P(mm)	ET_0(mm)	R(mm)
Toudaoguai	1986–2010	2.91	376.9	970.6	80.4
	2011 to 2050	4.08~4.56(4.35)	415.3~448.7(430.2)	1052.4~1080.4(1067.2)	87.9~100.5(93.9)
	Change	1.17~1.65(1.44)/°C	10.2~19.1(14.1)/%	8.4~11.3(9.9)/%	9.3~25.0(16.8)/%
Longmen	1986–2010	4.07	385.0	1001.0	67.4
	2011 to 2050	5.35~5.85(5.62)	422.0~454.4(434.0)	1091.6~1121.7(1106.3)	73.0~83.7(77.3)
	Change	1.28~1.78(1.55)/°C	9.6~18.0(12.7)/%	9.0~12.1(10.5)/%	8.3~24.3(14.7)/%
Huayuankou	1986–2010	5.64	422.4	1007.1	62.8
	2011 to 2050	6.94~7.44(7.20)	463.4~496.9(474.3)	1097.8~1128.1(1112.4)	68.3~78.4(71.8)
	Change	1.30~1.80(1.56)/°C	9.7~17.7(12.3)/%	9.0~12.0(10.4)/%	8.9~24.9(14.4)/%

According to the IPCC AR5, there exist a "wet-get-wetter" and "dry-get-drier" response pattern. In this context, it is necessary to construct water conservancy or water transfer project to adapt to climate change. Besides, it is essential to study the impact of climate variability on future water resources under different climate change scenarios, for planning of water conservancy construction.

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Compliance with ethical standards The authors declare that they have no conflict of interest. All procedures performed in studies do not involve human participants or animals. Informed consent was obtained from all individual participants included in the study.

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