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Research papers

Quantifying the effects of climate variability, direct and indirect land use change, and human activities on runoff

Baofu Li[a,b,*], Xun Shi[b], Lishu Lian[a], Yaning Chen[c], Zhongsheng Chen[d], Xiaoyin Sun[a]

[a] School of Geography and Tourism, Qufu Normal University, Rizhao, Shandong 276826, China
[b] Department of Geography, Dartmouth College, 6017 Fairchild, Hanover, NH 03755 USA
[c] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[d] College of Land and Resources, China West Normal University, Nanchong 637002, China

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ABSTRACT

Much attention has been recently focused on the direct hydrological effects (DHEs, such as runoff yield and concentration) of climate variability and land use/cover change (LUCC); however, the influence of LUCC on regional climate change and corresponding runoff change (indirect hydrological effect, IHE) have rarely been assessed quantitatively. This study employed the Mann-Kendall test and ensemble empirical mode decomposition (EEMD) method to analyze linear and nonlinear trends in potential evapotranspiration (PET), precipitation and runoff and their correlation in typical basin (Yihe River) in eastern China during 1951–2013. This study presents a framework to quantify runoff change in a detection and attribution study based on the Soil and Water Assessment Tool (SWAT) and Weather Research and Forecasting (WRF) model, and it quantifies the effects of climate variability, DHE and IHE of LUCC (1990–2010) and other human activities on runoff. The results indicate that (1) the annual PET in the Yihe River basin had an increasing trend, with a rate of 6.3 mm/decade, while the precipitation and runoff during the period 1951–2013 exhibited decreasing trends, at rates of 26.6 mm/decade ($a = 0.05$) and 0.16×10^8 m^3/decade, respectively. (2) The runoff, PET and precipitation had similar periodic at inter-annual scales (approximately 3 years and 6 years) and inter-decadal scales (approximately 13–16 years). The contribution rate of runoff to total change from the inter-annual scale was the largest, reaching 58%, and those from the inter-decadal scale and multi-decadal scale were 6% and 11%, respectively. (3) The results also revealed that climate variability was likely to be the principle cause of an obvious decrease in runoff, and the contribution rate was as high as 90% before the 1980s while declining to 66.3% in 1990–1999. Furthermore, DHE, IHE and other human activities were responsible for 18.5%, 9.2% and 6.0%, respectively, of the runoff change in the 1990s. It is worth noting that the percentage of downward runoff accounted for 35.8% and 21.3% from DHE and IHE, respectively, during 2000–2013, which implied that human activities have gradually become the dominant factors affecting runoff change, with a contribution of 77.1%.

1. Introduction

Given the background of increasing global climate variability and human activities, many scholars have attempted to study the effect of climate fluctuation and human activities on runoff and have yielded substantial results (Ahn and Merwade, 2014; Chen et al., 2013; Deng and Chen, 2017; Liu et al., 2016; Wang et al., 2013; Wang et al., 2015a; Yang et al., 2019). Many detection and attribution methodologies have been employed to detect changes in climatic factors and other variables (Jiang et al., 2015; Jiang et al., 2011; Liu et al., 2017; Ye et al., 2013; Zhan et al., 2014b). For example, many researchers (Hu et al., 2012; Yang and Yang, 2011; Zhan et al., 2014a; Zheng et al., 2009) have used the elasticity method to quantitatively evaluate the contribution of temperature and evapotranspiration (ET) to runoff changes. Wang et al. (2012) proposed a new method, the slope change ratio of the accumulative quantity, and calculated the contributions of different factors to the runoff change in the Huangfuchuan River basin. Brikowski (2015) adopted a multi-parameter elasticity method to assess water availability in a changing climate, e.g., in Texas, USA. Jiang et al. (2015) employed the Budyko-type equations with time-varying parameters to investigate the effects of climate factors and human activities on streamflow for the Weihe River. Zhou et al. (2016) adopted a new method to test the partitioned climate and catchment effect on runoff based on the Budyko complementary relationship. Wang et al. (2015b)

* Corresponding author at: School of Geography and Tourism, Qufu Normal University, Rizhao, Shandong Province 276826, China.
E-mail address: libf@qfnu.edu.cn (B. Li).

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decoupled the relative impacts of precipitation, ET and human activity on the runoff changes in the Songhua River basin using the slope change ratio of the accumulative quantity method. Evidently, statistical methods, such as the double mass curve, water balance method, elastic theory, and Budykoe equations, were widely used to quantitatively distinguish the impact of climate change and human activities on water resources (Guo et al., 2016; Li et al., 2016a; Li et al., 2016c; Wang et al., 2013; Yuan et al., 2016; Zeng et al., 2014; Zhang et al., 2016). These methods are characterized by two points: one is that they quantitatively assess the influence of precipitation and ET on runoff; the other is that the runoff change that was not caused by precipitation and ET was attributed to the impact of human activities on the hydrological processes. Hence, statistical methods can be adopted to effectively identify the climate and hydrology observation data but cannot fully reflect the effects of human activities (such as LUCC) on hydrological change.

Alongside these empirical methods, hydrological modeling provides an important means for testing changes in runoff related to physical mechanisms; thus, it is widely used to assess the influence of climate fluctuation and human activities on water resources (Zang et al., 2013; Zhang et al., 2012; Han et al., 2019). For example, variable infiltration capacity hydrological models can be adopted to quantitatively isolate the relative contributions that climate variability and human activities make to decadal streamflow changes in the Jinghe basin, located in Northwest China (Chang et al., 2016). Zang et al. (2013) evaluated the impacts of human activities and climate variability on water simulated by the Soil and Water Assessment Tool (SWAT) for the Heihe River basin. These studies analyzed the effect of climate factors on water resources and estimated the direct impacts (such as runoff yield and concentration) of LUCC on hydrological processes. However, the influence of other human activities, including dam construction, river diversion, irrigation, and other engineering and management practices, on runoff has been ignored (Song et al., 2013). Indeed, the direct hydrological effect (DHE) caused by LUCC has failed to fully reflect the influence of human activities on water resources. Furthermore, LUCC may have impacts on climate variation (Yang and Duan, 2016); when it has an effect on hydrological processes, we call it the indirect hydrological effect (IHE) of LUCC. Nevertheless, few researchers have considered both the DHE and the IHE of LUCC. However, this information is important for improving water management strategies for every basin. Table 1 presents a summary of the relevant literature on the quantified effects of climate variability and LUCC on runoff.

Most scholars have analyzed the linear variation in runoff and climate factors before exploring the effects of climate and human activity on runoff change (Dong et al., 2012; Xu et al., 2013; Zhou et al., 2012). However, due to complex nonlinear climate and hydrological systems, the inner relationship between climate factors and nonlinear trends of hydrological processes remains unclear. The mode mixing issue of some methods, such as empirical mode decomposition (EMD), in signal analysis leads to a non-unique decomposition process, resulting in the loss of physical meaning for modal components (Qin et al., 2018). However, ensemble empirical mode decomposition (EEMD) can overcome this problem. This method defines the true intrinsic mode function (IMF) components as the mean of an ensemble of trials, each consisting of a signal plus white noise of finite amplitude (Wu and Huang, 2009). Thus, the self-adaptability of EEMD has higher stability and consistency for decomposition results (Wu and Huang, 2009). EEMD prevents defects in scale mixing and processes non-linear and non-stationary time series with high accuracy compared to traditional statistical methods, such as moving averages, singular spectrum analysis, and empirical orthogonal functions (Bai et al., 2015; Liu et al., 2016; Qin et al., 2018).

The objectives of this paper were to (1) use empirical statistical methods to explore the linear and non-linear trends of climate factors (potential evapotranspiration (PET) and precipitation) and runoff and their relation at different time scales, (2) use the SWAT model to assess climate contribution to changes in runoff and the DHE, and (3) use WRF to assess the IHE (other human activities were considered as left overs).

These three objectives provide the structural sub-headings used the following sections: Methods, Results and Discussion (Sections 3–5, respectively).

2. Study site and materials

2.1. Study site

In this study, we chose the Yihe River basin as a case study. The Yihe River is one of the largest tributaries of the Yishusi water system in the Huaihe River and originates from Yiyuan County in Shandong Province (Fig. 1). The river flows from Yishui, Yinan, Mengyin, Pingyi, Tancheng counties into New Yihe River in Pi County in Jiangsu Province, reaching Yanwei port in the Yellow Sea (Gong, 2014). The basin has a drainage area of 17,000 km^2 and a length of 500 km. The hilly region in the Yihe basin occupies nearly 70% of the basin, and plain accounts for approximately 30%. The basin belongs to a warm temperate zone with a semi-humid continental monsoon climate due to the alternating influence of continental air and maritime air. It is characterized by distinct seasons, hot summers and cold winters. The mean annual rainfall is approximately 815 mm, with the most precipitation occurring in summer and autumn.

Over the past 20 years, the Yihe River basin had a population of 10 million; moreover, the per capita water resources were less than 1/6 of the national average, and water shortages have become a bottleneck for the sustainable development of the social economy. Additionally, the frequency of extreme weather events, such as frequent rainstorms and extreme drought, has increased remarkably (Dong et al., 2014; Li et al., 2015). Climate fluctuations and human activities in the basin have been identified as two primary causes of changes in water resources. Thus, this study advances our understanding of the hydrological evolution mechanism affected by climate variability and human activity and is of important theoretical and realistic significance to the scientific formulation of water resource management strategies and the sustainable utilization of water resources in the Yihe River basin.

2.2. Data processing

In the WRF model, the outer domains (domains 1 and 2) of control and sensitivity are derived from the United States Geological Survey and have resolutions of 10′ and 2′, respectively, for land use data. The innermost domains (domain 3) were extracted from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (http://www.resdc.cn) and have 1 × 1 km resolution land use data (after rearrangement, recollection, and reformatting) in 2010 and 1990. Measured data from meteorological stations in the study area were used to evaluate the controlled simulation results. Daily meteorological data were obtained from the stations at Yanzhou, Yiyuan, Juxian, and Xuzhou (Fig. 1). All 4 meteorological stations selected for this study were maintained following the standard of the National Meteorological Administration of China. In the SWAT model, the DEM and LUCC data were obtained from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (http://www.resdc.cn). The runoff data in each river were derived from the local hydrology bureaus. The data on the soil properties in the study area were from related references (SFSS, 1993).

Penman's (1948) formulation, as provided by Shuttleworth (1993), was used to calculate the potential evapotranspiration (E_p), of E_p which Donohue et al. (2010) showed to be the most appropriate form of E_p when considering a changing climate. The Penman formulation of E_p is also a physically based form of E_p, meaning that all the key variables that govern the evaporative process are explicit in the formula (McVicar et al., 2012; Liu and McVicar, 2012).

The E_p is calculated as follows:

Table 1
Summary of relevant literature on the hydrological effects of climate and LUCC in relation to the objectives of this study: (1) quantifying the effects of climate variability on runoff or water resources; (2) quantifying the direct hydrological effect (DHE, such as runoff yield and concentration) of LUCC; (3) quantifying the influence of LUCC on regional climate change and corresponding runoff change (indirect hydrological effect, IHE). The symbol 'N/A' means 'not reported'.

Study	Statistical methods/physical model	Location	Key results
1-Zheng et al., 2009	Climate elasticity/N/A	Yellow River, China	(1) Climate change contributed to less than 30% of the reduction in runoff (2) It is estimated that land use change is responsible for more than 70% of the streamflow reduction in the 1990s
2-Jiang et al., 2011	Multi-regression, hydrologic sensitivity analysis/VIC-3L model	Laohahe River, China	(1) The runoff reduction percentages due to climate variability were only 7–11%
3-Zhang et al., 2012	Mathematical statistics/SWAT model	Huifa River, China	(1) The results indicate that both climate change and human activities are responsible for the decrease in observed runoff
4-Dong et al., 2012	Hydrological sensitivity analysis method/N/A	Nenjiang River, China	(1) Climate change has been the dominant factor, accounting for 69.6–80.3% of the reduction in the total basin runoff
5-Hu et al., 2012	Climate elasticity method/HIMS model	Baiyangdian Lake, China	(1) Climate variations accounted for 38–40% of decreased streamflow
6-Zang et al., 2013	Mathematical statistics/SWAT model	Heihe River, China	(1) Total green and blue water flow increased from 1980 to 2005, mainly as a result of climate variability
7-Gong 2014	Mathematical statistics/SWAT model	Yihe River, China	(1) The correlation coefficient between runoff and precipitation is 0.809 (2) According to the simulated results by SWAT model, the effect of LUCC on runoff is significant
8-Guo et al., 2014	Mathematical statistics/SWAT model	Chaohe River, China	(1) Climate change gave rise to an annual streamflow reduction of 29.7 mm in the period from 1991 to 2000 (2) Compared with the baseline period (1981–1990), land use change caused an annual streamflow reduction of 4.1 mm during 1990–2000
9-Wang et al., 2015a	Similar Weather Condition (SWC) method/N/A	Yan River, China	(1) A similar weather condition (SWC) is defined to fix the weather factors in this method
10-Yuan et al., 2015	Mathematical statistics/SWAT model	Liuxihe River, China	(1) Climate variability caused an annual runoff to increase of 11.85 m^3/s (2) The land use change caused an annual runoff reduction of 0.62 m^3/s
11-Jiang et al., 2015	Budyko-type equations/N/A	Weihe River, China	(1) Climate change is the main driving factor to the decline in runoff
12-Li et al., 2016a	Elasticity method/N/A	Aksu River, China	(1) Temperature increase was the most important factor that increased runoff, with a contribution of 45%
13-Li et al., 2016c	Double mass curve method/N/A	Karst region, China	(1) Water discharge was mainly influenced by precipitation
14-Liu et al., 2017	Budyko-based hydrothermal balance model/N/A	China	(1) Fractional contributions of climate change and human activities to streamflow changes are, respectively, 53.5% and 46.5%
15-Deng and Chen, 2017	Mathematical statistics/N/A	Central Asia	(1) The decreasing trend of TWS in northern Central Asia (-3.86 ± 0.63 mm/a) is mainly attributed to soil moisture storage depletion, which is primarily driven by the increase in ET
16-Zhu et al., 2019	Budyko analysis/Statistical analysis	Chari/Logone River, China	(1) The relative contribution of climate and human activities is 26.83% and 73.17%, respectively
17-Han et al., 2019	Budyko framework/CREST-snow model	Lancang River/China	(1) Climatic change contributed ~57% to streamflow changes during the transition period (1987–2007)
18-This study	Mathematical statistics/SWAT model, WRF model	Yihe River, China	(1) Climate variability was likely to be the principle cause of decrease in runoff and the contribution rate was even as high as 90% before 1980 s but declined to 66.3% in 1990–1999 (2) The percentage of downward runoff accounted for 35.8% as a result of the DHE of LUCC during 2000–2013 (3) The percentage of downward runoff accounted for 21.3% as a result of the IHE of LUCC during 2000–2013

$$E_p = E_{pR} + E_{pA} = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} \frac{6430(1 + 0.536u_2)D}{\lambda} \quad (1)$$

where E_p is the potential evaporation (mm day^{-1}), and E_{pR} (mm day^{-1}) and E_{pA} (mm day^{-1}) represent the radiative and aerodynamic components of the Penman equation, respectively. R_n is the daily net radiation (MJ m^{-2} day^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa°C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), D is the vapor pressure deficit (Pa), u_2 is the daily average wind speed at 2 m height (m s^{-1}), and λ is the latent heat of vaporization of water (2.45×10^6 J kg^{-1}).

3. Methods

3.1. The linear and nonlinear trends of runoff, PET and precipitation

First, we used the Mann-Kendall test to calculate the linear trends in runoff, PET, and precipitation, and then used the EEMD method to analyze their nonlinear trends.

The Mann-Kendall non-parametric statistical test (Mann, 1945; Kendall, 1975) was applied to detect linear trends in the PET, runoff and precipitation time series (Li et al., 2020). For a time series X = {x_1, x_2, …, x_n}, in which n > 10, the standard normal statistic Zc is estimated by the Mann-Kendall method. The statistic Zc follows the standard normal distribution. At a 5% significance level, the null hypothesis of no trend is rejected if $|Zc| > 1.96$. A positive value of Zc denotes an increasing trend, and a negative value corresponds to a decreasing trend. The Mann-Kendall method is sensitive to autocorrelation, so we adopt the method proposed by Yue et al. (2002) to remove lag-1 autocorrelation. Details of the method can be found in the literature (Yue et al., 2002).

The EEMD method was developed from Empirical mode decomposition (EMD). EMD is an effective method for non-stationary series (Huang and Wu, 2008). Each intrinsic mode function (IMF) contains information from different time scales in a climate system corresponding to different climatic hierarchies. However, specific climate levels tend to be produced by the common or alternative action of physical factors. Therefore, the steady IMF decomposed by the runoff sequence can provide some guidance for runoff forecasting. The main decomposition steps are as follows.

First, determine the maxima of the original sequence Y (t) and connect it with a cubic spline to obtain the maxima Y max (t) and minima Y min (t) of the upper and lower envelope sequence.

Take the average of Y max (t) and Y min (t) for each moment and

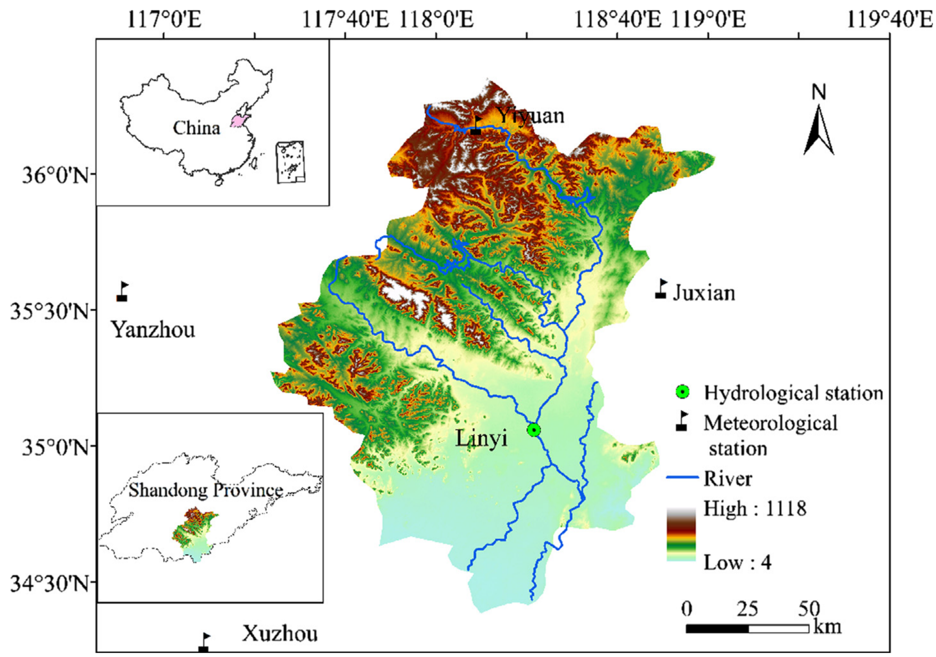

Fig. 1. Location map of the study area and distribution of meteorological and hydrological stations in the Yihe River basin.

obtain the average envelope sequence: m (t) = [Y max (t) + Y min (t)]/2.

Take the original sequence Y (t) and subtract the average envelope sequence m (t) to obtain the sequence h (t) = Y (t) – m (t).

If the number of extreme and zero crossings are equal or differ at most by one and the mean value of the envelope m (t) tends to zero, then it is the first intrinsic mode function IMF_1; otherwise, take the h (t) as the original sequence and repeat the above steps until it meets the above definition.

The EEMD algorithm is straightforward and can be described as follows (Wu and Huang, 2009): (1) add a white noise series to the original signal; (2) decompose the signal with added white noise into IMF_S using EMD; (3) repeat steps (1) and (2) with a different white noise series each time; and (4) obtain the corresponding IMF components of the decompositions and adopt the means of the ensemble corresponding to the IMF_S of the decompositions as the final result.

To ensure the reasonable results for IMFs, in this study, we adopt the method recommended by Rilling et al. (2003) to define the criteria. The method of stopping criteria for sifting are as follows.

$$a(t) = \left| \frac{e_{max} + e_{min}}{e_{max} - e_{min}} \right| \tag{2}$$

where e_{max}, e_{min} are upper and lower envelopes, respectively. The criterion is based on two thresholds ($\theta_1 = 0.05$, $\theta_2 = 0.5$) and a tolerance parameter ($\alpha = 0.05$). The sifting is iterated until $a(t) < \theta_1$ for some prescribed fraction (1-α) of the total duration, while $a(t) < \theta_2$ for the remaining fraction.

In the EMD method, the fitting of upper and lower envelope lines is a problem. So EMD's improved algorithm, called “local EMD”, was used in the EEMD method. For the detailed algorithm, please refer to the reference (Rilling et al., 2003). This algorithm can identify and isolate the local zones where the error remains large (Rilling et al., 2003), which alleviates the defects of the previous EMD in upper and lower envelope fitting to a certain extent (Wu and Huang, 2009).

As a new self-adaptive decomposition method, EEMD has been widely used in the study of nonlinear climate and hydrological changes (Ji et al., 2014; Franzke, 2014; Tan et al., 2018). In this study, we use the EEMD to analyze the nonlinear trends of runoff, PET and precipitation.

3.2. The DHE of LUCC and climate based on the SWAT model

This study estimated the hydrological effect of climate and the DHE of LUCC using the SWAT model. According to the physical basis, the SWAT model is considered to be an important indicator for reflecting the impact of climate factors, such as precipitation, ET and LUCC, and other human factors on hydrological processes. When LUCC is given only as a variable, the SWAT model can simulate the DHE of LUCC, including runoff yield and runoff concentration.

$$Q_{lucc1} = Q_{lucct} - Q_{luccb} \tag{3}$$

where Q_{lucc1} is the DHE of LUCC in a certain period; Q_{lucct} is the simulated runoff when LUCC is seen only as a variable in the t period; Q_{luccb} is the simulated runoff when LUCC is considered as a variable in the baseline period. This study selected the LUCC in 1985 as the land use information in the baseline period. This value was selected because data from 1985 were the earliest LUCC data we were able to obtain. According to our knowledge of the study area, around that period, the impact of human activities on runoff was minimal.

when climate factors were seen only as variables:

$$Q_{c1} = Q_{ct} - Q_{cb} \tag{4}$$

where Q_{c1} is the runoff change caused by the total climate variability, Q_{ct} is the simulated runoff in the t period, and Q_{cb} is the simulated runoff in the baseline period.

The total climate variability (Q_{c1}) is separated into two parts: climate variability caused by LUCC and climate variability. Thus,

$$Q_c = Q_{c1} - Q_{lucc2} \tag{5}$$

where Q_c is the effect of climate variability (except the climate effect of LUCC) on runoff; and Q_{lucc2} is the influence of climate factors caused by LUCC on runoff change, called the indirect hydrological effect (IHE).

As noted before, the runoff change can be attributed to:

$$Q_T = Q_c + Q_h \tag{6}$$

$$Q_h = Q_{lucc1} + Q_{lucc2} + Q_{other} \tag{7}$$

where Q_T is the total runoff change in the t period compared with the baseline period; Q_h is the runoff change caused by human activities; Q_{other} is the runoff change attributed to other human activities (such as water conservancy facilities and water storage).

This study simulated the runoff in 1951–1990, 1991–2000, 2001–2008 and 2009–2013 based on the LUCC data of 1985, 1995, 2005 and 2010, respectively.

3.3. The IHE of LUCC based on the WRF model

The WRF model system is a new generation mesoscale numerical weather forecast model and data assimilation system. There are highly modular, transportable, and efficient components in massively parallel computing environments, numerous physics options in the model, and advanced data assimilation systems that have been developed in tandem with the model itself (Huang et al., 2016).

The study employed WRF3.7 to analyze regional climate change caused by LUCC and explored the IHE of LUCC. Because precipitation was the leading climate factor influencing the runoff change in the study area (Gong, 2014), this article mainly explores the regional precipitation changes caused by LUCC based on the WRF model and its effect on runoff.

This study included controlled and sensitivity experiments. LUCC data in 2010 and atmospheric circulation field in 2013 were applied as controlled experiments to simulate the daily precipitation change characteristics during 2013 in the Yihe River basin. The center of the model domain is located at 35.8°N, 118.1°E. Three nested domains with horizontal grid resolutions of 27 km (domain 1), 9 km (domain 2), and 3 km (domain 3, study area) were composed of grids containing 27 × 36, 49 × 67, and 91 × 130 cells, respectively. In reference to previous research (Dong et al., 2014; Zhang et al., 2015) and sensitivity tests, we ran the WRF model with the following physics parameterization schemes: Lin physical scheme, RRTM scheme, Dudhia scheme, Monin-Obukhove scheme, Noah land surface scheme, YSU scheme, and Kain-Fritsche shallow convection (new Eta) scheme. Initial and boundary conditions were derived from 1 × 1° National Centers for Environmental Prediction final analysis reanalysis data provided by the National Center for Atmospheric Research. The sensitivity experiment involved the LUCC in domain 3 from 1990 to 2010. Except for the use of different LUCC data, all the simulations had the same setup and physical parameterization schemes so that any differences between the controlled and sensitivity experimental results reflected how the LUCC in the study area affected regional climate variables in the last 20 years.

WRF can simulate the weather characteristics better in the short time rather than in the long time. Therefore, it is assumed that LUCC has a linear change trend over time, and the precipitation variation caused by LUCC is proportional to the actual precipitation. Thus, changes in the regional climate caused by LUCC can be calculated as follows:

$$Q_{lucc2} = (P_t/P_{2013}) \times (P_{2010} - P_{1990})/20 \times t \quad (8)$$

where Q_{lucc2} is the LUCC result in terms of the regional precipitation changes in the t (year) period; P_t is the average annual precipitation in the t (year) period, such as 1990–1999, i.e., 9-year interval, so $t = 9$; P_{2013} is the actual precipitation in 2013 in the study area; P_{2010} and P_{1990} are the simulated precipitation values in 2013 based on the LUCC data of 2010 and 1990, respectively, with all other parameters being the same in the WRF model. Thus, P_{2010}-P_{1990} can reflect precipitation changes caused by LUCC over 20 years.

4. Results

4.1. The linear and nonlinear trends of runoff, PET and precipitation

The average annual runoff was $21.5 \times 10^8 m^3$ during 1951–2013 in the Yihe River basin. The maximum runoff was in 1963 (Fig. 2a), up to 62.1×10^8 m^3, while the minimum appeared in 1989, at only 1.45×10^8 m^3. The Mann-Kendall statistical test showed that runoff had a downward trend with a rate of 0.16×10^8 m^3/decade. However, runoff exhibited different change trends in other time periods. Therefore, this research attempted to explore its nonlinear characteristics at different time scales due to the complexity of the hydrological evolution process.

The EEMD analysis results showed that the time series of runoff can be decomposed into four IMF components (IMF1-4) and one trend component in the Yihe River basin (Fig. 2b). IMF1-2 reached the 95% confidence interval, and IMF3-4 reached the 90% confidence interval, indicating that all the IMFs were significant components. The runoff changes clearly exhibited an inter-annual scale (quasi-3.2 and quasi-5.7-year), inter-decadal scale (quasi-12.6-year) and multi-decadal scale (quasi-31.4-year). The variance contribution rate of runoff in the IMF1 component to the overall runoff change was the largest, reaching 36%; this component was followed by IMF2 and IMF4, with contribution rates of 22% and 11%, respectively, while the contribution rate of the IMF3 component was the lowest, at only 6%. Thus, the contribution rate of the nonlinear trend in runoff contributed 25% to the overall runoff change, which indicates that the natural fluctuations in the hydrological system trend have an important impact on runoff variability. The results also showed that the periods of runoff change were similar to those of PET and precipitation changes at different time scales.

During the period of 1951–2013, the annual PET exhibited a slight upward trend with a rate of 6.3 mm/decade (Fig. 3a). The annual precipitation is between 318.3 and 1017.1 mm, and the perennial mean precipitation is 601.0 mm in the Yihe River basin (Fig. 3b). In the past 60 years, the precipitation showed a significant decreasing trend with a rate of 26.6 mm/decade ($a = 0.05$), which was different from the obvious increase in precipitation observed in southern and northwestern China (Li et al., 2016b; Wu et al., 2018). The diagram revealed that there was more precipitation in the 1950s, and precipitation decreased significantly after 1960, while precipitation increased slightly after 1990 but was obviously still lower than that in the 1950s.

The EEMD analysis results show that PET and precipitation can be decomposed into four IMF components (IMF1-4) and one trend component in the Yihe River basin (Fig. 4). IMF1-2 reached the 90% confidence interval, and IMF3-4 reached the 80% confidence interval. Each IMF component can reflect the characteristics of inherent vibration frequency and nonlinear trend of climate factors at different time scales and the periodical change of the climate system. The PET changes have clearly exhibited an inter-annual scale (quasi-3.3 and quasi-5.7-year), inter-decadal scale (quasi-15.8-year) and multi-decadal scale (quasi-31.3-year). The variance contribution rate of PET in the IMF1 component to the overall PET change was the largest, reaching 60%; this component was followed by IMF2 and IMF3, with contribution rates of 10% and 19%, respectively, while the contribution rate of the IMF4 component was the lowest, at only 6%. Thus, the contribution rate of the nonlinear trend in PET to the overall PET change was up to 5%. In addition, the precipitation changes have shown an inter-annual scale (quasi-2.9 and quasi-6.3-year), inter-decadal scale (quasi-12.6-year) and multi-decadal scale (quasi-53.5-year, Fig. 4b). The variance contribution rate of precipitation in the IMF1 component to the overall precipitation change was the highest, reaching 53%; this component was followed by IMF2 and IMF3, with contribution rates of 24% and 8%, respectively, while the contribution rate of the IMF4 component was the lowest, at only 5%. Thus, the nonlinear trend in precipitation contributed 10% to the overall precipitation change.

In 1951–2013, runoff and precipitation were closely linked and showed a significant positive correlation ($a = 0.001$), and the correlation coefficient was 0.79 (Table 2). From the perspective of each component, the relationship between the runoff of IMF1 and IMF2 on an inter-annual scale and precipitation decreased, and the correlation coefficients were 0.61 and 0.54, respectively, but were up to a level of significance of $a = 0.001$. At the inter-decadal (IMF3) and multi-decadal (IMF4) scales, the relationship between runoff and precipitation was closer, and the correlation coefficients were as high as 0.88 and 0.98, respectively. The changes showed significant synchronicity, which illustrated that the effect of precipitation on runoff on inter-

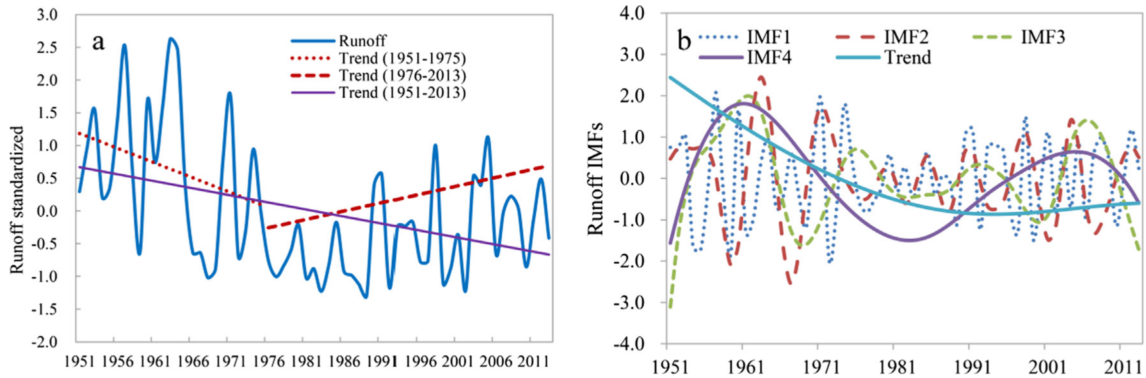

Fig. 2. The linear (a) and nonlinear (b) changes in annual runoff during 1951–2013 for the Yihe River.

decadal and multi-decadal scales was significantly greater than that on inter-annual scales.

From 1951 to 2013, the correlation coefficient between the average PET and runoff in the Yihe River basin was −0.55 ($a = 0.001$), but its correlation was obviously lower than that between precipitation and runoff. From the perspective of different time scales, the correlation between PET and runoff in the IMF1 and IMF2 components were −0.52 and −0.51, respectively, while the correlation in the IMF3 component increased and the coefficient was −0.63. In particular, the correlation coefficient (-0.20) in the IMF4 component was significantly lower than that in the other components, indicating that the influence mechanism of the PET on runoff on inter-annual, inter-decadal and multi-decadal scales is significantly different.

4.2. The DHE of LUCC and climate based on the SWAT model

According to the actual situation in the study area, the LUCC and other human activity intensities were relatively minor before 1990, while human activities intensified from 1990 over the last 20 years and have exerted increasing influence on the regional climate. Therefore, we chose the land use types in 1990 and 2010 in the Yihe River basin as a case study to explore the characteristics of LUCC.

The main types of land cover in the study area are dry lands, which covered 70.3% and 68.6% of the total area in 1990 and 2010, respectively, and were followed by paddy land, with coverages of 11.4% and 11.1%, respectively, and grassland and forestland, with coverages of 5.4% to 7.2%, respectively. The coverage by other types was very small (Fig. 5).

The increase rates in land use types between 1990 and 2010 indicate that construction land shrank the most, 177%, followed by bare land and water areas, which shrank by 106% and 31%, respectively. Shrub land decreased by 11%, while paddy land and dry land decreased by 2.8% and 2.5%, respectively. The changes in other land uses were very small. Therefore, in the past 20 years, 2% of land was converted from dry land to construction land (747 km^2) and bare land (132 km^2).

Fig. 6 demonstrates the relation between simulated annual runoff and measured runoff during 1951–2013 in the study area. The results illustrated that the correlation coefficient between the simulated values and measured values was 0.94, reaching a significance level of $a = 0.001$. However, there were certain error between the simulation values and the measured values because the average simulated runoff for many years was slightly lower than the measured runoff 2.0×10^8 m^3, and the average error rate was 9.3%. Evidently, this study and previous results (Gong, 2014) show that SWAT hydrological models are strongly recommended for the research on hydrological processes in the study area due to the high precision of the runoff simulation.

The field investigation showed that the construction of reservoirs and other water conservancy facilities began in the middle of the 1960s, and then, the influence of human activities gradually increased over time. Therefore, the average runoff from 1951 to 1959 was taken as the reference value to analyze the runoff change and its attribution in different decades.

The runoff depth in the Yihe River basin decreased by 26.6 mm from 1960 to 1969 relative to that in the period of 1951–1959, which implied that climate change exerted a substantial influence on runoff, while the contribution of human activities was only 4.9% (Table 3). Apparently, although some reservoirs were constructed in this period, human activities had a negligible influence on hydrological processes. From 1970 to 1979, the runoff depth in the Yihe River basin decreased by 131.4 mm relative to that in the baseline period, which was similar to that of the 1960s, and the contribution rate of climate change was 96.5%. In the 1980s, a further reduction in runoff was detected in the Yihe River basin. Human activities (e.g., water conservancy facilities) sharply affected runoff, and the contribution to runoff was 9.2%; however, climate fluctuation was still the main driving factor affecting the runoff reduction. The runoff depth in the Yihe River basin decreased by 158.5 mm from 1990 to 1999 compared with that in the baseline period, and the contribution rate of the climate fluctuation decreased

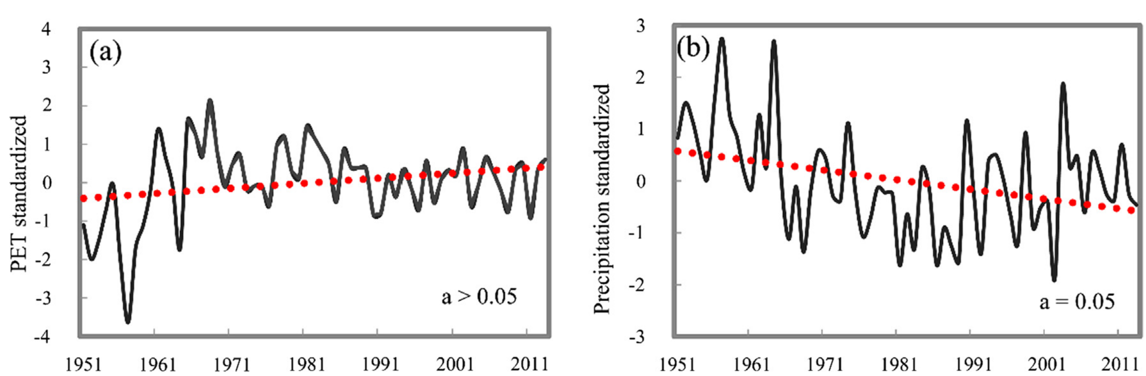

Fig. 3. The linear trend of PET (a) and precipitation (b) in the Yihe River during 1951–2013.

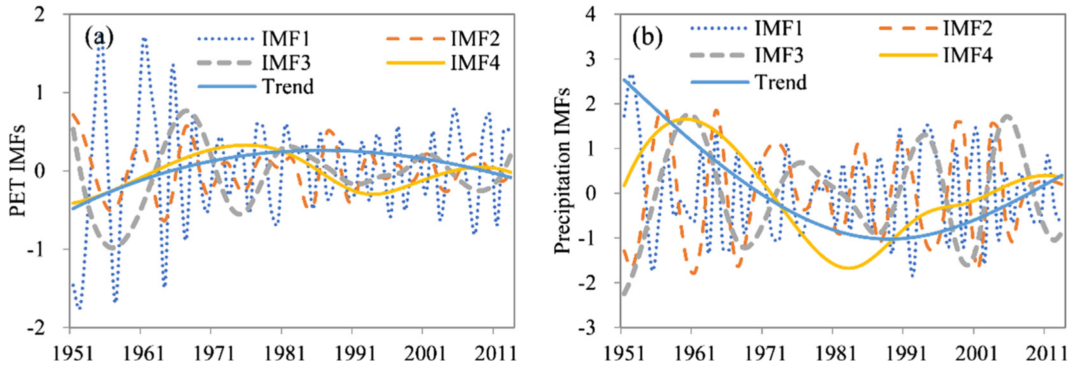

Fig. 4. The decompositions of the PET (a) and precipitation (b) in inter-annual (IMF1, IMF2), inter-decadal (IMF3) and multi-decadal (IMF4, trend) scales based on the EEMD method from 1951 to 2013 in the Yihe River basin.

Table 2
The correlation between runoff and PET and precipitation on different time scales (each modal component) in the Yihe River during 1951–2013.

	Original data	IMF1	IMF2	IMF3	IMF4
Runoff and precipitation	0.79***	0.61***	0.54***	0.88***	0.98***
Runoff and PET	−0.55***	−0.52***	−0.51***	−0.63***	−0.20

***Significant at a = 0.001.

by 66.3%. The DHE of LUCC contributed 18.5% to the runoff variation from 1990 to 1999. In 2000–2013, the climate fluctuation contributed only 22.9% to the runoff decrease, while the DHE of LUCC increased significantly, with a contribution rate of 35.8%.

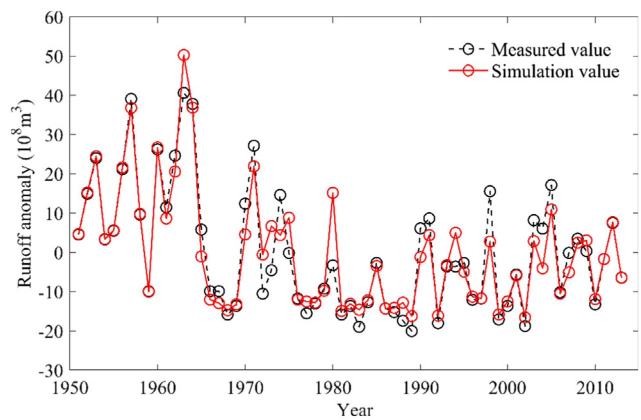

Fig. 6. The correlation between the measured and simulated runoff during 1951–2013 in the Yihe River basin.

4.3. The IHE of LUCC based on the WRF model

Fig. 7 shows the relationship between daily precipitation and measured data for 1, 4, 7 and 10 months in 2013 based on WRF model simulations. The results showed that the correlation between the daily simulated precipitation and the measured precipitation in different months reached the significance level of a = 0.05. The correlation coefficient between the simulated and the measured values was as high as 0.91 in January (Fig. 7a, a = 0.001), followed by that in April (Fig. 7b, a = 0.001) and October (Fig. 7d, a = 0.01). The correlation coefficients were 0.53 and 0.50, respectively, while the simulated precision of daily precipitation in July was relatively low, and the correlation coefficient was 0.41 (Fig. 7c, a = 0.05). At the monthly scale, the simulated total precipitation in January and April 2013 was

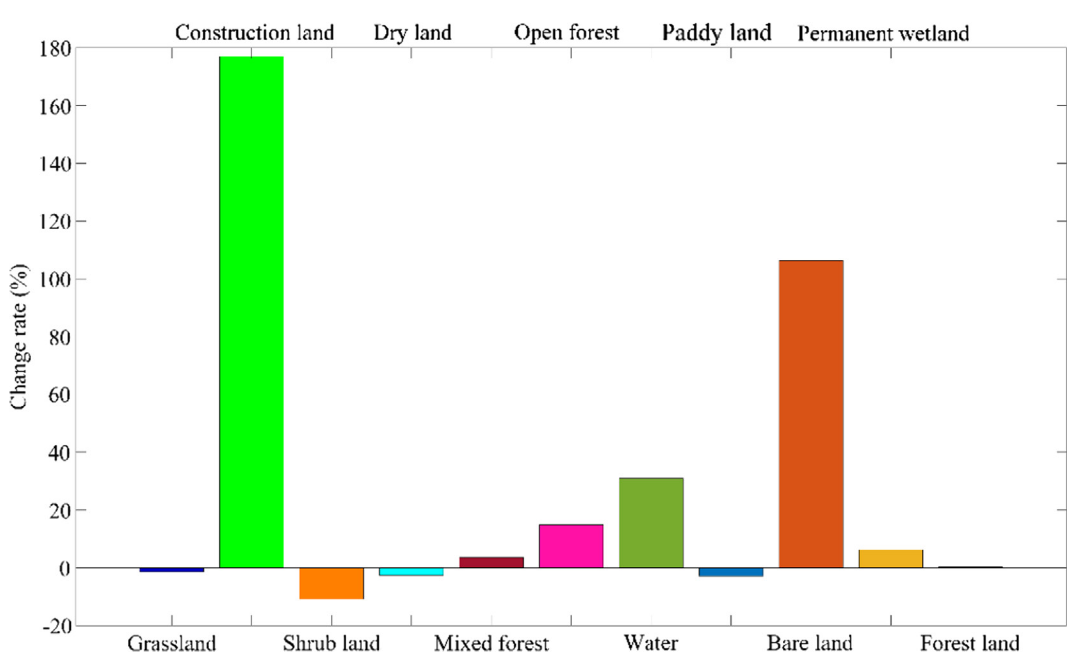

Fig. 5. The change rates of LUCC in the Yihe River basin during 1990–2010.

Table 3
The change in runoff and its attribution in different decades in the Yihe River basin.

Period	Q_T (mm)	Q_c (mm)	Q_H (mm)		
			Q_{LUCC1}	Q_{LUCC2}	Q_{other}
1960–1969	26.6	25.3 (95.1%)	——	——	1.3 (4.9%)
1970–1979	131.4	126.7 (96.5%)	——	——	4.7 (3.5%)
1980–1989	251.2	228.0 (90.8%)	——	——	23.2 (9.2%)
1990–1999	158.5	105.1 (66.3%)	29.3 (18.5%)	14.6 (9.2%)	9.5 (6.0%)
2000–2013	139.8	32.0 (22.9%)	50.0 (35.8%)	29.8 (21.3%)	27.9 (20.0%)

slightly lower than the actual value based on the WRF model, and the error rates were 4.8% and 14.3%, respectively. The simulated total precipitation in July and October was slightly higher, and the error rates were 6.7% and 17.1%, respectively. At the annual scale, the simulated total precipitation in 2013 was slightly higher than the measured value, and the error rate was 5.1%. Overall, the WRF model is reliable for simulating precipitation in the study area and can reflect the temporal and spatial variation in precipitation.

In 1990–1999, the IHE of LUCC contributed 9.2% to runoff variation (Table 3), and the impact of other human activities on runoff variation was less, at only 6.0%. In 2000–2013, the IHE of LUCC increased significantly, and the contribution rate was 21.3%. Thus, the contribution of other human activities to runoff change also significantly increased to 20%, which may be closely related to the rapid socio-economic development in the Yihe River basin and LUCC change represented by urbanization.

Generally, before the 1980s, the climate fluctuation was the main driving factor affecting the surface runoff variation in the Yihe River basin, and the contribution rate was more than 90%, while after 1990, the runoff reduction implied that climate change was not the main influencing factor affecting runoff. Instead, human activities, including LUCC, industrial and domestic water, dam construction, river diversion, irrigation, and other engineering and management practices, may also be regarded as the main factors that modify the local hydrological cycles; furthermore, the temporal and spatial distribution of surface water resources, especially the DHE and IHE of LUCC, increased significantly.

5. Discussion

5.1. The linear and nonlinear trends of runoff, PET and precipitation

The PET in the Yihe River basin changed significantly in 1960. The annual average PET in the Yihe River in the 1950s was 1012 mm, obviously lower than that of 1176 mm in 1960–2013. This change is mainly because the average temperature in the 1950s was significantly lower than that after the 1960s (Tang and Ren, 2005).

The climate and hydrological systems are complex non-stationary and nonlinear systems with oscillations at different time scales and periods. The latest research indicates that the decomposition results of the EEMD method were more stable and avoided the defects of scale mixed processing of non-stationary time series compared with the moving average, wavelet analysis and the EMD method (Bai et al., 2015; Qin et al., 2018). The EEMD method was used to decompose the precipitation, PET and runoff in the Yihe River basin from 1960 to 2013 and reflected the nonlinear changes at different time scales. Firstly, the climate system itself can change at different time scales. Secondly, the water cycle is not only affected by climate change, but also feeds back into the climate system. This feedback is also different on different timescales. Thus, the variation in inter-annual and inter-decadal scales and the general trend of climate change were extracted in the time series, which was conducive for clarifying the changes in climate change at different time scales. In particular, the relationships in different components of climate factors and runoff were obviously different. We found that the PET had an increasing trend, while the precipitation exhibited a decreasing trend in the study area in recent

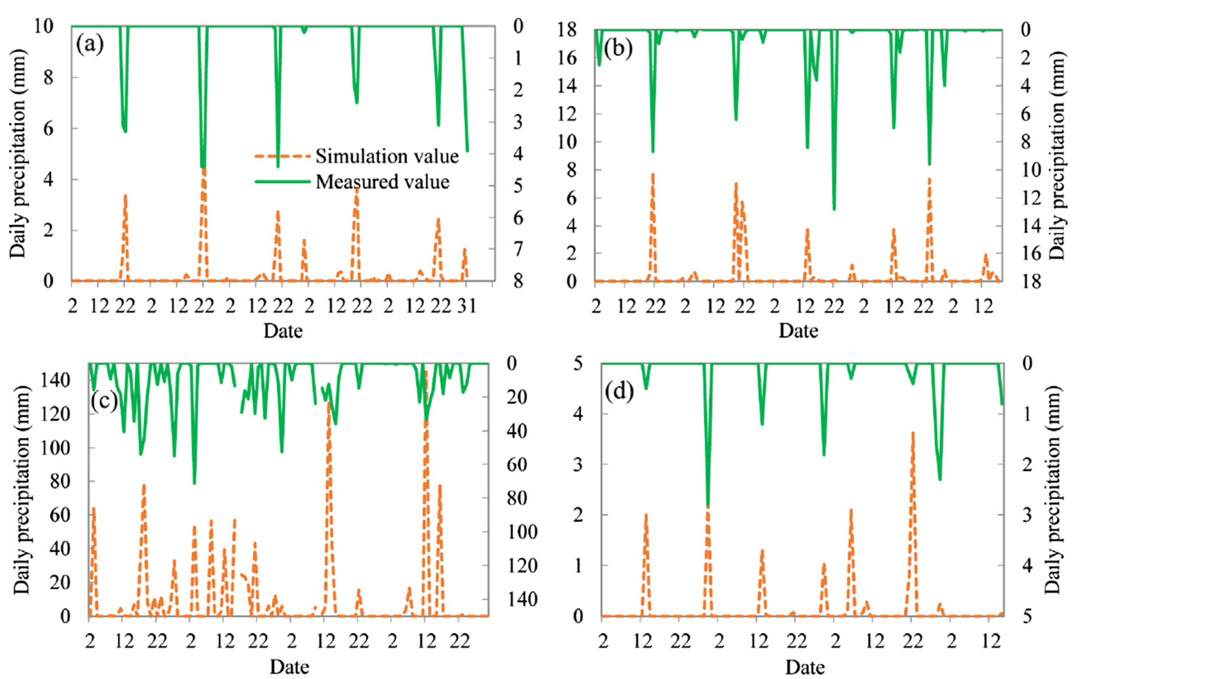

Fig. 7. Measured and modeled (controlled simulations) precipitation changes in January (a), April (b), July (c), and October (d) 2013.

60 years. These changes will inevitably have a certain impact on the depth of groundwater and soil water. But the extent to which groundwater and soil water changes over time affect runoff is unknown. Therefore, the influence mechanism of the climate on runoff at interannual, inter-decadal and multi-decadal scales had significant differences and must be further studied.

This study and many other studies have shown that there is a significant correlation between runoff and precipitation at an interannual scale (Wang et al., 2012, 2013). This study also showed that the impacts of precipitation on runoff were more significant at a multi-decadal scale than on an inter-annual scale. The reasons for these differences were as follows: (1) The sources of runoff supply in the Yihe River mainly include precipitation, groundwater and a small amount of soil water. At a long-term scale, climatic factors such as precipitation have a greater impact on groundwater than do other factors such as human activities (Mani et al., 2016). Therefore, at multi-interdecadal scales, runoff is not only directly related to precipitation but also related to groundwater (that is, indirectly related to precipitation). (2) At the interannual scale, groundwater is relatively stable, and the factors of human activities and climate fluctuations have a greater impact on runoff (Taylor et al., 2013). Therefore, runoff is not only related to precipitation; it is also related to other natural and human factors, which causes runoff to have large interannual fluctuations. (3) The interannual fluctuation in runoff has the highest contribution rate to its total change, which indicates that the interannual variation in runoff contains the most physical meaning; thus, it is more affected. Meanwhile, runoff contains the least amount of information at multi-interdecadal scales and is mainly influenced by the main controlling factor (precipitation), while other factors such as human activities are relatively less affected. For example, in the decades before 1990, climatic factors were the main factors influencing the change in runoff.

Based on the results of nonlinear decomposition in runoff, PET, and precipitation, it can be seen that runoff, evaporation, and precipitation all have four modes, and the change periods at inter-annual (approximately quasi-3 and quasi-6-year), inter-decadal (approximately quasi-5.7-year) and multi-annual (quasi-31-year scale) scales are similar, which indicates that there is an intrinsic connection between runoff and evaporation and precipitation. Therefore, climate factors are the main cause of runoff changes during periods of weak human activity.

5.2. The DHE of LUCC and climate based on the SWAT model

The per capita water resources of the Yihe River basin are only 1/6 of the average in China. With the rapid development of industrialization and urbanization in the basin, water consumption has increased substantially, and the contradiction between the water supply and demand and the ecological environment has become increasingly prominent (Gong, 2014). The upper limit for the development and utilization of water resources in river basins recognized internationally is 40%, while the current utilization rate of surface water in the Yihe River basin is 74% (Xue and Tan, 2011). Therefore, the sustainable use of water resources and the sustainable economic and social development in the Yihe River basin are facing a severe test. This study shows that after 2000, the conversion of cultivated land to construction land and bare land resulted in changes in production and convergence processes in the river basin, resulting in a 35.8% reduction in surface runoff. In the process of urbanization, the regional climate has changed and precipitation has decreased, further aggravating the contradiction between the supply and demand of water resources. In addition, human activities, such as the river basin industry, domestic water consumption and water conservancy facilities, contribute 20% to changes in water resources. For example, there is the world's longest (1135 m) rubber dam in the Yihe River. It was completed in 1997. Rubber dams will affect many water hydrological factors such as river level, velocity, flow, and sediment content. Based on the above attribution analysis of surface runoff in the Yihe River basin, relevant departments must formulate corresponding strategies to alleviate the pressure caused by water shortages as much as possible, thus promoting sustainable economic and social development.

This study shows that after 2000, the contribution rate of other human activities to runoff changes reached 20%, which was related to the rapid economic and social development of the basin. From 1961 to 1989, the economy in the Yihe River basin developed slowly, with an average annual GDP of only approximately 2.2 billion yuan. However, the economy developed rapidly after 1990. In 2000, the GDP of the basin was 24.8 billion yuan, while the GDP increased rapidly and was up to 87.4 billion yuan in 2010 (Gong, 2014). In addition, the population was 3.89 million in the 1980s, increased by 490,000 in the 1990s, and increased to 4.53 million in the 2000s. There has been a rapid social and economic development trend since 1990. After 2000, the impact of human activities, such as industrial and agricultural water and residential water consumption on runoff, has increased significantly.

This study shows that after 2000, the impact of human activities on runoff was larger than that of climate change. This difference was because the total economic output was directly proportional to the consumption of water resources (Hao et al., 2014). From 1961 to 1989, the total GDP in the Yihe River basin was only 64.5 billion yuan and was 141 billion yuan in the 1990s, while it was as high as 545.4 billion yuan in the 2000s (Gong, 2014). For example, in 2000, the total urban water supply in Linyi city was 73.67 million cubic meters and was 102.85 million cubic meters in 2005, while the urban water supply increased rapidly to 217.15 million cubic meters in 2013. The water resources used by human activities before 1990 were relatively small; after 2000, the urbanization process accelerated, and the water consumption of human activities increased significantly.

The results indicated that SWAT can be applied to study hydrological processes in the study area, but there is uncertainty. Runoff data were used to calibrate the relevant parameter of SWAT, which inevitably caused error that damaged the precision of study results. Furthermore, there are some spatial differences in soil properties in the study area (Zhang et al., 2013). This causes changes in parameters related to the soil water movement. Thus, field observed data will be used to calculate the relevant parameters of the hydrological model in further research.

The analysis showed that industrial and domestic water and water infrastructure have important impacts on hydrological processes. However, these data cannot be obtained in the study area; thus, this study cannot directly evaluate the impact of water infrastructure, such as reservoirs or irrigation projects, on runoff. We should conduct a detailed investigation into water infrastructure to illustrate its impact on water resources.

5.3. The IHE of LUCC based on the WRF model

After 2000, the IHE in the Yihe River basin increased significantly and reached 21.3%, which showed that the influence of LUCC on the regional climate increased. First, with the rapid development of the economy, the rates of land use change have increased since 2000. The rate of land use change after 2000 was 2–3 times faster than that before 2000 (Gong, 2014). Second, due to the continuous expansion of the city scale, the effects of urban “heat islands” have gradually increased. Additionally, changes in other land types also showed similar trends.

LUCC is one of the major driving factors affecting climate change. The results showed that LUCC caused the local climate to change significantly in the past 20 years based on the WRF model, which had a large impact on runoff. Shao and Zeng (2012) suggested that the impact of LUCC on regional climate is robust. The net geophysical impact of LUCC results from the competition between the effects of change of albedo, evapotranspiration efficiency, and surface roughness. Thus, the indirect hydrological effect should be considered and will be the key emphasis of future studies. Meanwhile, the results illustrated that the precipitation effect caused by LUCC can be canceled out when positive effects combine with negative effects, which is consistent with previous research (Zhang et al., 2015; Wang et al., 2016). Thus, a high temporal and spatial resolution should be used to reveal the impact of LUCC on local climate change.

We chose to use 2010 LUCC data, mainly because that was the only LUCC data available to us for that period. It is also based on our consideration that the effect of LUCC on climate may appear a few years after the change. This study demonstrates that the effect of LUCC is detectable with a three-year lag. Unfortunately, we do not have LUCC data for multiple time points to further investigate this lag, but this study provides empirical evidence of such a lag and may have reference value to other similar studies.

6. Conclusion

In 1960–2013, the PET increased slightly, with a rate of 6.3 mm/decade, while the precipitation showed a progressive decline ($\alpha = 0.05$), with a rate of 26.6 mm/decade. Meanwhile, the PET and precipitation at inter-annual (3 years and 6 years) and decadal (13–16 years) scales had similar periodic changes.

The runoff showed a downward trend during 1951–2013, with a rate of 0.16×10^8 m^3/decade. However, before (after) 1976, the runoff showed a significant downward (upward) trend. Runoff also exhibited a nonlinear trend from the inter-annual scale (quasi-3 and quasi-6-year), inter-decadal scale (quasi-13-year) and multi-decadal scale (quasi-31-year). The variance contribution rate of components from the inter-annual scale was the largest, reaching 58%, and those from the inter-decadal scale and multi-decadal scale were 6% and 11%, respectively, which indicated that the inter-annual change had a strong influence on the overall runoff change. The results also implied that the effect of precipitation on runoff at scales of inter-decadal and multi-decadal variability was more important than that at the other scales, which indicated that the impact mechanism of climate factors on runoff had obvious differences at different scales.

Before the 1980s, the climate fluctuation was the main factor affecting the runoff change, and the contribution rate was above 90%. From 1990 to 1999, the contribution rate of climate fluctuations decreased to 66.3%, and the DHE and IHE of LUCC contributed 18.5% and 9.2% to runoff change, respectively. Other human activities, including irrigation, dam construction, river diversion, and other engineering and management practices, contributed 6.0% to runoff change. From 2000 to 2013, human activity gradually became the main driving force affecting runoff change (77.1%), and the contribution rates of DHE and IHE of LUCC to runoff changes were 35.8% and 21.3%, respectively.

CRediT authorship contribution statement

Baofu Li: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing - original draft, Writing - review & editing. **Xun Shi:** Supervision, Validation, Visualization, Formal analysis, Writing - review & editing. **Lishu Lian:** Methodology, Supervision, Validation, Visualization, Software. **Yaning Chen:** Resources, Supervision. **Zhongsheng Chen:** Methodology, Supervision, Validation. **Xiaoyin Sun:** Supervision, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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