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RESEARCH ARTICLE

Effects of climate and land use changes on runoff, sediment, nitrogen and phosphorus losses in the Haihe River Basin

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Abstract Investigating the impacts of climate and land use changes on the hydrological cycle and water environment at the basin scale is important for providing scientific evidence to manage the trade-offs and synergies among water resources, agricultural production and environmental protection. We used the Soil and Water Assessment Tool (SWAT) with various spatiotemporal data to quantify the contributions of climate and land use changes to runoff, sediment, nitrogen (N) and phosphorus (P) losses in the Haihe River Basin since the 1980s. The results showed that 1) climate and land use changes significantly increased evapotranspiration (ET), transport loss, sediment input and output, and organic N and P production, with ET, sediment input and organic N affected the most; 2) runoff, sediment and ammonia N were most affected by climate and land use changes in the Daqing River Basin (217.3 mm), Nanyun River Basin (3917.3 tons) and Chaobai River Basin (87.6 kg/ha), respectively; 3) the impacts of climate and land use changes showed explicit spatiotemporal patterns. In the Daqing, Yongding and Nanyun River Basins, the contribution of climate change to runoff and sediment kept increasing, reaching 88.6%–98.2% and 63%–77.2%, respectively. In the Ziya and Chaobai River Basins, the contribution of land use was larger, reaching 88.6%–92.8% and 59.8%–92.7%, respectively. In the Yongding, Chaobai, Ziya and Daqing River Basins, the contribution of land use to N and P losses showed an increasing trend over the past 40 years (maximum 89.7%). By contrast, in Nanyun and Luanhe River Basins, the contribution of climate change to N and P losses increased more (maximum 92.1%). Our evaluation of the impacts of climate and land use changes on runoff, sediment, and N and P losses will help to support the optimization of land and water resources in the Haihe River Basin.

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1 Introduction

Land use/cover change (LUCC) caused by climate change and human activities is the main factor affecting surface water runoff, sediment yield and water quality changes (Zuo et al., 2013; Zhang et al., 2016a; Yin et al., 2017; Zhang et al., 2017). It has long been known that the land use changes caused by human activities, e.g., afforestation, deforestation, agricultural practices and urbanization, can significantly affect land surface processes (Skaggs et al., 2006). Climate change can also exert a profound impact on hydrological conditions and the spatiotemporal patterns of water resources (Kim et al., 2013; Chang et al., 2015; Chang et al., 2016). The impacts of LUCC and climate change on basin ecology have attracted increasing attention, particularly in the past two decades, with the acceleration of global warming and human activities.

Researchers have investigated the possible impacts of LUCC and climate change on land surface hydrological and ecological processes. Climate change affects temperature, precipitation and evaporation patterns in the water cycle (Kundu et al., 2017), which cause temporal and spatial changes in water and sediment resources. Therefore, climate change affects ET, surface runoff, soil moisture and groundwater recharge in river basins and will further affect the hydrological processes (Luo et al., 2016; Yan et al., 2016). For example, an increase in precipitation in summer and winter leads to an increase in surface runoff (Zhou et al., 2015; Liu et al., 2017; Yin et al., 2017). The changes in precipitation intensity caused by climate change also affect the sediment yields within river basins. For example, the frequent occurrence of extreme precipitation enhances the scouring of the soil, which increases the erosion of sediment and leads to the elevation of riverbeds, and consequently increases the risk of flooding (Sorribas et al., 2016; Yang et al., 2017). Along with changes in precipitation intensity and surface runoff, the nutrient load (such as nitrogen (N) and phosphorus (P)) in rivers will also change significantly. Increased loads of N and P lead to a deterioration in water quality (Gao et al., 2016; Liu et al., 2017).

LUCC alters the hydrological cycle and soil erosion through canopy interception and transpiration and the redistribution of rainfall erosivity (Gao et al., 2016; Liu et al., 2017). LUCC caused by human activities is also one of the main reasons for the changes in the hydrological processes of river basins. For example, declines in vegetation coverage and the destruction of the soil structure caused by deforestation could decrease rainfall interception (Wang et al., 2010; Kim et al., 2013; Zhao et al., 2015; Guo et al., 2021). Changes in the soil infiltration rate and volume (Jia et al., 2018; Huang et al., 2019) could increase surface runoff (Yang et al., 2019), flooding and soil erosion (Chawla and Mujumdar, 2015; Zheng et al., 2018). In addition, the expansion of cultivated land and the widespread use of chemical fertilizers and pesticides leads to an increase in the quantity of erosion nutrients, which impairs water quality and affects the security of the water supply (Nian et al., 2014; Viola et al., 2014; Chang et al., 2015; Huang et al., 2019).

Changes in runoff and corresponding river sediment transport are crucial components of global ecological and environmental change. Investigating the changes in LUCC and their impacts on runoff and river sediment transport is crucial to develop strategies for the sustainable management of catchments (Wang et al., 2015; Shi et al., 2020; He et al., 2021). In the past two decades, with acceleration of global warming and an increase in human activities, the reserves and availability of water resources have faced increasing pressure and the hydrological cycle has become more unstable (Fu et al., 2007; Zhao et al., 2014). Therefore, identifying the main factors that affect the hydrological cycle has become a primary objective in the field of hydrology (Scanlon et al., 2007). The negative impacts of climate change and LUCC on the environment of surface water basins will affect the hydrological, ecological, agricultural and socioeconomic systems (Piao et al., 2007). Therefore, quantifying the impact of climate change and LUCC on the hydrological environment in river basins has become a research focus (Pechlivanidis et al., 2017; Sorribas et al., 2016; Sunde et al., 2017). Some previous studies have investigated the combined hydrological influences of LUCC and climate change (Choi, 2008; Franczyk and Chang, 2009; Qi et al., 2009; Tu, 2009; Zhang et al., 2015). However, the individual contributions of LUCC and climate change have not been quantified sufficiently owing to the nonlinear nature of hydrological processes (Wang et al., 2013; Dey and Mishra, 2017). To better manage river basins, it is vital to investigate not only the joint impacts of LUCC and climate change, but also their individual and relative contributions (Wang et al., 2013; Zhang et al., 2016b). In addition, to comprehensively evaluate the impacts of LUCC and climate change on basin ecology, we should focus not only on runoff but also on sediments and nutrients, which will further support the allocation and optimization of regional water and land resources (Zhao et al., 2015).

The Haihe River Basin is one of the most severely water-deficient areas in China. Owing to human activities, such as interception and irrigation, the water resources in the middle and lower reaches are scarce and seriously polluted (Shen et al., 2017). In this study, taking Haihe River Basin as an example, we evaluated the impact of climate change and LUCC from 1980 to 2019 on the spatial and temporal patterns of runoff, sediment, and N and P losses, using the Soil and Water Assessment Tool (SWAT), together with various spatiotemporal data. The results provide scientific evidence for the allocation and optimization of water and land resources in the Haihe River Basin.

2 Materials and methods

2.1 Study area

The Haihe River Basin is in north China, with a total area of 320600 km^2, of which 41.3% are plains and 58.7% are mountainous areas (Yang et al., 2018). Farmland is the main land use type in the Haihe River Basin, accounting for 51% and 40.5% in 1985 and 2015, respectively, followed by forest, accounting for 19.1% and 24.7%, respectively (Xu et al., 2018). The Basin has a temperate semi-arid and semi-humid East Asian continental monsoon climate, with precipitation mainly concentrated in summer (He et al., 2017). The annual average precipitation is 539 mm, with the lowest precipitation in the coastal area. The interannual variability of precipitation is large and the annual precipitation has decreased significantly in the 21st century (Zhou, 2015). The annual average temperature of the Haihe River Basin ranges from 1.5°C to 14°C. The highest temperature—over 40°C in July—shows an overall trend of decreasing from the plain to the mountainous area and from south to north. The total population of the basin is 122 million, with an urbanization rate of 38% (Feng et al., 2003). Owing to the construction of a large number of water conservancy projects and coal mining activities in the upper reaches of Shanxi Province, only the Luanhe River in the lower reaches of the Haihe River Basin has water all year round. Groundwater overexploitation in the basin has also become increasingly severe (Zhang and Zheng, 2011). According to the Haihe River Basin Hydrological Yearbook, the Haihe River Basin was divided into six sub-basins for research, including Chaobai River, Ziya River, Daqing River, small rivers along the banks of the Luanhe River in Hebei Province, Nanyun River and Yongding River (Fig. 1).

2.2 Data

The data required for calibrating and validating the SWAT model include a digital elevation model (DEM), soil, land use, hydrology, N, P and meteorological data (Table S1). The DEM data were collected from the Geospatial Data Cloud (available at Yale University webiste), with a spatial resolution of 30-m GDEM. The soil data were provided by the 1:1 million Chinese soil data set based on the world soil database (available at National Cryosphere Desert Data Center website). The China Multi-Period Land Use and Land Cover Remote Sensing Monitoring Data set was provided by the Data Registration and Publishing System of the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (available at Resource and Environment Science and Data Center website) (Xu et al., 2018). The hydrological data, including monthly runoff and sediment data from 1986 to 2009 at six hydrological stations around the outlet of the river sub-basins (i.e., Luan County, Hangu, Xiangshuibao, Daomaguan, Sixth Fort and Nanpi Station), were collected from the Hydrological Yearbook of the People's Republic of China. The N and P data, including the ammonia N and total P content during 1986–1990 and 2005–2009, were collected from the weekly and monthly reports of the automatic water quality monitoring stations, the China Statistical Yearbook, and the statistical yearbooks of each province. The daily meteorological data from 68 stations in the Haihe River Basin from 1980 to 2019 were obtained from the China Meteorological Data Sharing Service Network (available at China Meteorological Data Service Center website). Daily average temperature, precipitation, average wind speed, relative humidity and sunshine hours were used in this study.

2.3 SWAT model

The SWAT model is a distributed basin hydrological model based on a geographic information system (Kueppers and Snyder, 2012; Zhang et al., 2016b). The initial purpose of the model was to predict the long-term effects of land management on water, sediment and chemicals under the conditions of complex and changeable soil types, land use patterns and management measures in large basins. SWAT is a deterministic model that is able to isolate the role of a single variable in affecting runoff and water quality (Awan and Ismaeel, 2014; Wu et al., 2014).

2.4 Model parameter calibration and validation

According to data availability, the model calibration period was set to 1986–1990 and the verification period was set to 2005–2009. The model was run on a monthly scale and the model parameters were calibrated and verified for each outlet station. During the calibration

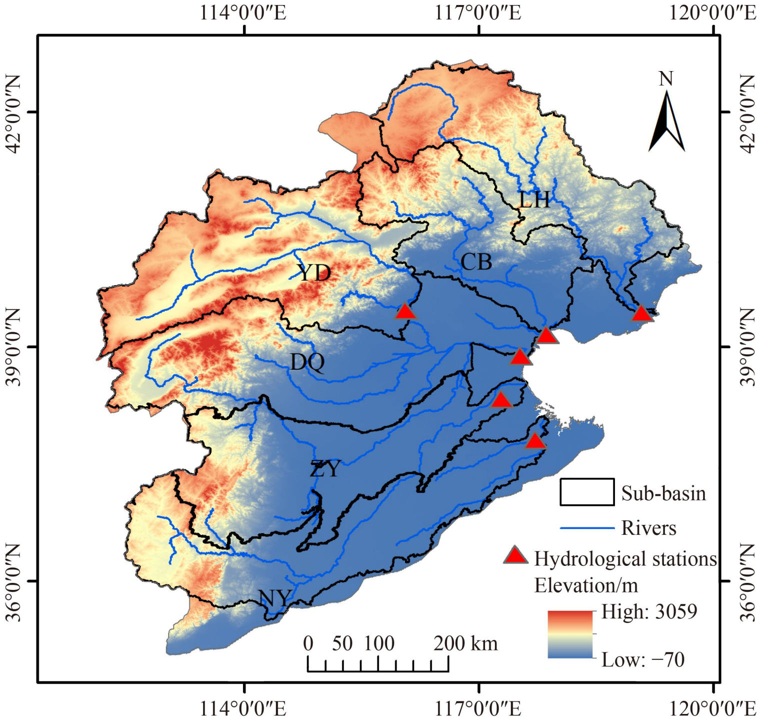

Fig. 1 Water system diagram of Haihe River Basin and locations of hydrological stations.

period, the land use data for 1985 were used. During the verification period, the land use data for 2005 were used. The soil data were fixed during the study period. The model was calibrated on the basis of the monthly runoff, sediment, N and P data. The Nash-Sutcliffe efficiency coefficient (Ens) and coefficient of determination (R^2) were used to evaluate model efficiency. Larger Ens and R^2 values indicate simulation results that are closer to reality (Nash and Sutcliffe, 1970; Thanapakpawin et al., 2007; Cuartas et al., 2012; Du et al., 2014; Alvarenga et al., 2016).

2.5 Methods

In this study, we used factorial modeling experiments to assess the impacts of climate change and LUCC. The methods compared the simulation results from different modeling settings on the runoff, sediment, N and P losses in the Haihe River Basin during 1980–2019. We show that the temporal trends of annual average temperature and precipitation and the LUCC in the six sub-basins of the Haihe River Basin over the past 40 years. This study comprehensively evaluated the impacts of climate change and LUCC on runoff, sediment, N and P loss. The variables related to runoff included ET, surface runoff (SQ), groundwater recharge (GW), transmission loss (TL) and lateral runoff (LA). The variables related to sediment included sediment input (SI), sediment output (SO), sediment yield (SY) and channel deposition (CD). The variables related to N and P losses included organic N (ON), organophosphorus (OP), nitrate in surface runoff (NS) and lateral flow (NL).

2.6 Simulation protocol

To quantify the contributions of climate and land use changes to the changes in runoff, sediment and N and P losses, we designed a series of factor-controlled simulation experiments (Tables 1 and 2). Factorial modeling experiments are commonly used to disentangle the contribution of different factors (Zhai and Tao, 2021). Different combinations of meteorological data and land use data were used to drive the calibrated SWAT model. The simulation results were used to quantify and analyze the contributions of climate and land use changes to variations in runoff, sediment and N and P losses during the 1980s (1980–1989), 1990s (1990–1999), 2000s (2000–2009) and 2010s (2010–2019). The settings for modeling experiments were as follows.

Table 1 Simulation settings to investigate the effects of LUCC and climate change on runoff, sediment, N and P losses in Haihe River Basin

Modeling experiment	LUCC	Climate change
M1	1980s (1985)	1980s (1980—1989)
M2	1980s (1985)	1990s (1990—1999)
M3	1990s (1995)	1980s (1980—1989)
M4	1990s (1995)	1990s (1990—1999)
M5	1990s (1995)	2000s (2000—2009)
M6	2000s (2005)	1990s (1990—1999)
M7	2000s (2005)	2000s (2000—2009)
M8	2000s (2005)	2010s (2010—2019)
M9	2010s (2015)	2000s (2000—2009)
M10	2010s (2015)	1980s (1980—1989)
M11	1980s (1985)	2010s (2010—2019)

Table 2 Methods to investigate the effects of LUCC and climate change on runoff, sediment, N and P losses in the Haihe River Basin in different time periods

Variable	LUCC	Climate change	LUCC & Climate change
1990s	M3—M1	M2—M1	M4—M1
2000s	M6—M4	M5—M4	M7—M4
2010s	M9—M7	M8—M7	M12—M7
1980s—2010s	M10—M1	M11—M1	M12—M1

Considering the data availability, here we used the land use data in 1980 to represent the land use from 1980 to 1989. Similarly, the land use data in 1995, 2005 and 2015 were used to represent the land use during 1990s, 2000s and 2010s, respectively. The meteorological data in the corresponding periods were used, for example, the data from 1980 to 1989 represented the climate in the 1980s. Different combinations of land use data and climate data were used in different modeling experiments to drive the SWAT model. As shown in Table 1, experiments M1 and M11 used the same land use data (1980s) but different meteorological data (1980s vs 2010s) to drive the simulation. Thus, the differences in the simulation results of M1 and M11 (M11−M1) could disentangle the effects of climate change from 1980s to 2010s on runoff, sediment and N and P losses. Experiments M1 and M10 used the same meteorological data (1980s) but different land use data (1980s vs 2010s). Thus, the difference between the simulation results of M1 and M10 (M10−M1) reflected the effects of land use change from 1980s to 2010s. For experiments M1 and M12, different meteorological data and land use were used to analyze the comprehensive effects of climate and land use change from 1980s to 2010s on runoff, sediment and N and P losses (M12−M1). Likewise, as shown in Table 2, we used M3−M1, M2−M1 and M4−M1 to quantify the effects of LUCC, climate change, and LUCC and climate change, respectively, in the 1990s. We used M6−M4, M5−M4 and M7−M4 to quantify their effects in the 2000s; and M9−M7, M8−M7 and M12−M7 to quantify their effects in the 2010s (Tables 1 and 2).

2.7 Contributions of climate change and LUCC to runoff, sediment, nitrogen and phosphorus changes in the Haihe River Basin

Using factorial modeling experiments, we calculated the contributions of climate and land use changes to runoff, sediment and N and P losses as follows. Taking the contribution of LUCC during 1990s ($CR_{\text{land 90s}}$) as an example (Luo et al., 2016):

$$CR_{\text{land 90s}} = \frac{Y_{\text{M3}} - Y_{\text{M1}}}{Y_{\text{M4}} - Y_{\text{M1}}} \times 100\%, \tag{1}$$

where Y_{M3}, Y_{M1} and Y_{M4}, are the simulation results for a specific variable (runoff, sediment or N or P loss) under modeling experiment M3, M1 and M4, respectively.

Similarly, the contribution of climate change to runoff, sediment and N and P losses in the 1990s was quantified as

$$CR_{\text{climate 90s}} = \frac{Y_{\text{M2}} - Y_{\text{M1}}}{Y_{\text{M4}} - Y_{\text{M1}}} \times 100\%. \tag{2}$$

In addition, the residuals of the model simulation and the contribution rate of the model residuals were calculated as

$$CR_{\text{residual 90s}} = \frac{(Y_{\text{M4}} - Y_{\text{M1}}) - (Y_{\text{M2}} - Y_{\text{M1}}) - (Y_{\text{M3}} - Y_{\text{M1}})}{Y_{\text{M4}} - Y_{\text{M1}}} \times 100\%. \tag{3}$$

This method was used to calculate the contributions of land use and climate change to runoff, sediment and N and P losses in each of the six sub-basins during 1990s, 2000s and 2010s. Meanwhile, the contributions of land use and climate change during the entire study period (1980s–2010s) were evaluated using modeling experiment M1, M10, M11, and M12 (Table 3).

3 Results

3.1 Model calibration and validation

The calibration and verification results of the SWAT model for runoff, sediment, N and P in the Haihe River Basin are shown in Fig. 2. For runoff, the Ens reached 0.4–0.8, with the best Ens in the Luanhe River and the worst in the Chaobai River. The R^2 reached 0.53–0.8, with the best in the Luanhe River and the worst in the Chaobai River (Figs. 2(a)–2(f)). For sediment, the Ens of verification ranged from 0.4 to 0.7, with the best in the Luanhe River and the worst in the Chaobai River; the R^2 ranged from 0.4 to 0.8, with the best in the Luanhe River and worst in the Chaobai River (Figs. 2(g)–2(l)). For N, the model performed best in the Luanhe River with an Ens of 0.4 and R^2 of 0.7, while it performed worst in Ziya River (Figs. 2(m)–2(r)). In terms of P, the model performed best in the Yongding River (R^2 = 0.48, Ens = 0.4) and worst in the Chaobai River (R^2 = 0.32, Ens = 0.35) (Figs. 2(s)–2(x)). In summary, the model calibration and validation results indicated that the model was suitable for use in further simulations and analyses (Table S2).

3.2 Spatiotemporal changes of climate and land use since the 1980s

Generally, temperature increased in all the sub-basins except the Luanhe, Chaobai, Daqing and Yongding Rivers in the 10s–00s. The temperature increased the most in the Daqing River during the 00s–90s (1.22°C/10yr) and in the Yongding River during the 90s–80s (0.94°C/10ye) (Fig. 3(a)). Over the past 40 years, annual precipitation generally increased continuously, with a few decreases in some sub-basins during 00s–90s. Precipitation increased the most in the Nanyun River Basin, by 83.6 mm/10yr, followed by the Luanhe River Basin (71.3 mm/10yr).

Figure 4 shows the LUCC between the decades. "1985–1995" means the percentage of LUCC in 1995 compared with 1985. In the Haihe River Basin, cultivated land, forest land, grassland and construction land changed by −4.0%, −0.7%, 0.6%, and 39.7%, respectively, in the past 40 years. The LUCC in the six sub-basins showed a similar trend over the past 40 years. Specifically, the area of cultivated land increased from 1995 to 2005 but decreased in other time periods. The area of forest land increased from 1985 to 1995 but decreased in other time periods. The area of construction land increased in all the periods.

3.3 Impacts of climate change and LUCC on hydrological characteristics in the Haihe River Basin

The impacts of climate change and LUCC (Figs. 5(a), 5(d), 5(g), 5(j), 5(m), and 5(p)), climate change alone (Figs. 5(b), 5(e), 5(h), 5(k), 5(n), and 5(q)) and LUCC alone (Figs. 5(c), 5(f), 5(i), 5(l), 5(o), and 5(r)) on runoff-related variables in the six sub-basins are shown in Fig. 5.

Table 3 Methods to estimate the contributions of climate change and LUCC to runoff, sediment, N and P changes in the Haihe River Basin

Modeling experiment variable	M1	M2	M3	M4	Residual
Runoff, sediment and nitrogen and phosphorus	Y_{M1} c)	Y_{M2} c)	Y_{M3}	Y_{M4} c)	
Changes		$Y_{\text{M2}}-Y_{\text{M1}}$	$Y_{\text{M3}}-Y_{\text{M1}}$	$Y_{\text{M4}}-Y_{\text{M1}}$	$(Y_{\text{M4}}-Y_{\text{M1}})-(Y_{\text{M2}}-Y_{\text{M1}})-(Y_{\text{M3}}-Y_{\text{M1}})$
Contribution rate/%		$CR_{\text{land 90s}}$ a)	$CR_{\text{climate 90s}}$ b)	100	$CR_{\text{residual 90s}}$

Notes: a) $CR_{\text{land 90s}}$: the contribution of LUCC from the 1980s to 1990s; b) $CR_{\text{climate 90s}}$: the contribution of climate change from the 1980s to 1990s; c) Y_{M4}, Y_{M2} and Y_{M1}: the simulation results of the variables (runoff, sediment or N and P) from the modeling experiment M4, M2 and M1, respectively.

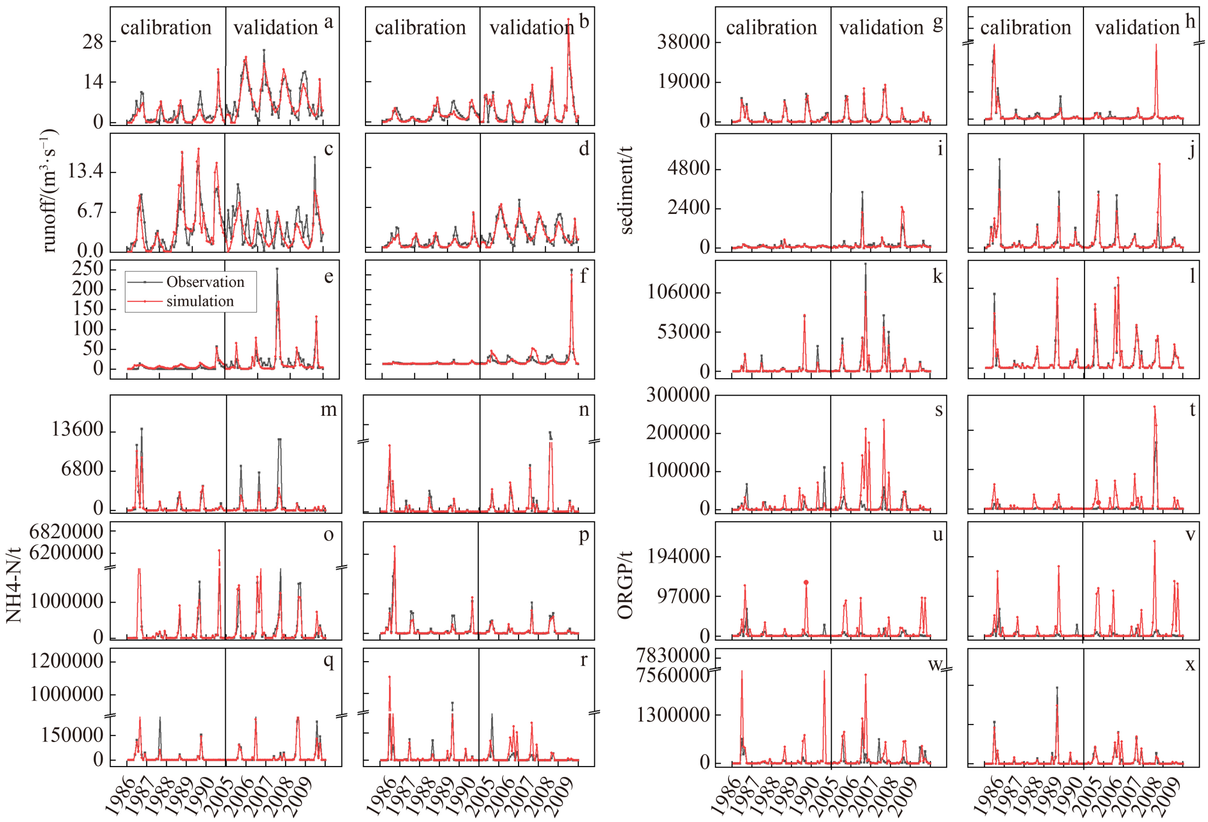

Fig. 2 Calibration and validation of SWAT model in simulating runoff, sediment, NH4-N, and organic P in the basin of Ziya River (a, g, m, and s), Nanyun River (b, h, n, and t), Chaobai River (c, i, o, and u), Luanhe River (d, j, p, and v), Yongding River (e, k, q, and w) and Daqing River (f, l, r, and x).

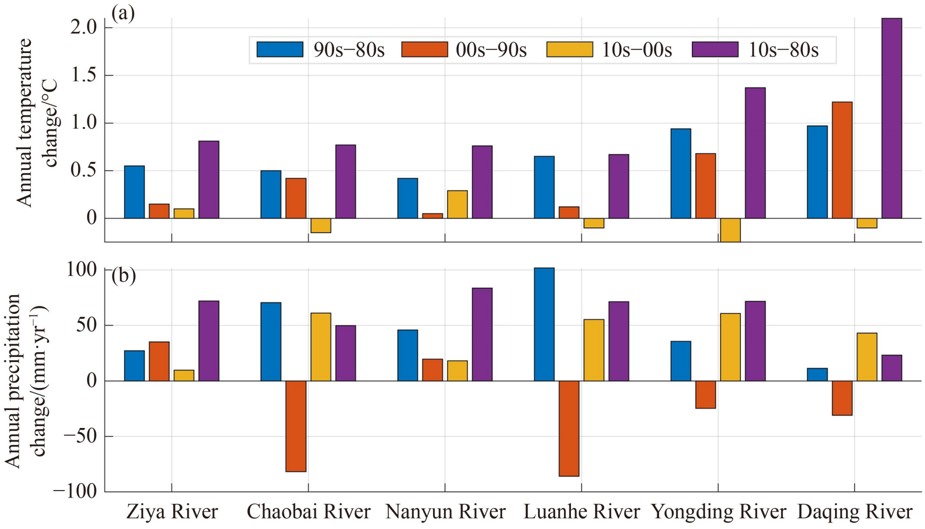

Fig. 3 Trends in annual mean temperature (a) and annual precipitation (b).

Over the past 40 years, ET in the Haihe River Basin showed an overall upward trend (Fig. 5), with the highest value in the Daqing River Basin (217.3 mm) (Fig. 5(q)) and the lowest in the Chaobai River Basin (89.3 mm) (Fig. 5(e)). Taking the interdecadal changes into consideration, climate change had the highest impact on ET in the Daqing River Basin in 2010s (157.3 mm) and the lowest in the Chaobai River Basin in the 1990s (37.5 mm) (Figs. 5(e) and 5(q)). It had the highest impact on SQ in the Daqing River Basin, increasing by 83.5 mm (Fig. 5(q)), followed by the Nanyun River Basin (42.6 mm) (Fig. 5(k)). Considering the interdecadal influence, climate change had the highest impact (47.5 mm) on SQ in the Daqing River Basin in the 2010s, and the lowest

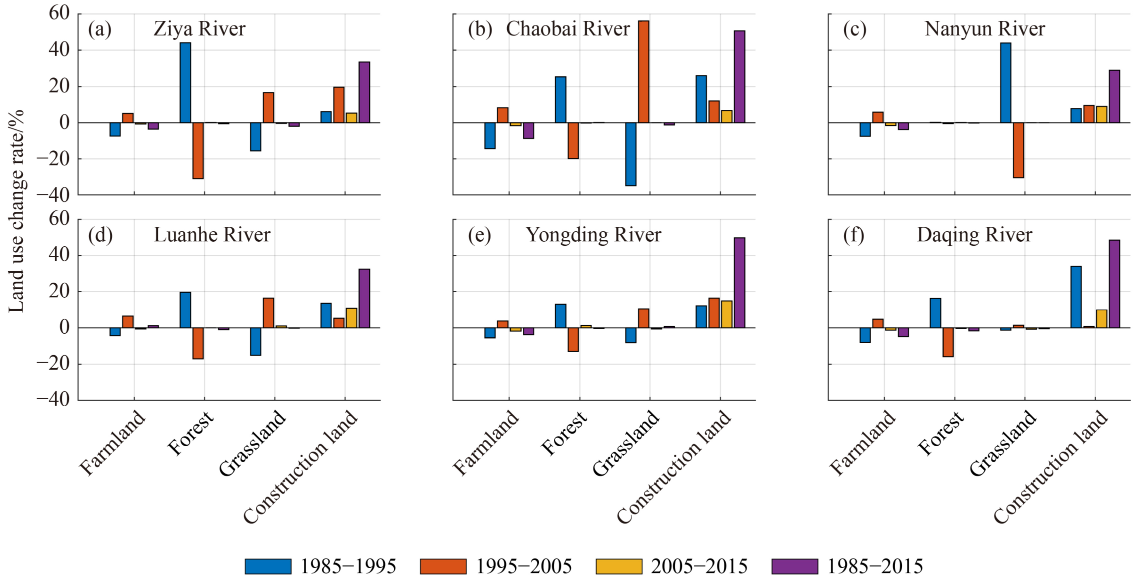

Fig. 4 LUCC in different sub-basins during different time periods.

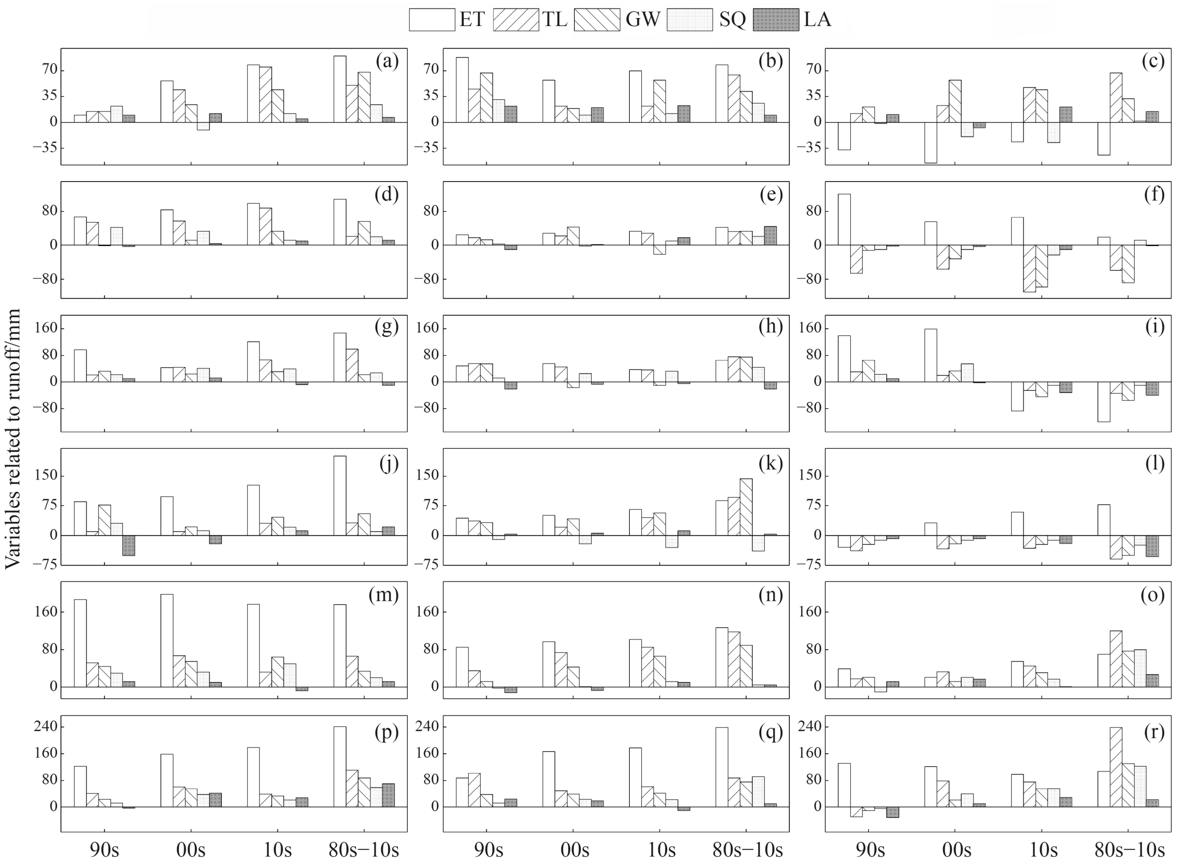

Fig. 5 Impact of climate change and LUCC jointly (a, d, g, j, m, and p), climate change only (b, e, h, k, n, and q) and LUCC (c, f, i, l, o, and r) only on the runoff-related variables in the sub-basins of the Ziya River (a–c), Chaobai River (d–f), Nanyun River (g–i), Luanhe River (j–l), Yongding River (m–o) and Daqing River (p–r).

(3.3 mm) in the 1990s in the Chaobai River Basin (Figs. 5(e) and 5(q)). With climate change, GW generally showed a rising trend in each sub-basin and each time period. GW increased most evidently (30.8–83.7 mm) in the Daqing River Basin (Fig. 5(q)), while the growth was relatively low in the Chaobai River Basin. The TL was affected most (81.6 mm) by climate change in the Daqing River Basin and least (10.6 mm) in the Chaobai River

Basin (Figs. 5(e) and 5(q)). Climate change had little effect on LA with a variation of approximately 4.6–10.4 mm.

LUCC had a substantial impact on ET and TL in the past 40 years. ET increased the most (268.3 mm) in the Daqing River Basin, but the least (4.6 mm) in the Nanyun River Basin (Figs. 5(i) and 5(r)). LUCC led to the largest impact (92.3 mm) on ET in the Daqing River Basin (Fig. 5(r)), followed by the Yongding River Basin, with an increase of 82.1 mm (Fig. 5(o)). GW showed the largest impact (−77.3–89.2 mm) in the Daqing River Basin, whereas the growth rate was relatively low in the Chaobai River Basin (Figs. 5(f) and 5(r)). LUCC had the largest impact on TL in the Daqing River Basin, with an increase of 123.4 mm, but the smallest (−4.8 mm) in the Ziya River Basin (Figs. 5(c), 5(f), and 5(r)). LA was not significantly impacted by LUCC and only changed in the Ziya River Basin (Fig. 5(c))

Climate change and LUCC jointly had the highest impact on ET and the lowest on LA over the past 40 years. They had a major impact on ET in the Daqing River Basin, followed by the Yongding River Basin, but a minor effect in the Ziya River Basin (Figs. 5(f), 5(o), and 5(r)). Owing to their joint impacts, the runoff-related variables such as ET and TL in the six sub-basins had a rising trend and only LA dropped in Luanhe River Basin in the 1990s and the 2000s (Fig. 5(l)).

3.4 Impacts of land use and climate change on sediment

The impacts of climate change and LUCC (Figs. 6(a), 6(d), 6(g), 6(j), 6(m), and 6(p)), climate change only (Figs. 6(b), 6(e), 6(h), 6(k), 6(n), and 6(q)) and LUCC only (Figs. 6(c), 6(f), 6(i), 6(l), 6(o), 6(r)) on sediment-related variables in the six sub-basins are presented in Fig. 6. Over the past 40 years, climate change had the highest impact on SI and SO in the Daqing River (Fig. 6(q)), followed by the Yongding River (Fig. 6(n)). The interdecadal impact was the highest in the Nanyun River Basin (3917.3 tons) (Fig. 6(h)) and the Yongding River Basin (3729.7 tons) (Fig. 6(n)) in the 1990s, followed by the Luanhe and the Daqing River Basins in the 2000s (Figs. 6(k) and 6(q)), while the lowest was in the Chaobai River (−34.9 tons) and the Yongding River (28.5 tons) in the 2010s (Figs. 6(e) and 6(n)). The impact on the SY in the Yongding River Basin was most evident, increasing by 10.3 tons/ha (Fig. 6(n)), followed by Nanyun River Basin (6.4 tons/ha) (Fig. 6(h)). Climate change had the lowest impact on CD.

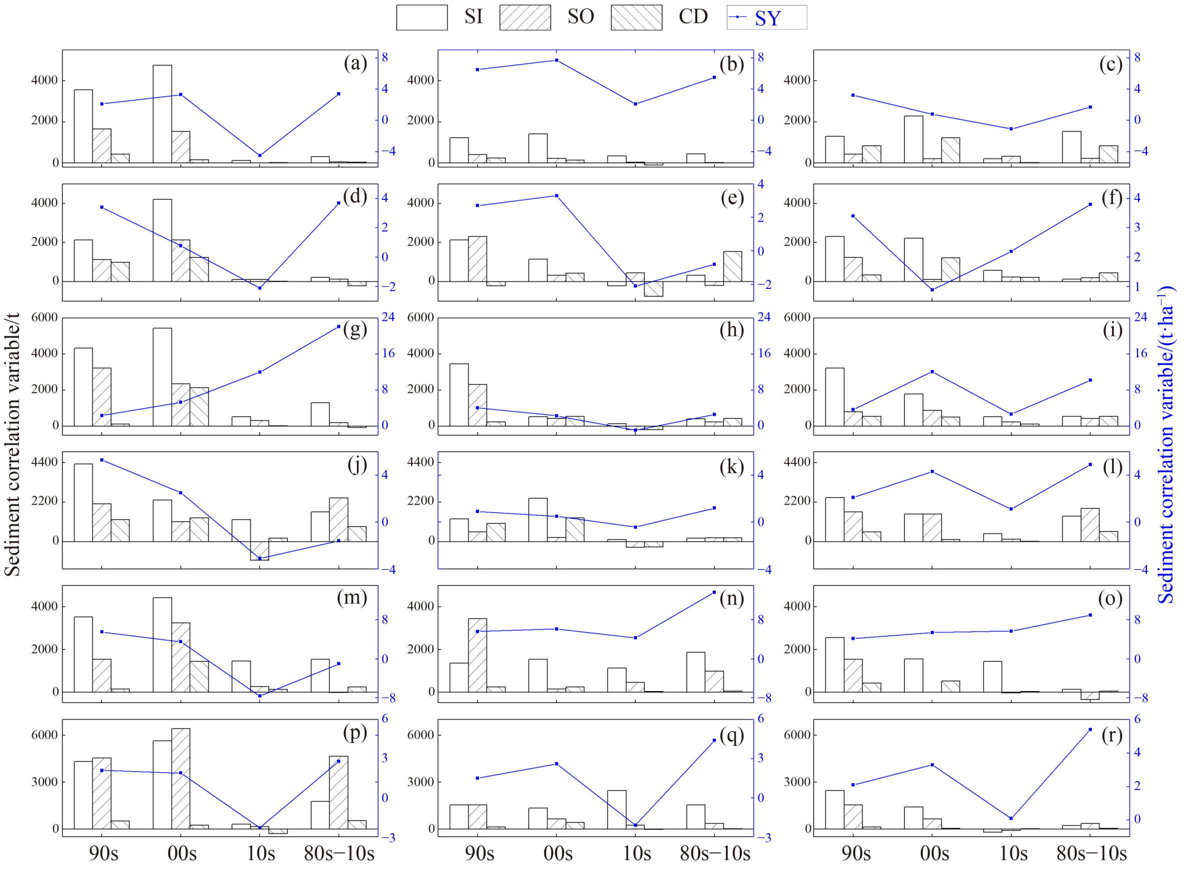

Fig. 6 Impacts of climate change and LUCC (a, d, g, j, m, and p) jointly, climate change only (b, e, h, k, n, and q), LUCC only (c, f, i, l, o, r) on sediment-related variables in the sub-basins of the Ziya River (a–c), Chaobai River (d–f), Nanyun River (g–i), Luanhe River (j–l), Yongding River (m–o) and Daqing River (p–r).

The LUCC impact on SI and SO was the largest in the Nanyun River (2980.3 tons) and the Yongding River (1973.5 tons) in the 1990s, followed by the Nanyun River and the Yongding River in the 2000s (Figs. 6(i) and 6(o)), whereas the lowest was in the Ziya River in the 2010s (Fig. 6(c)). The impact of LUCC on SY was the highest in the Nanyun River Basin in the 1990s, with an increase of 9.3 tons/ha and the lowest was in Chaobai River Basin in the 2000s (−1.9 tons/ha) (Figs. 6(f) and 6(i)). LUCC had the lowest impact on CD (Fig. 6(f)).

The joint impacts of climate change and LUCC were the highest in the 1990s and 2000s, but lower in the 2010s; The impacts were the highest in the Daqing and the Nanyun River Basins and the lowest in the Ziya and Luanhe River Basins (Figs. 6(a), 6(g), 6(j), and 6(p)). The impacts of climate change and LUCC were the highest on SI and SO, which showed an upward trend, but they had little impact on CD.

3.5 Impacts of land use and climate change on N and P in the Haihe River Basin

The impacts of climate change and LUCC (Figs. 7(a), 7(d), 7(g), 7(j), 7(m), and 7(p)), climate change only (Figs. 7(b), 7(e), 7(h), 7(k), 7(n), and 7(q)) and LUCC only (Figs. 7(c), 7(f), 7(i), 7(l), 7(o), and 7(r)) on the related variables of N and P in the six sub-basins are shown in Fig. 7. Over the past 40 years, climate change had the highest impact on ON and OP in the Chaobai River Basin (62.8 kg/ha and 87.6 kg/ha, respectively) (Fig. 7(e)), but the lowest in the Ziya River Basin (10.3 kg/ha and 8.5 kg/ha, respectively) (Fig. 7(b)). The highest interdecadal impact was found in the Luanhe River Basin (59.3 kg/ha and 53.5 kg/ha, respectively) in 2010s (Fig. 7(k)) and the lowest in the Ziya River (10.8 kg/ha and −2.1 kg/ha, respectively) in 1990s (Fig. 7(b)). Climate change had the lowest impact on the amount of NS and lateral flow NL. NS ranged from –2.9 to 4.4 tons/ha, which was relatively large in the Nanyun River Basin (Fig. 7(h)). NL ranged from –2.0 to 3.0 tons/ha, which was relatively large in the Chaobai River Basin (Fig. 7(e)).

LUCC had the highest impact on ON and OP in the Luanhe River Basin (Fig. 7(l)), but the lowest in the Ziya River (Fig. 7(c)) over the past 40 years. The highest interdecadal impact was found in the Nanyun River Basin (80.3 kg/ha) (Fig. 7(i)) in the 1990s and the Chaobai River Basin (54.6 kg/ha) (Fig. 7(o)) in the 1990s, while the lowest was found in the Ziya River Basin (Fig. 7(c))

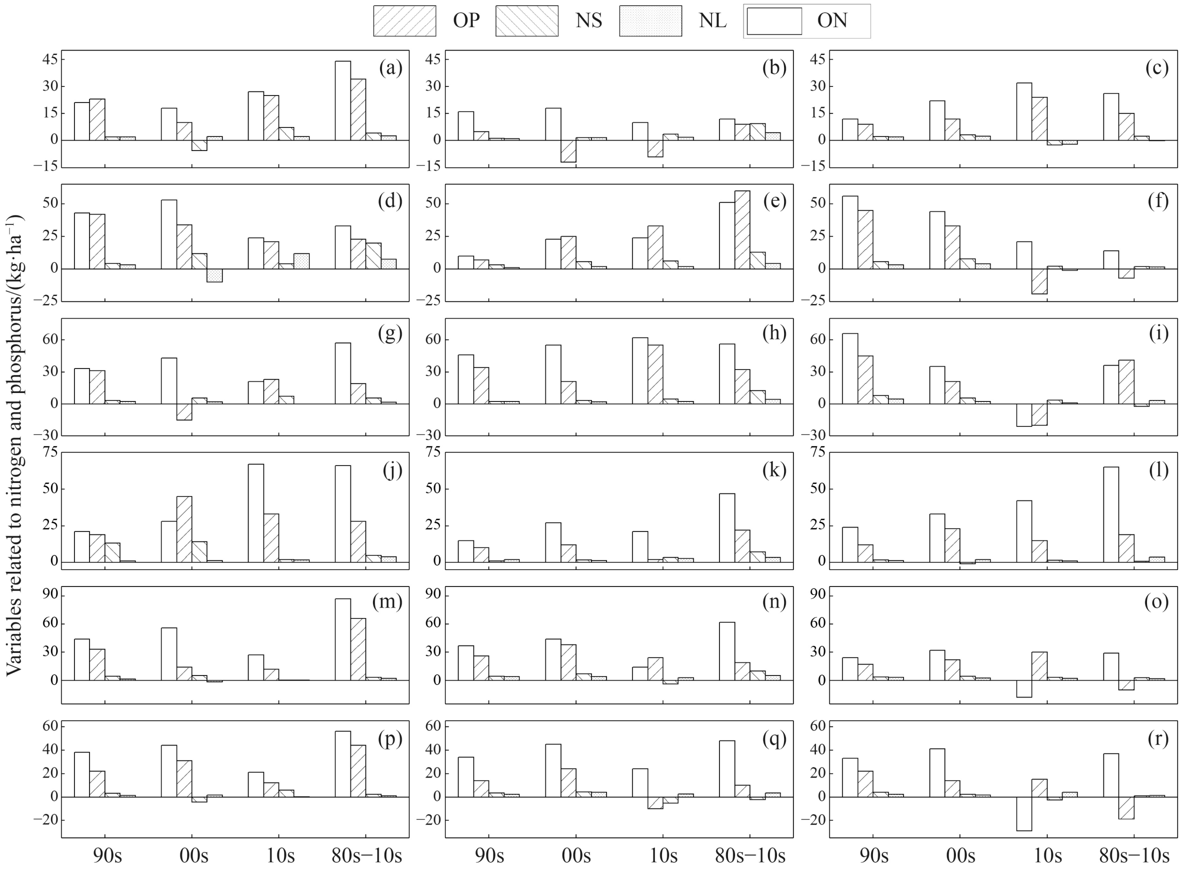

Fig. 7 Impacts of climate change and LUCC (a, d, g, j, m, and p) jointly, climate change only (b, e, h, k, n, and q) and LUCC only (c, f, i, l, o, and r) on N and P related variables in the sub-basins of the Ziya River (a–c), Chaobai River (d–f), Nanyun River (g–i), Luanhe River (j–l), Yongding River (m–o) and Daqing River (p–r).

in the 2010s. LUCC had the lowest impact on NS and NL. NS varied from −10.3 to 21.9 kg/ha and was most obvious in the Chaobai River Basin (Fig. 7(f)). NL ranged from 10.9 to 20.1 kg/ha and was most obvious in the Nanyun River Basin (Fig. 7(i)).

Climate and LUCC had a higher impact on ON and OP than that on NS and NL. The change was the highest in the Yongding River Basin and lowest in the Ziya River Basin (Figs. 7(a) and 7(m)). The ON and OP in all six sub-basins showed an increasing trend, indicating that climate warming and LUCC may lead to rising N and P contents in the soil and thus to water pollution.

3.6 Contribution rate of climate change and LUCC to changes in runoff, sediment, N and P

The contribution rates of climate change and LUCC to changes in runoff, sediment, N and P are presented in Fig. 8. In terms of runoff, the contribution of climate change was dominant in the Daqing, Yongding and Nanyun Rivers. Its rate over the past 40 years reached 59.4%–97.6% in the Daqing River Basin, 55.7%–98.2% in the Yongding River Basin and 44.7%–88.6% in the Nanyun River Basin. Moreover, the contribution in the Daqing River Basin showed an increasing trend during the study period. In contrast, the runoff variation in the Chaobai and Ziya River Basins was mainly dominated by LUCC and its contribution rates were 79.2%–92.8% and 57.5%–88.6%, respectively; they grew during the study period.

For sediment, climate change had a more significant impact in the Daqing and Nanyun River Basins and its contribution presented a rising trend. The contribution rate in the Daqing River Basin reached 52.1%–83.3% and that in the Nanyun River Basin reached 42%–93.4%. However, in the Luanhe and Chaobai River Basins, LUCC had a higher contribution rate, up to 44.9%–77.3% and 57.3%–92.7%, respectively.

With regard to N and P, climate change had a higher contribution rate in the Luanhe and Nanyun River Basins, with a rising trend during the study period. The rate in the Nanyun River Basin was the highest, reaching 57.8%–92.1% for N and 62.5%–88.7% for P. LUCC had a higher contribution rate in the Yongding, Chaobai, Ziya and Daqing River Basins. The highest rate was in the Chaobai River Basin, reaching 55.8%–91.4% (for N) and 52.1%–88.6% (for P), respectively.

4 Discussion

4.1 Impacts of climate change and LUCC on hydrological characteristics, sediment, N and P

Previous studies have indicated that global warming will intensify the hydrological cycle, which may affect runoff

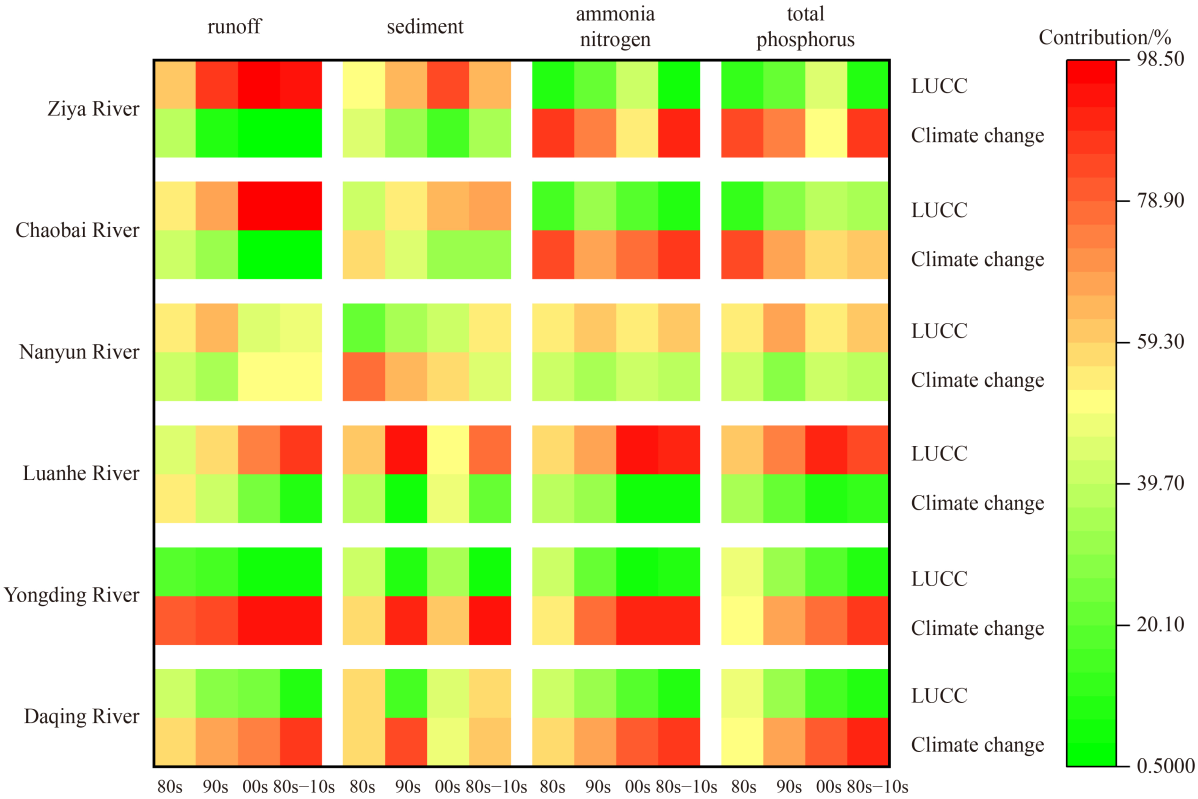

Fig. 8 Contributions of climate change and LUCC to runoff, sediment, and N and P losses over the past 40 years.

by increasing evapotranspiration and thereby affect the amount of sediment, N and P (Su et al., 2015; Wang et al., 2016). Meanwhile, it is expected that LUCC will continue in the future with a major impact on the regional water balance (Kundu et al., 2017). Land use, population growth and socioeconomic development continue to exert a huge pressure on water resources (Zhou et al., 2015). Therefore, the impacts of LUCC and climate change on runoff, sediment, N and P in the Haihe River Basin needed to be investigated.

In relation to the impacts on runoff-related variables, ET, TL and GW were most affected by climate change. Previous studies have indicated that climate change will affect water cycle processes and cause changes in ET, while changes in ET will also have an adverse impact on the climate locally and regionally (Wang et al., 2013). We found that the changes in ET, TL and GW over the past 40 years were closely related to temperature change in the Haihe River Basin, especially in the regions with more substantial temperature increases, such as the Daqing and Yongding River Basins. For example, in the Daqing River Basin with a large temperature change (Fig. 3(a)), ET (217.3 mm), TL (81.6 mm) and GW (83.7 mm) were affected substantially (Fig. 5(q)), while in the Chaobai River Basin with a small temperature change (Fig. 3(a)), the changes in ET (89.3 mm), TL (10.6 mm) and GW (−5.77 mm) were relatively small (Fig. 5(e)).

Although runoff was greatly affected by climate change, many areas in the Haihe River Basin had also experienced intensive human activities, such as agriculture, industry, domestic water withdrawal, LUCC, damming and reservoir operations, which can have a considerable impact on water resources (Wang et al., 2016; Zhai and Tao, 2017). In addition, human activities can directly and indirectly change the hydrological cycle (Chien et al., 2013). There was a land reform in approximately 1980 when the government began to encourage farmers to manage their resettlement land and to produce more food. As a result, the use of agricultural irrigation water increased (Yang et al., 2018). With the expansion of agricultural land, there was an increase in TL and GW owing to enhanced infiltration and in ET owing to flood irrigation (Luo et al., 2016). We found that changes in ET, TL and GW in the past 40 years were closely associated with LUCC in the sub-basins. For example, the substantial changes in the area of cultivated land in the Daqing River Basin (Fig. 4(f)) affected ET (268.3 mm), TL (123.4 mm) and GW (89.2 mm) to a great extent (Fig. 5(r)), while in the Chaobai River Basin rapid urbanization (Fig. 4(b)) had a relatively minor effect on ET (4.6 mm), TL (3.77 mm) and GW (9.5 mm) (Fig. 5(i)).

4.2 Adaptive strategies and options

The Haihe River Basin is densely populated and has many large and medium-sized cities, which plays an important role in China’s political economy. However, a series of environmental problems such as soil erosion, land desertification, groundwater overexploitation and water pollution are intensifying (Jian, 2016). Therefore, there is an urgent need to the study of the Haihe River Basin and to provide a reference for China’s water resource planning and management. This study indicated that the contributions of LUCC and climate change to basin hydrological change varied regionally owing to the heterogeneity of hydrological conditions. This suggested that different priorities for LUCC management and climate change adaptation should be made for different regions. For instance, with accelerating urbanization in the Chaobai River Basin, the increase in agricultural water use has absorbed most of the ecological water use. Currently, flood irrigation is the least efficient way to use water for agriculture, resulting in a significant waste of the limited water resources in the Haihe River Basin (Luo et al., 2016). To solve the problem of water shortages, some low productivity farmland should be transformed into grassland and some farming systems with high water consumption should be transformed into those with lower water consumption. This is consistent with the policy of converting farmland to grassland or forest in recent years (Wang et al., 2014; Jiang and Wang, 2016).

Owing to the impacts of climate change and human activities, the water resource problem in China is becoming increasingly serious (Hu et al., 2015). Since 2000, human activities have been the main reason for the problem (Jiang and Wang, 2016). In particular, the catchments located in the middle or lower reaches of river basins may be more susceptible to human influence than those located in the upper reaches (Liu et al., 2017). With the aims of not damaging the ecological environment or reducing the quality of people’s lives, the local government needs to take steps to protect the water resources in different catchments (Zhai and Tao, 2017). Considering the local situation, the ecological environment should be protected and urban overexpansion, deforestation, overgrazing and other unreasonable changes in land use/cover should be avoided, because they will impact water resources (Yuan et al., 2016).

4.3 Uncertainties of this study

In the current study, we used the SWAT model and factorial modeling experiments to assess the impacts of climate change and LUCC on the runoff, sediment and N and P losses in the Haihe River Basin during 1980–2019. Although the SWAT model performed reasonably in reproducing the runoff and hydrological processes in the Haihe River Basin, there were some uncertainties, particularly those caused by data shortages during the model simulations. First, the impacts of human activities and climate change on local hydrological conditions were complex. Water conservancy projects, such as reservoir, dams and irrigation areas, had a great impact on the hydrological processes in the middle and lower reaches of the Basin. The SWAT model and its parameterization could be modified to better account for the water conservancy projects and the reservoir characteristics. The dams and reservoirs were not included in the current modeling owing to a lack of data, resulting in some differences between the simulated and measured stream flows in the calibration and validation periods. Secondly, different human activities may exacerbate or cancel out each other. The interactions between human activities and climate change were also complex. For instance, in the Haihe River Basin, 30% of water was consumed by industry and domestic use. However, the impacts of these uses were not evaluated in the current study owing to the limitations of data and the model. Likewise, the impacts of the South-to-North Water Diversion were not included either. Finally, although SWAT can establish a model using different spatial resolutions of data, the difference in spatial resolution may have an effect on the model's final estimated results. For example, data with a coarse resolution may be less accurate in representing reality. Also, the mismatch among data with different resolutions may lead to uncertainties in the spatial location of the simulation results. However, previous studies have validated the SWAT model for reproducing simulating the water cycle, sediment and nutrient transport with limited data (Pechlivanidis et al., 2017). More data can be applied to improve the model simulations when they are available (Liu et al., 2021; Shi et al., 2021).

5 Conclusions

Most existing studies only focus on the impacts of climate change and LUCC on runoff and they rarely examine the effect on runoff, sediment, N and P losses comprehensively. To better reveal the impacts of climate change and LUCC in basins, taking the Haihe River Basin as an example, we first investigated the spatio-temporal aspects of climate change and LUCC in the Basin since 1980, then validated a SWAT model in the region and finally quantified the impacts of climate change and LUCC on runoff, sediment and N and P losses since 1980 through modeling experiments. We showed that climate change and LUCC had different impacts on runoff, sediment and N and P losses in the different sub-basins of the Haihe River. In general, climate change and LUCC reduced runoff, increased sediment in the river course and aggravated N and P losses in the Haihe River Basin. In terms of the impacts on runoff-related variables, ET was substantially affected and showed an upward trend generally. The total sediment input was also greatly affected. Among the N- and P-related variables, ON was affected the most. LUCC and climate change made different contributions to runoff, sediment and N and P change. The results of this study help to understand the driving factors affecting runoff, sediment and N and P losses in the Haihe River Basin and to provide evidence for the planning and management of water and land resources in the Basin.

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Appendices

Table S1 Inputs of the SWAT model

Data set	Data content	Resolution	Whether to consider (why?)
Chinese soil data set based on world soil database (hwsd)	Soil raster map Soil physical attribute table	1:1000000	Yes
Daily Value Dataset of China’s Surface Climate Data	Daily average temperature, precipitation, average wind speed, relative humidity and sunshine hours	1/60°	Yes
Hydrological Statistical Yearbook of Haihe River Basin	Monthly average flow rate, monthly average sediment concentration, monthly average suspended load transport rate, measured flow rate results table and other runoff and sediment data	/	Yes
DEM	DEM-30 GDEM	30 m	Yes
China Multi-period Land Use and Land Cover Remote Sensing Monitoring Dataset (CNLUCC)	1980, 1995, 2005, 2015 Remote sensing monitoring data of China’s land use status	1 km	Yes
Water quality monitoring section data of Beijing-Tianjin-Hebei China Statistical Yearbook Beijing-Tianjin-Hebei City, District and County-level Statistical Yearbook	NH3-N, TN, TP and nitrogen fertilizer and phosphate fertilizer application data	/	Yes
China’s administrative division data	China’s provincial administrative boundary data China’s administrative boundary data	/	Yes
China’s physical geographic area data	China’s nine major river basins	/	Yes
Soil data	Spatial distribution data of soil types, erosion and texture in China	1:1000000	Yes
	Reservoir and dam data	/	No (data limit)
	Overlapping effects of human activities	/	No (can’t evaluate)

Table S2 The R^2 and Ens in the calibration and validation of SWAT model in the six tributaries

Water system	Calibration variable	Calibration		Validation	
		R^2	Ens	R^2	Ens
LH	Runoff	0.9	0.9	0.8	0.8
DQ	Runoff	0.83	0.72	0.8	0.6
CB	Runoff	0.88	0.69	0.53	0.4
NY	Runoff	0.8	0.79	0.53	0.48
YD	Runoff	0.77	0.62	0.59	0.58
ZY	Runoff	0.79	0.6	0.54	0.4
LH	Sediment	0.74	0.7	0.7	0.7
DQ	Sediment	0.72	0.69	0.68	0.54
CB	Sediment	0.77	0.6	0.5	0.38
NY	Sediment	0.8	0.7	0.55	0.39
YD	Sediment	0.68	0.59	0.6	0.47
ZY	Sediment	0.6	0.61	0.58	0.53
LH	N	0.52	0.49	0.5	0.39
DQ	N	0.57	0.6	0.5	0.49
CB	N	0.66	0.6	0.36	0.35
NY	N	0.6	0.56	0.55	0.53
YD	N	0.6	0.58	0.5	0.38
ZY	N	0.58	0.49	0.44	0.27
LH	P	0.38	0.52	0.4	0.45
DQ	P	0.5	0.46	0.36	0.4
CB	P	0.44	0.42	0.32	0.35
NY	P	0.58	0.46	0.3	0.35
YD	P	0.6	0.56	0.48	0.4
ZY	P	0.52	0.44	0.37	0.25