RESEARCH PAPER

Impacts of land use and climate change on runoff in the Shaying River Basin based on SWAT model

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Abstract

In the past decades, land use pattern and climate conditions of Shaying River Basin have changed significantly, which will inevitably have a significant impact on the river hydrological situation. Therefore, in order to study the response of the hydrological cycle process of the Shaying River Basin to land use and climate changes, this paper constructed the Soil and Water Assessment Tool (SWAT) hydrological model of the Shaying River Basin based on historical meteorological and hydrological data, and conducted parameter calibration and model verification to quantitatively explore the response of the runoff of the Shaying River Basin to different land use and climate change scenarios. The results showed that: (1) In calibration and verification periods, the determination coefficients (R^2) were 0.80 and 0.83 respectively, the Nash–Sutcliffe efficiency coefficients (NSE) were 0.77 and 0.73 respectively, and the percentage deviation (PBIAS) was within $\pm 25\%$. (2) Setting different combinations of land use and climate changes into four scenarios S1, S2, S3, and S4, the simulated runoff depths were 257 mm, 298 mm, 259 mm, and 301 mm, respectively. The impacts of land use and climate changes on the annual runoff of Shaying River were 0.9% and 16.1% respectively. (3) In the scenario with 4 °C reduction and 20% precipitation increase and scenario 4 °C increase and 20% precipitation reduction, the maximum and minimum annual runoff were increased by 81.9% and decreased by 70.9% compared with the baseline period, respectively. (4) Under the seven scenarios, the precipitation, temperature and runoff in the middle and late 21st century showed an increasing trend, and precipitation will be the main controlling factor affecting runoff. The annual runoff depth showed an increasing trend, and the change of runoff depth in the lower reaches of the basin will be the most obvious.

Introduction

Under the dual impacts of climate change and land use change, the hydrological response of river runoff has become a research hotspot in hydrology and water resources discipline in recent years. (Ji et al. 2021; Jiao et al. 2020; Jin et al. 2019). Climate change directly or indirectly affects hydrological cycle and runoff formation process through precipitation, temperature, insolation, wind speed, relative humidity and other factors. The Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2021) pointed out that the current global average surface temperature is about 1 °C higher than that before industrialization, and the average increase in global temperatures in the next 20 years will be expected to reach or exceed 1.5 °C (Lynn and Peeva 2021; Fan et al. 2021). Global warming has led to more frequent extreme events such as extreme high temperature

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and extreme rainfall, which has increased the frequency and intensity of droughts and floods (Khan et al. 2018). At the same time, it has also affected the runoff and hydrological cycle process of the basin, changing the spatial and temporal distribution pattern of water resources (Xia et al. 2011; Zhang et al. 2017a, b). Land use change is the most direct manifestation of the interaction between human activities and the natural environment, mainly through affecting the conditions of vegetation interception, evapotranspiration, the filling of depressions, infiltration, and soil moisture status, which in turn affects runoff and hydrological cycle of the basin (Prestele et al. 2017; Prokesova et al. 2022; Wang et al. 2021). Moreover, the climate and the land use changes would have an impact on the river flow, and then affect the structure and function of the aquatic ecological systems, which involve a series of problems such as scientific planning and management of water and earth resources, and sustainable socio-economic development. Therefore, it is very important to study the characteristics and rules of the river flow under the changes of land use and climate.

At present, many researchers have already conducted relevant research on different watersheds and obtained substantial achievements (Lin et al. 2015; Wu et al. 2020; Rafee et al. 2021; Tian et al. 2021), while it is becoming clear that the combined effect resulting from the interaction of climate and land use changes most likely is not a simple sum of each individual effect (Chawla and Mujumdar 2015; Wang et al. 2014), because a complex response mechanism exists between them. The degree and speed of climate and land use changes vary among different watersheds, depending on soil types and the response of runoff to land use and climate changes (Tankpa et al. 2020; Wang and Kalin 2018). Therefore, to clarify the impacts of climate and land use changes on runoff in a certain basin, it will be necessary to quantitatively assess the change of runoff under different conditions.

Hydrological models are widely used in the assessment of impacts of climate and land use changes on runoff (Chen et al. 2016; Wu et al. 2017; De Girolamo et al. 2022; Brouziyne et al. 2021; Sharma et al. 2022; Idrees et al. 2022). Among them, the Soil and Water Assessment Tool (SWAT) has a strong physical foundation and computing ability, and has been widely used to predict the impacts of medium and long-term changes in soil, land use and climate changes on runoff, sediment and agricultural chemicals in large and complex watersheds (Chawla and Mujumdar 2015; Chen et al. 2020, 2023; Siderius et al. 2013; Dile et al. 2016; Ricci et al. 2022). For example, Zuo et al. (2016a, b) used SWAT model to quantify the impact of land use and climate changes on runoff and sediment in small watershed of the Loess Plateau and Giri et al. (2020) used SWAT model to find that future climate change will be the main factor to increase runoff and pollutant loads in the Southern New Jersey Watershed in the northeastern United States.

Shaying River Basin is located in Henan and Anhui Province of China. It is the largest tributary of Huaihe River, mainly in plain areas, and nearly 70% of the area is cultivated land, also an important grain production base in China. In order to prevent floods, develop and utilize water resources, some water conservancy projects were implemented to build a large number of reservoirs and sluices in the basin. In recent years, with the acceleration of population growth, economic development and urbanization, combined with the impact of global climate change, water resources related problems have become increasingly prominent, and river channels have been cut off or dried up (Luo and Zuo 2019; Zuo et al. 2016a, b). Therefore, in recent decades, many researches had been carried out for the runoff change and influencing factors of Shaying River Basin, but most of them analyzed the influence of meteorological factors or dam construction on runoff in historical periods, less comprehensive research had been conducted in combination with land use change (Dai et al. 2018), and there is also a lack of runoff prediction research under future climate change. Therefore, based on the SWAT model, we carry out the runoff simulation prediction under climate and land use changes in the Shaying River Basin. The specific objectives are: (1) To test the SWAT model for predicting hydrological processes in the Shaying River Basin; (2) Evaluate the impact of historical land use and climate changes on runoff in the Shaying River Basin; (3) Based on the land use data of 2015, analyze the changes in runoff of the Shaying River under hypothetical climate change scenarios and global climate model scenarios.

Data and methods

Study area

Shaying River Basin (32°29′ N to 34°57′ N and 111°56′ E to 116°31′ E) in the eastern region of China, which is composed of the largest tributary on the left bank of the Huaihe River and formed by the confluence of the Shahe and Yinghe rivers, originates from Lushan County, Henan Province, and flowing into the Huai River in Yingshang County, Anhui Province. The Shaying River, originating from Shaying River, is 621.2 km long and drains a catchment area of 39,075 km². The upper, middle, and lower reaches boundary points are as follows, respectively: Above the junction of the Jialu River into the Shaying River Basin (including the Jialu River Basin) is the upper Shaying River Basin; From the junction of the Jialu River into the Shaying River to Fuyang Sluice forms the middle reaches; Fuyang Sluice to Shaying River Estuary makes up the lower reaches (Zuo et al. 2016a, b).

The Shaying River Basin has a warm temperate semi-humid continental climate, which is droughty in winter and spring, hot and rainy in summer and autumn. The average annual temperature is 14–16 °C, and the average annual precipitation is 600–900 mm. The spatial–temporal gradient of precipitation changes greatly across the landscape, decreasing gradually from southeast to northwest. The annual precipitation in rainy years is three to five times higher than that in drought years, and the precipitation from June to September accounts for about 60% of the annual precipitation.

To mitigate the threat of floods and meet the growing demand for water resources, a large number of gate dams and reservoirs have been built in the basin. Large reservoirs mainly include the reservoirs known as Baiguishan, Baisha, Zhaopingtai, and Gushitan, while sluices mainly include Zhoukou and Huaidian (Fig. 1).

Data sources

The basic data required for model construction included the DEM (digital elevation model), data related to land use and soil, and hydro-meteorology. The DEM data was the statistical data of 2000, which was derived from geospatial data cloud (http://www.gscloud.cn/) with a resolution of 90 m × 90 m. The land use data was the statistical data of 1980 and 2015, which was derived from the land use data of the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) with a resolution of 1 km × 1 km. Soil data for 2009 were collected from the Harmonized World Soil Database (http://www.fao.org/) with a resolution of 1 km × 1 km. The hydro-meteorological data used in this study included wind speed, temperature, solar radiation, precipitation, and relative humidity data, which were obtained from the National Meteorological Science Data Center (http://data.cma.cn). The daily hydro-meteorological data, taken from 1960 to 2019, were collected from five basic national hydro-meteorological stations: Zhengzhou, Xuchang, Xihua, Baofeng, and Fuyang. The daily streamflow data from 1980 to 2018, obtained from the Shaying River Basin Authority for the three hydrological stations of Luohe, Zhoukou, and Huaidian, were used for calibrating as well as validating the SWAT model.
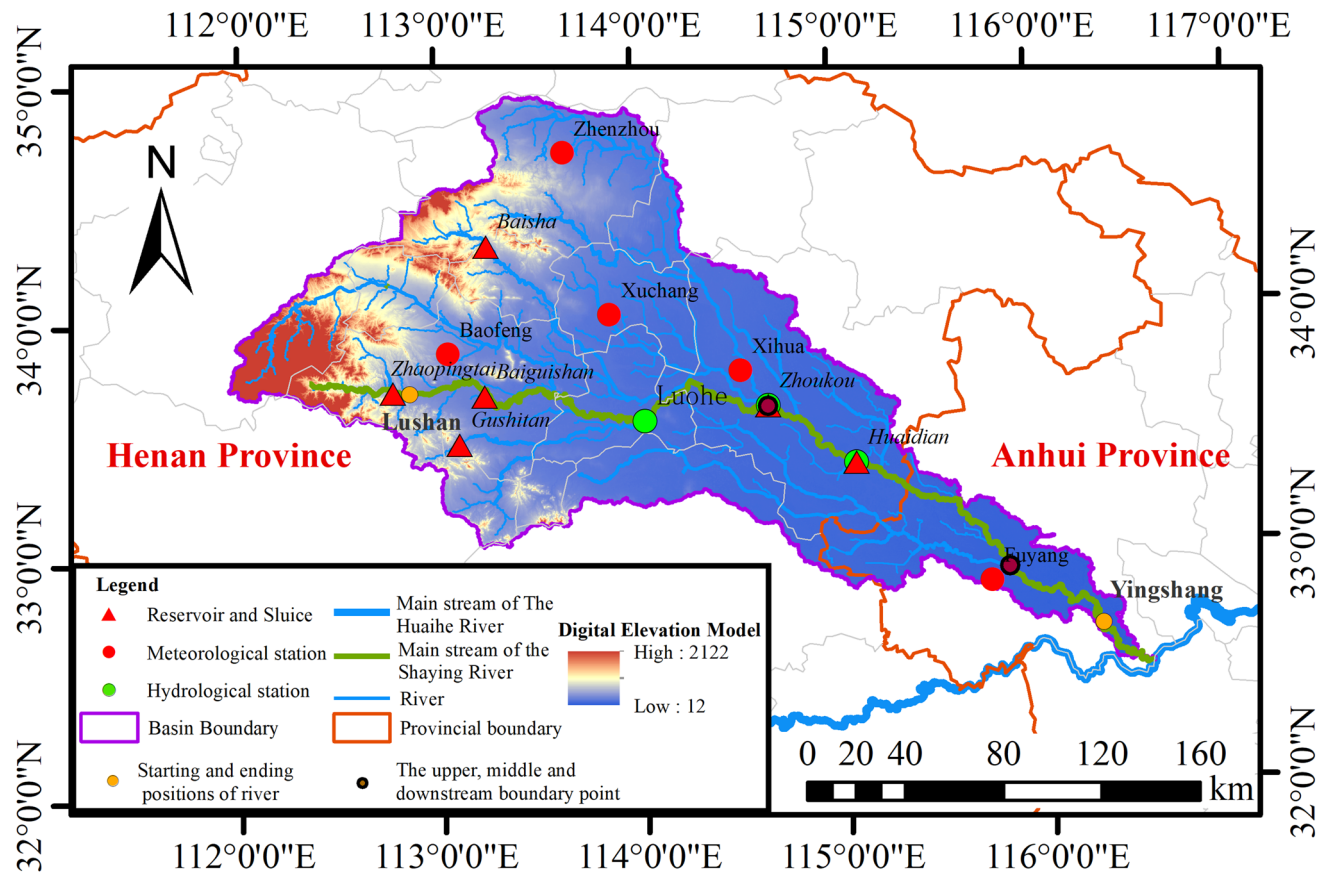

Fig. 1 A digital elevation model (DEM) in Shaying River Basin and Gate Dam Location Diagram

Model construction

Principle of the SWAT model

SWAT model is a long-term distributed hydrological model based on physical process. The model can integrate climate scenarios and underlying surface factors of the basin, and reflect the real natural abiotic factors of the basin in combination with soil type, land use mode and digital elevation information. It can simulate the runoff change process of a long time and large scale complex basin (Ridwansyah et al. 2020; Zhang et al. 2022; Chordia et al. 2022). Based on the water balance formula, the model combines land use, soil type and slope, and divides a watershed into several sub watersheds and Hydrological Response Units (HRUs), through the analysis of canopy interception, infiltration, redistribution, evapotranspiration, interflow, surface runoff, subsurface runoff, and return flow of water in the unit, the water cycle processes are calculated individually for each hydrological unit; next, the hydrological response units and sub-basins are connected through the calculation of slope-based runoff yield, confluence, and river network confluence to simulate runoff for an entire basin. The water balance formula used in the model is as follows:

$$SW_i = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad (1)$$

where SW_i represents the final soil moisture content, mm; SW_0 is the initial soil moisture content on day i, mm; t represents time, d; R_{day} is the precipitation on day i, mm; Q_{surf} is the surface runoff on day i, mm; E_a is the evaporation on day i, mm; W_{seep} stands for the amount of seepage flow and bypass flow leaving the bottom of the soil profile on day i, mm; and Q_{gw} is the amount of water returned on day i, mm.

Terrain and the treatment of the gate dams

Shaying River basin is dominated by plain terrain (Fig. 2a). The plain terrain is flat and interlaced, and the river extracted from DEM cannot be completely consistent with the actual situation, so the basin terrain needs to be treated during model construction to ensure that the river network under the plain terrain of the basin is reasonable (Gan et al. 2021). The processing steps are as follows: (1) River network file is superimposed into DEM through the (burn in) function, which can be more consistent with the actual river water system, while conducive to the model of hydrological division and sub-basin boundary extraction; (2) The threshold value of sub-watershed area is adjusted to an appropriate value: the minimum, maximum and recommended sub-watershed areas are given by calculating the filling depression and flow

direction of DEM. The appropriate threshold value determines the appropriate river network fineness and number of sub basins, so that there will not be many tributaries and sub-watersheds that are inconsistent with the actual situation and maintain a high simulation accuracy. In this study, we compared the extracted water system map with the actual water system map by importing the river network files and setting different sub-basin areas thresholds, and finally concluded that when the number of sub-basins was 51, the extracted water system would be more consistent with the actual water system. The water system and the sub-basin division diagrams were shown in Fig. 2b.

The Shaying River Basin has many gate dams. The SWAT model can simulate the impact of reservoirs on the water cycle by adding reservoir as an independent unit to the outlet of the corresponding sub-basin. Each sluice can be regarded as a river type of reservoir, characterized by both river evolution and weak reservoir regulation and storage. Therefore, the simulation of the regulation and storage of water flow in each sluice can allow researchers to draw lessons from the concept of the regulation and water storage of reservoirs; that is, the water first performs the confluences calculation in the river and flows into a virtual reservoir, and then, it flows out through the regulation and storage systems of the virtual reservoir (Gan et al. 2021). We collected monthly outflow data for four reservoirs (Baisha, Zhaotai, Baiguishan, and Gushitan) and two sluices (Zhoukou and Huaidian), four of which were located in the upper reaches of the Shaying River Basin, and two were located in the middle and lower reaches.

Parameter sensitivity analysis, model calibration and verification

In the process of SWAT hydrological model construction, the SWAT-CUP was used for the sensitivity analysis and for the calibration (Qi et al. 2020). The significance of each parameter is evaluated by t-test and is evaluated by sensitivity indicators t-Stat and *P*-value (Li et al. 2018; Abbaspour et al. 2015). *P*-value is the significance of t-Stat. The *P* value closes to 0 with the increasing t-Stat, which means that the parameter sensitivity is strong. Select the sensitive parameters that affect runoff, iterate several times in SWAT-CUP, and finally determine the parameter sensitivity ranking of runoff in the study area according to the t-Stat and *P*-value of each parameter.

After the sensitivity analysis, the parameters are selected to calibrate SWAT hydrological model with reference to the best simulation parameter values and recommended parameter range values to test whether the model can reflect the situation of the study area. The model needs to be preheated during the preheating period to exclude the influence of parameter variables on the results (Chordia et al. 2022).
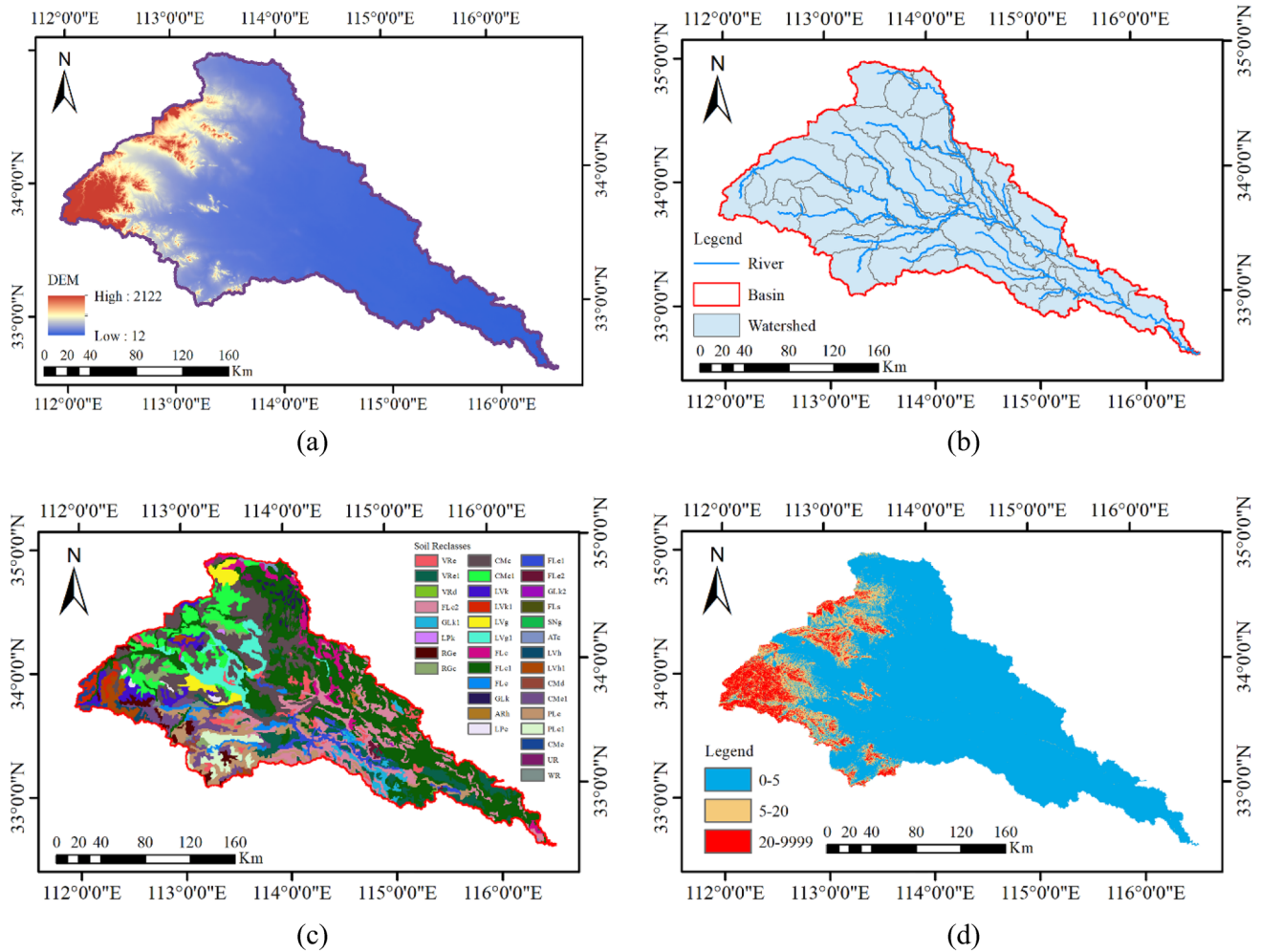
Fig. 2 The maps of **a** digital elevation model, **b** sub-basin divisions, **c** soil distribution, and **d** slope divisions in the Shaying River Basin model

The determination coefficient (R^2), Nash–Sutcliffe efficiency coefficient (NSE) and percentage deviation (PBIAS) were selected to evaluate the model simulation effect on monthly scale. The R^2 and NSE values close to 1 means that the model simulation effect is better (Bennour et al. 2022). In this study, it was considered that the runoff simulation results were qualified when $R^2 > 0.7$, $NSE > 0.6$, $|PBIAS| < 25\%$ (Gan and Chen 2021; Zhang et al. 2017a, b).

Scenario setting

Historical scenario setting

Combined with the analysis results of the evolution characteristics of water cycle factors in the Shaying River Basin (Han et al. 2020), it can be seen that the annual precipitation in the study area changed abruptly around 1982, annual average temperature began to change around 2001. Therefore, taking 2000 as the boundary, the meteorological data were divided into two periods of 1982–2000 and 2001–2019, and two periods of the land use data in 1980 and 2015. Different scenarios of land use and meteorological data were set (Table 1). Among them, the comprehensive impact of climate and land use changes on Shaying River runoff was obtained by comparing scenarios S1 and S4; the impacts of climate change on runoff were obtained by comparing scenarios S1 and S2; the impact of land use change on runoff was obtained by comparing scenarios S1 and S3.

Table 1 Scenario settings of different land use and climate data

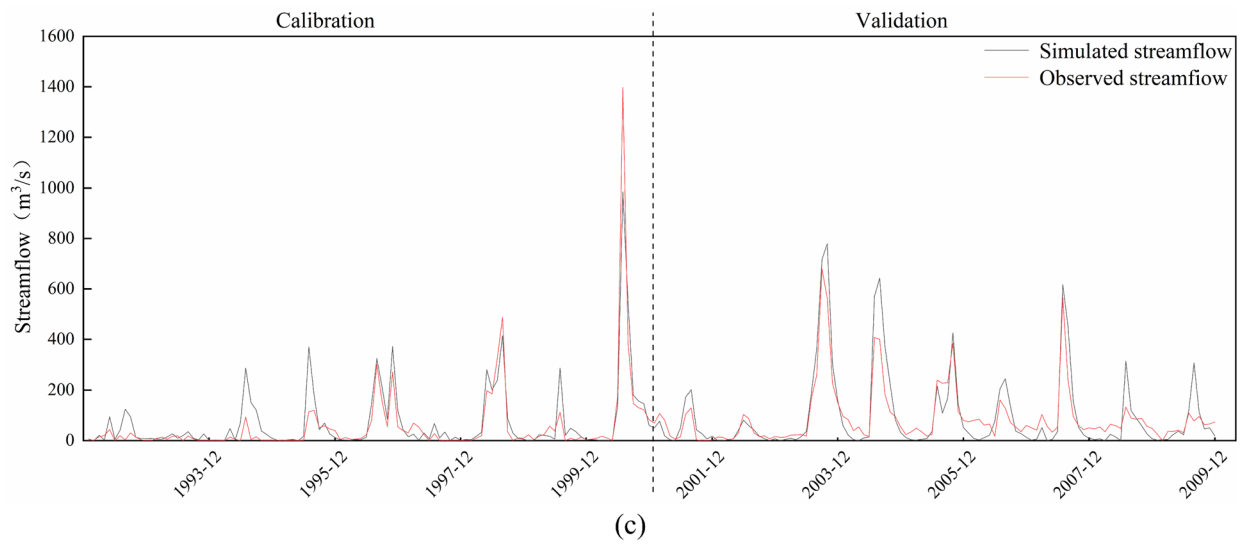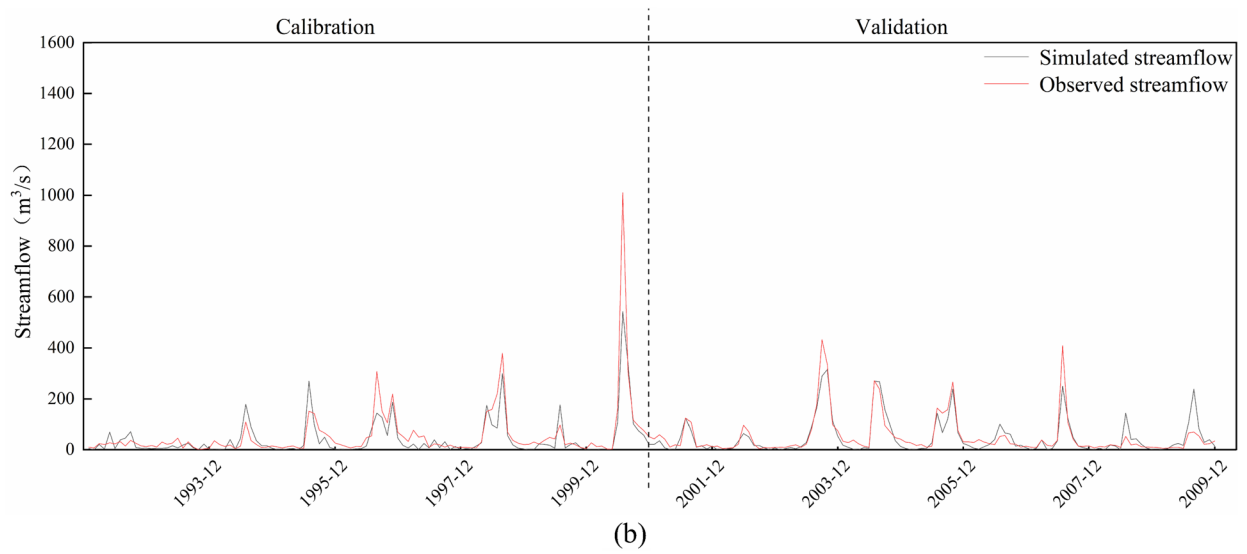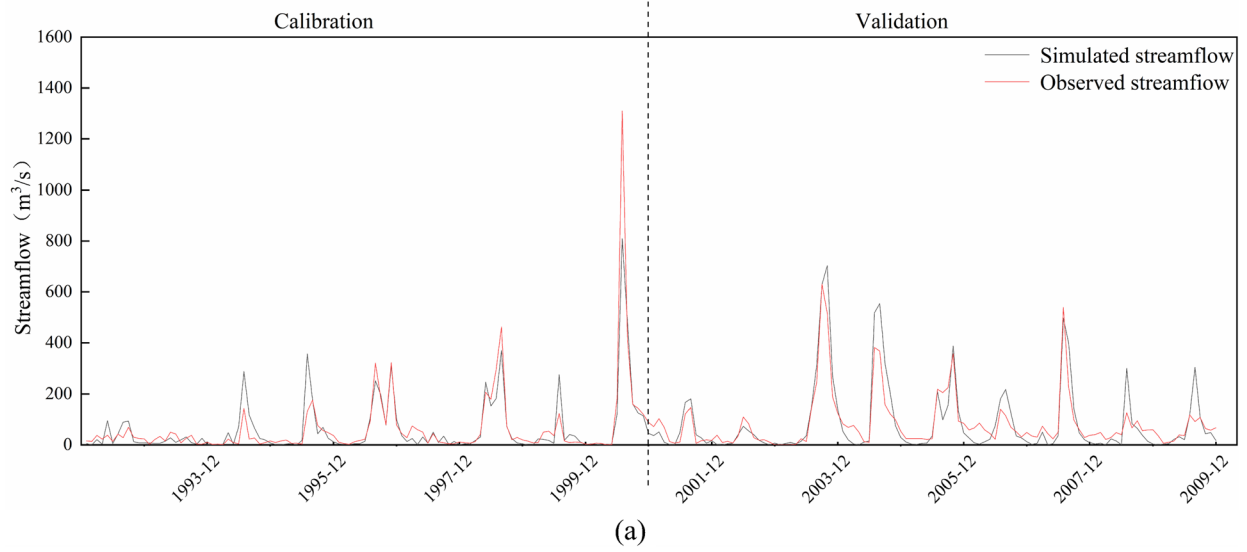| Scenario	Data type (year)		Scenario	Data type (year)	
	Land use	Meteorological		Land use	Meteorological
S1	1980	1982–2000	S2	1980	2001–2019
S3	2015	1982–2000	S4	2015	2001–2019

(a)

(b)

(c)

◀**Fig. 3** Comparison of simulated and observed monthly streamflow at the stations of **a** Zhoukou, **b** Luohe, **c** Huaidian; dashed lines represent the demarcation lines between calibration (1992–2000) and validation periods (2001–2009)

Climate change scenario setting

Different combinations of precipitation and temperature scenarios

Based on the daily average temperature and precipitation data from 1960 to 2019, we increased the temperature by − 4 °C, − 2 °C, − 1 °C, 1 °C, 2 °C, and 4 °C; increased the precipitation by − 20%, − 10%, 10%, and 20%; and obtained a total of 34 climate change scenarios by combining different climate factors with single factor change scenarios. Also, constant averages of daily average temperature and precipitation from 1960 to 2019 were used as the baseline period to compare the changes in streamflow at the basin outlet under different climate change scenarios.

Global climate model scenario

CMIP6 is the largest participation mode, the most perfect design and test, and the largest data provided since the implementation of CMIP plan. It improves the long-standing problems of model deviation and poor quantification of radiation forcing in CMIP5 (Eyring et al. 2016). Seven types of shared socio-economic path scenarios (SSPs) of five global climate models (CanESM5, IPSL-CM6A-LR, MIROC6, MRI-ESM2-0 and CNRM-ESM2-1) in the CMIP6 plan were selected, and the five climate models had good applicability in the Shaying River Basin (Jiang et al. 2020). The SSPs scenarios represent the possible development direction and situation of the future socio-economy under the influence of climate change and government-related policies (Eyring et al. 2019), mainly including SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0 and SSP5-8.5. The SSP1-1.9 and SSP1-2.6 belong to the low radiation forcing scenario, representing a sustainable development path. The SSP2-4.5 belongs to the medium radiation forcing scenario, representing the medium development path. The SSP3-7.0 belongs to the middle and high level forced scenario, representing the regional competition path. The SSP4-3.4 belongs to the low radiation forcing scenario, representing the unbalanced development path, and the SSP4-6.0 belongs to the medium emission scenario. The SSP5-8.5 belongs to the high radiation forcing scenario, representing the path dominated by traditional fossil fuels (O'Neill et al. 2014). Extraction of precipitation and temperature data from 2015 to 2200 under seven paths of CMIP6 climate model (https://esgf-node.llnl.gov/search/cmip6/), and it was divided into three stages in the short-term (2025–2040), mid-term (2055–2070) and long-term periods (2085–2000) of the twenty-first century to simulate the runoff response of Shaying River Basin under different future path scenarios.

Because the spatial resolution of CMIP6 is generally low, there will be a large deviation when describing regional small-scale climate information. Therefore, the Delta downscaling method was used to combine the climate model data with the reanalysis data of ground high-altitude resolution, so as to achieve spatial downscaling and improve data accuracy (Harris et al. 2014; Xu et al. 2017).

Results

Model calibration and validation

Based on the parameter sensitivity ranking in the process of model calibration, eight parameters were selected for runoff simulation, as follows specifically: surface runoff (CN2), groundwater (ALPHA_BF, GWQMN, GW_REVAP), soil evaporation (ESCO), and soil characteristics (SOL_AWC, SOL_K, SOL_Z). Among them, GWQMN (threshold depth in mm of water in the shallow aquifer required for return flow to occur) and CN2 (initial SCS runoff curve number for moisture condition II) are the most sensitive parameters affecting the Shaying River Basin. In addition, the groundwater related parameter (GW_REVAP) also has high sensitivity in the Shaying River Basin, which is the groundwater "revap" coefficient.

We selected 1990–1991, 1992–2000, and 2001–2009 as the preheating, calibration, and model validation periods, respectively. The SWAT model was calibrated and validated based on data from three hydrological stations, Zhoukou, Luohe, and Huaidian. Figure 3 and Table 2 showed that the simulated and observed values of the three stations match well. The R^2 and NSE for the calibration and verification periods were greater than 0.7 and 0.6, respectively, and |PBIAS| < 25%, indicating that there was good consistency between the simulated and observed monthly runoff in calibration and validation periods. Therefore, the model was applicable to the runoff simulation analysis in the Shaying River Basin.

Analysis of runoff responses to land use and climate changes

Land use change conditions

From Fig. 4 and Table 3, it can be seen that agricultural land accounts for the largest proportion (73.6% and 69.0% in 1980 and 2015, respectively) in the catchment of Shaying River Basin, followed by built-up area with 12.2%

Table 2 SWAT model performance for the calibration and verification of monthly runoff in the Shaying River Basin

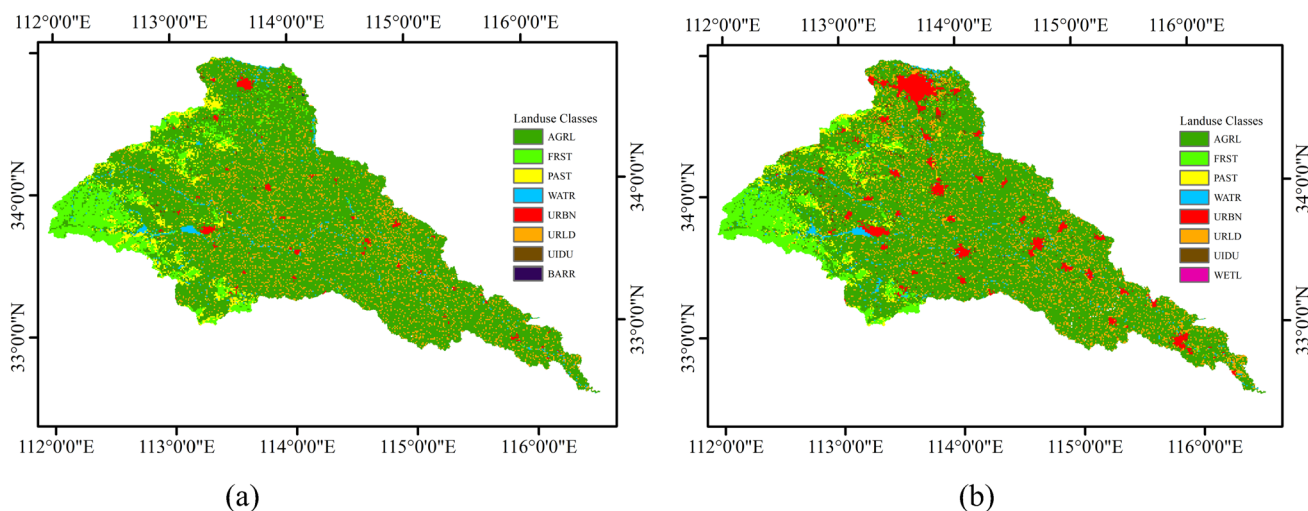| Station	Calibration (1992–2000)			Validation (2001–2009)		
	NSE	R^2	PBIAS (%)	NSE	R^2	PBIAS (%)
Zhoukou	0.81	0.83	− 6.4	0.72	0.84	2.1
Luohe	0.74	0.81	− 15.5	0.81	0.81	− 8.9
Huaidian	0.81	0.83	13.8	0.68	0.87	5.5

(a)

(b)

Fig. 4 Spatial distribution of land use in the Shaying River Basin in 1980 (**a**) and 2015 (**b**). Note: AGRL, agricultural land; FRST, forest land; PAST, pasture; WATR, water area; URBN, urban residential land; URLD, rural homestead (low density); UIDU, industrial land; WETL, wet land

Table 3 Land use change in the Shaying River Basin in 1980 and 2015

Land use types	1980		2015		1980–2015	
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Change in area (km^2)	Proportion (%)
Agricultural land	30,234.7	73.6	28,322.0	69.0	− 1912.7	− 4.6
Forest land	3439.4	8.4	3338.8	8.1	− 100.6	− 0.3
Pasture	1603.5	3.9	1160.6	2.8	− 442.9	− 1.1
Water area	658.1	1.6	768.5	1.9	110.4	0.3
Residential land (including low density)	5022.7	12.2	6924.3	16.9	1901.6	4.7
Industrial land	87.8	0.2	537.0	1.3	449.2	1.1
Unused land	6.2	0.1	1.2	0.0	− 5.0	− 0.1
Total	41,052.4	100	41,052.4	100		

and 16.9%, respectively, and the rest were forest land, grassland, water area, industrial land and unused land in descending order. With economic and social development and the acceleration of urbanization in recent decades, the proportion of agricultural land, forest land, grassland and unused land have decreased to a certain extent, while the proportion of other land have increased.

The spatial extent of residential land increased significantly in 2015 compared to 1980, by 4.6%, with an average annual increase of 52.8 km^2. This was caused by rapid economic development and population growth, while agricultural land, forest land, grassland, and unused land were also affected, with forest land and grassland decreasing in proportion by 1.4% over the past 36 years, with an average

annual decrease of 15.1 km². In addition, owing to the construction of gate dams and reservoirs in the basin, the water area increased to 768.5 km² in 2015.

Response of runoff to land use and climate changes

The rainfall and runoff processes of Shaying River Basin under S1-S4 scenarios were simulated respectively, and the annual average runoff depth changes of the basin were compared (Table 4). The runoff depths of scenario S1, S2, S3 and S4 were 257 mm, 298 mm, 259 mm and 301 mm respectively, and the conversion rates of precipitation to runoff were 34.3%, 38.5%, 34.6% and 38.9% respectively. Comparing between scenario S1 and S4, the comprehensive impact of land use and climate changes caused the annual runoff depth to increase by 44 mm, which increased by 17.1%. The comparison between scenarios S1 and S3, and between scenarios S2 and S4 showed that the average annual runoff depth caused by land use change decreases by 2 mm and 3 mm respectively with the same precipitation and temperature. The comparison between scenarios S1 and S2, and between scenarios S3 and S4 showed that the precipitation and temperature in 2001–2019 increased by 25 mm and 0.8 °C respectively compared with 1982–2000, and under the same land use conditions, the average annual runoff depth increased by 41 mm and 42 mm respectively. The impacts of land use and climate changes on annual runoff depth were 0.9% and 16.1% respectively, which meant that climate change has a greater impact on runoff.

Figure 5 shows the differences in annual average runoff depth under different scenarios in each sub-basin of the Shaying River. Figure 5a shows that the runoff depth of the catchment area of tributaries in the middle and upper reaches of the Shaying River Basin had an increasing trend, especially in the mainstream of the middle reaches, while the increase of runoff depth in the upper reaches in Zhengzhou were mainly caused by the rapid development of urbanization and the drastic changes in the underlying surface conditions. From Fig. 5b, one can see that an increasing trend was observed for runoff depth in the upstream region, and the runoff depth of the tributary confluence areas in the upper

and middle reaches changed drastically, and a significant impact on the runoff depth in the lower reaches of the main stream. Figure 5c shows that the runoff depth of the entire basin had an increasing trend, and the increase in the mainstream of the middle and lower reaches was the most obvious. Meanwhile, the variation trend in Fig. 5c was consistent with that in Fig. 5b, which indicates that the climatic conditions were the dominant factor affecting the runoff change in the Shaying River Basin.

Analysis of runoff responses to climate change

Runoff responses with single climatic factor

When the annual precipitation remained constant and temperature decreased by 4 °C, 2 °C, 1 °C or increased by 1 °C, 2 °C, 4 °C, the average annual streamflow in the Shaying River Basin increased by 20, 9, 7 m³/s or decreased by 7, 13, 21 m³/s, respectively (Fig. 6). Meanwhile, the difference of simulated average annual streamflow values versus that of the baseline period (1960–2019) ranged from −17.2% to 15.8%. The greater the variation in temperature, the greater the difference in streamflow. When the temperature remained constant and precipitation decreased by 20%, 10% or increased by 10%, 20%, the average annual streamflow decreased by 72, 41 m³/s or increased by 43, 109 m³/s, respectively; the difference of simulated average annual streamflow versus that of the baseline period ranged from −59.8% to 92.9%. When compared with the temperature, one can concluded that precipitation had a greater impact on streamflow of the Shaying River Basin.

Responses of runoff with multi-climate factors

It can be seen from Fig. 7 that the lower the temperature and the more the precipitation, the greater the annual average flow simulated, that is, the impact of rainfall and temperature on runoff was usually opposite. Among them, the simulated average annual streamflow under the combined scenario with the minimum temperature and maximum precipitation ($\Delta T = -4$ °C, $\Delta P = +20\%$) was the greatest, with

Table 4 Changes in runoff depth under land use and climate changes scenarios in the Shaying River Basin

| Scenario	Data type (year)				Average annual runoff depth (mm)	Changes in runoff depth under different scenarios (mm)		
	Land use	Meteorologicalcondition				Response to land use change	Response to climate	Comprehensive response to land use and climate
		Year	Precipitation (mm)	Temperature (°C)				
S1	1980	1982–2000	749	15.1	257	S3–S1 = 2	–	–
S2	1980	2001–2019	774	15.9	298	S4–S2 = 3	S2–S1 = 41	–
S3	2015	1982–2000	749	15.1	259	–	–	–
S4	2015	2001–2019	774	15.9	301	–	S4–S3 = 42	S4–S1 = 44
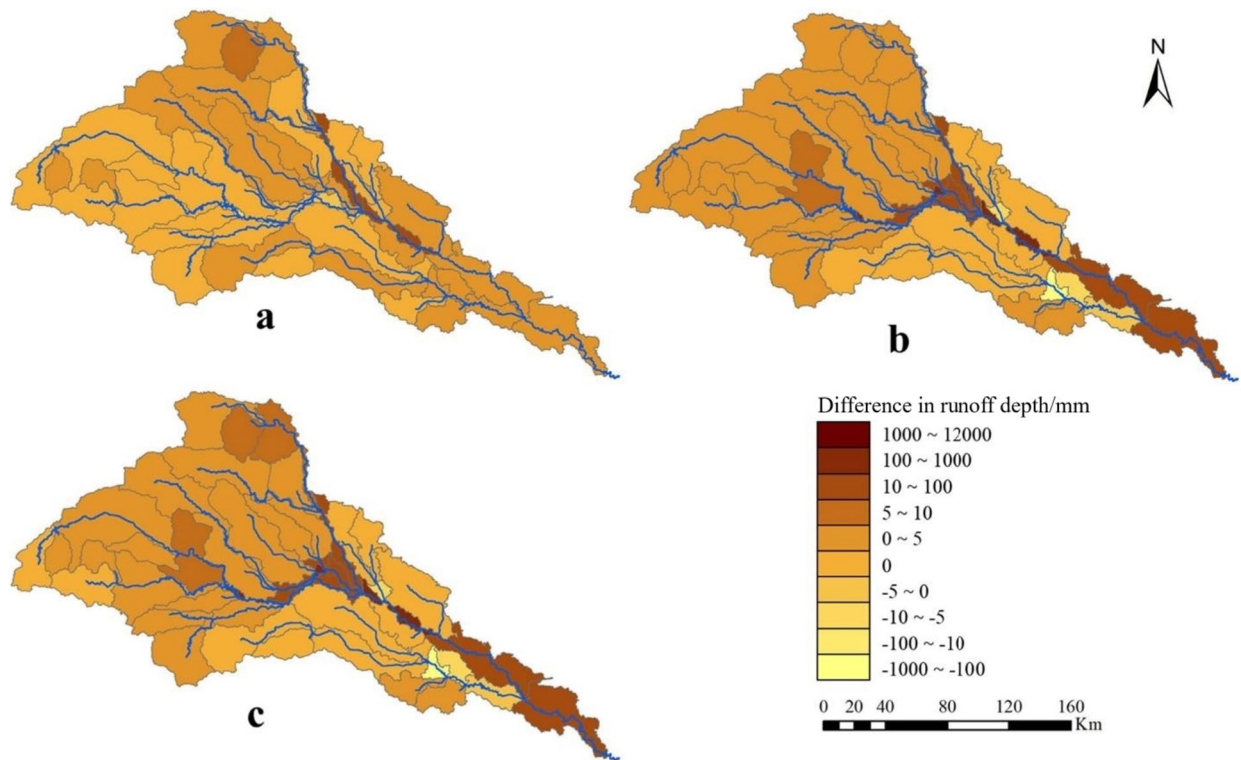
Fig. 5 Spatial distribution of average annual runoff depth under four change scenarios in the Shaying River Basin: **a** land use change scenarios (differences in average runoff depth between S1 and S3 as well as S2 and S4), **b** climate change scenarios (differences in average run-off depth between S1 and S2 as well as S3 and S4), and **c** integrated land use and climate change scenarios (difference in average runoff depth between S1 and S4)
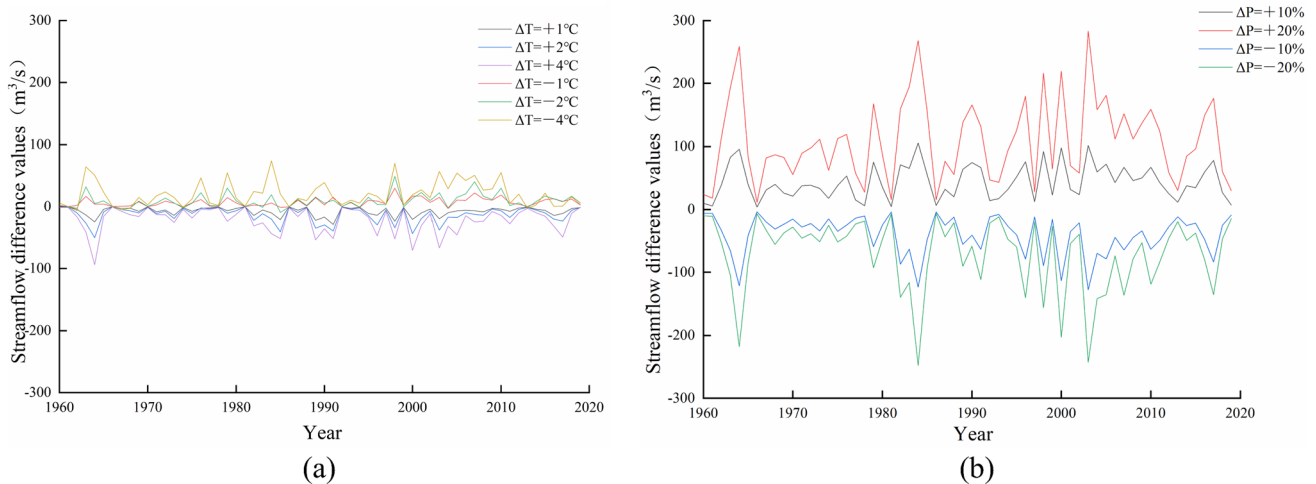

Fig. 6 Streamflow response to change in single climate factor, **a** temperature or **b** precipitation

a maximum increase of 324 m³/s (81.9%) compared to that of the baseline period (Fig. 7). When under another combined scenario (ΔT = 4 °C, ΔP = −20%), the average annual streamflow declined by 282 m³/s (70.9%) at most compared to the baseline period. The Shaying River Basin has high

temperature and rainy in summer, and low temperature and little rain in winter. Precipitation is an important supplement to annual runoff. However, the impact of temperature on runoff in winter and early spring is mainly through the melting of ice and snow in the basin, and the contribution to
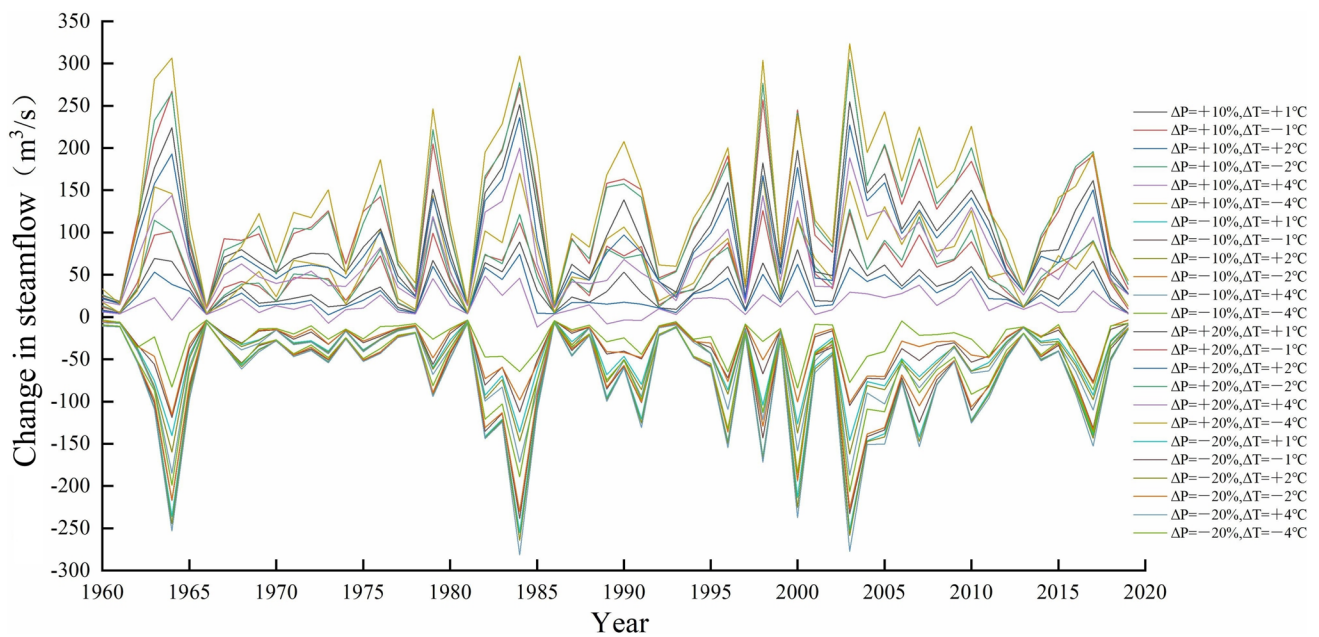
Fig. 7 Simulation result of 24 different climate scenarios on streamflow

runoff change in this season is greater than that of precipitation (Gu and Shan 2022).

Analysis of runoff responses to global climate model

Correlation analysis of climatic and hydrological elements under different scenarios

According to the global future climate scenario from 2015 to 2100, the monthly runoff changes in the Shaying River Basin

during the short-term (2025–2040), mid-term (2055–2070) and long-term periods (2085–2000) were simulated. And based on the historical climate development patterns from 1960 to 2019 (baseline), future monthly scale precipitation, temperature, and runoff were simulated according to the linear trend. The correlation between monthly precipitation, temperature and runoff depth in Shaying River Basin was calculated (Table 5). It can be seen from Table 5 that under the baseline and seven scenarios, precipitation showed an increasing trend over time, especially during the long-term

Table 5 The predicted values of average annual runoff depth, precipitation and temperature in Shaying River Basin from 2015 to 2100 with correlation coefficients between the runoff depth and the precipitation or temperature

		Baseline period	SSP119	SSP126	SSP245	SSP370	SSP434	SSP460	SSP585
P1 (2025–2040)	Runoff depth/mm	236.29	222.74	206.07	185.26	211.58	230.69	190.29
	Precipitation/mm	646.92	653	612	572	625	675	606
	Correlation		0.39*	0.25**	0.34	0.37	0.41**	0.51**	0.35
	Temperature /°C	16.2	16.9	16.9	17.1	16.2	16.3	16.3
	Correlation		0.17	0.24*	0.31	0.20	0.04*	0.25	0.24**
P2 (2055–2070)	Runoff depth/mm	243.23	210.85	296.17	249.92	236.87	242.96	236.44
	Precipitation/mm	673.93	627	728	678	659	666	687
	Correlation		0.45	0.50	0.63**	0.33*	0.47	0.43**	0.27
	Temperature /°C	16.9	16.9	17.0	17.2	17.3	17.3	17.1
	Correlation		0.23*	0.01*	0.29	0.15	0.25**	0.05	0.25*
P3 (2085–2100)	Runoff depth/mm	297.68	253.28	249.19	328.91	246.45	270.71	276.99
	Precipitation/mm	736.84	675	671	752	693	713	720
	Correlation		0.48**	0.36*	0.54**	0.58	0.60**	0.53**	0.44**
	Temperature/°C	17.2	16.3	16.6	17.5	18.5	17.7	18.0
	Correlation		0.25*	− 0.01	0.01*	0.24*	0.24	0.28	0.27**

*$P < 0.05$, **$P < 0.01$

period, in which four scenarios had an average annual precipitation of more than 700 mm. A strongly positive correlation existed between precipitation and runoff depth.

Under the baseline, the temperature increased with time and reached the maximum of 17.2 °C during the long-term period; And there was a maximum temperature during the mid- and long-term periods of the SSP585 scenario, with values of 18.0 °C and 19.9 °C, respectively, indicating that the temperature will increase significantly under the high radiative forcing. Except for SSP1-1.9 and SSP1-2.6 scenarios, the temperature under other scenarios showed an increasing trend over time. The correlation between temperature and runoff depth in each period was not significant and smaller than the correlation between precipitation and runoff depth. Therefore, the main controllng factor of annual runoff in Shaying River Basin is precipitation, and the temperature mainly affects the runoff by affecting evapotranspiration and ice-snow melting.

Analysis on variation trend of runoff depth under different scenarios

Comparing the simulated monthly runoff depth during the three periods under seven scenarios with the simulated baseline monthly runoff depth based on the continuation of historical climate development laws, spatio-temporal variations

in runoff depth in the Shaying River Basin are shown in Table 6 and Fig. 8.

With the combined effects of precipitation and temperature, the depth of runoff under seven scenarios was predicted to increase significantly from February to May, and decreased obviously from July to October. In the short-term, the maximum rate of increase in runoff depth occurred in February under the SSP126 pathway scenario, reaching 400%. Meanwhile, the minimum increase occurred in October under the SSP245 pathway and August under the SSP370 pathway, reaching −81%. In the long-term, the increase rate of runoff depth from February to May was more obvious than that in the short- and mid-terms, by as much as 835%. Meanwhile, the reduction in runoff depth from July to October was smaller than that in the short- and mid-terms. Therefore, there may be a trend of increasing runoff depth in the Shaying River Basin in the future.

Under the future global climate scenario, the runoff depth in the mainstream area of the basin was predicted to increase and that in the non-mainstream area was predicted to decrease under the seven pathways, and the degree of decrease was predicted to be smaller than that of the increase (Fig. 8). In the catchment area of tributaries in the middle and upper reaches of the basin, the runoff depth was predicted to change significantly, while the runoff depth in the middle and lower reaches of the mainstream also was also predicted to increase significantly. Under the same pathway,

Table 6 Monthly and long-term variations in runoff depth in the Shaying River Basin under the seven SSP scenarios

| Term	Scenario	January	February	March	April	May	June	July	August	September	October	November	December
P1 (2015–2040)	SSP1-1.9	56%	274%	154%	79%	110%	−6%	−39%	−65%	−61%	−38%	−39%	−25%
	SSP1-2.6	−5%	400%	235%	82%	86%	13%	−47%	−26%	−42%	−71%	−44%	−43%
	SSP2-4.5	−70%	223%	201%	162%	153%	45%	−61%	−44%	−64%	−81%	−81%	−49%
	SSP3-7.0	−28%	243%	255%	234%	197%	−14%	−69%	−81%	−80%	−60%	−56%	−11%
	SSP4-3.4	−38%	316%	87%	221%	244%	43%	−51%	−37%	−31%	−69%	−66%	−43%
	SSP4-6.0	−22%	142%	345%	118%	25%	−28%	−66%	−65%	−52%	−68%	−70%	−39%
	SSP5-8.5	8%	321%	365%	176%	151%	156%	−56%	−67%	−76%	−72%	−62%	−45%
P2 (2055–2070)	SSP1-1.9	−36%	179%	470%	107%	135%	−16%	−73%	−59%	−70%	−59%	−57%	−12%
	SSP1-2.6	2%	498%	198%	158%	232%	59%	−43%	−45%	−41%	−40%	−52%	−10%
	SSP2-4.5	−2%	482%	431%	262%	317%	−6%	−35%	−61%	−36%	−58%	−56%	−44%
	SSP3-7.0	−47%	293%	217%	133%	177%	−6%	−55%	−8%	−46%	−47%	−26%	−30%
	SSP4-3.4	−18%	414%	349%	267%	192%	−53%	−9%	−52%	−49%	−45%	−13%	65%
	SSP4-6.0	−6%	360%	332%	263%	56%	97%	−32%	−66%	−74%	−61%	−56%	−41%
	SSP5-8.5	−56%	498%	299%	288%	180%	243%	−40%	−52%	−54%	−67%	−79%	−45%
P3 (2085–2100)	SSP1-1.9	26%	551%	264%	165%	140%	7%	−48%	−65%	−74%	−47%	2%	93%
	SSP1-2.6	−10%	404%	504%	345%	197%	16%	−62%	−71%	−68%	−52%	−41%	39%
	SSP2-4.5	−3%	691%	835%	320%	305%	243%	−36%	−4%	−26%	−51%	−55%	−5%
	SSP3-7.0	−16%	183%	602%	170%	220%	177%	−29%	−40%	−37%	−65%	−51%	4%
	SSP4-3.4	107%	466%	301%	215%	158%	16%	−32%	−41%	6%	−56%	−32%	61%
	SSP4-6.0	29%	644%	368%	236%	287%	114%	−48%	−6%	72%	−33%	1%	22%
	SSP5-8.5	37%	538%	563%	282%	204%	50%	−35%	−16%	−47%	−62%	−45%	38%
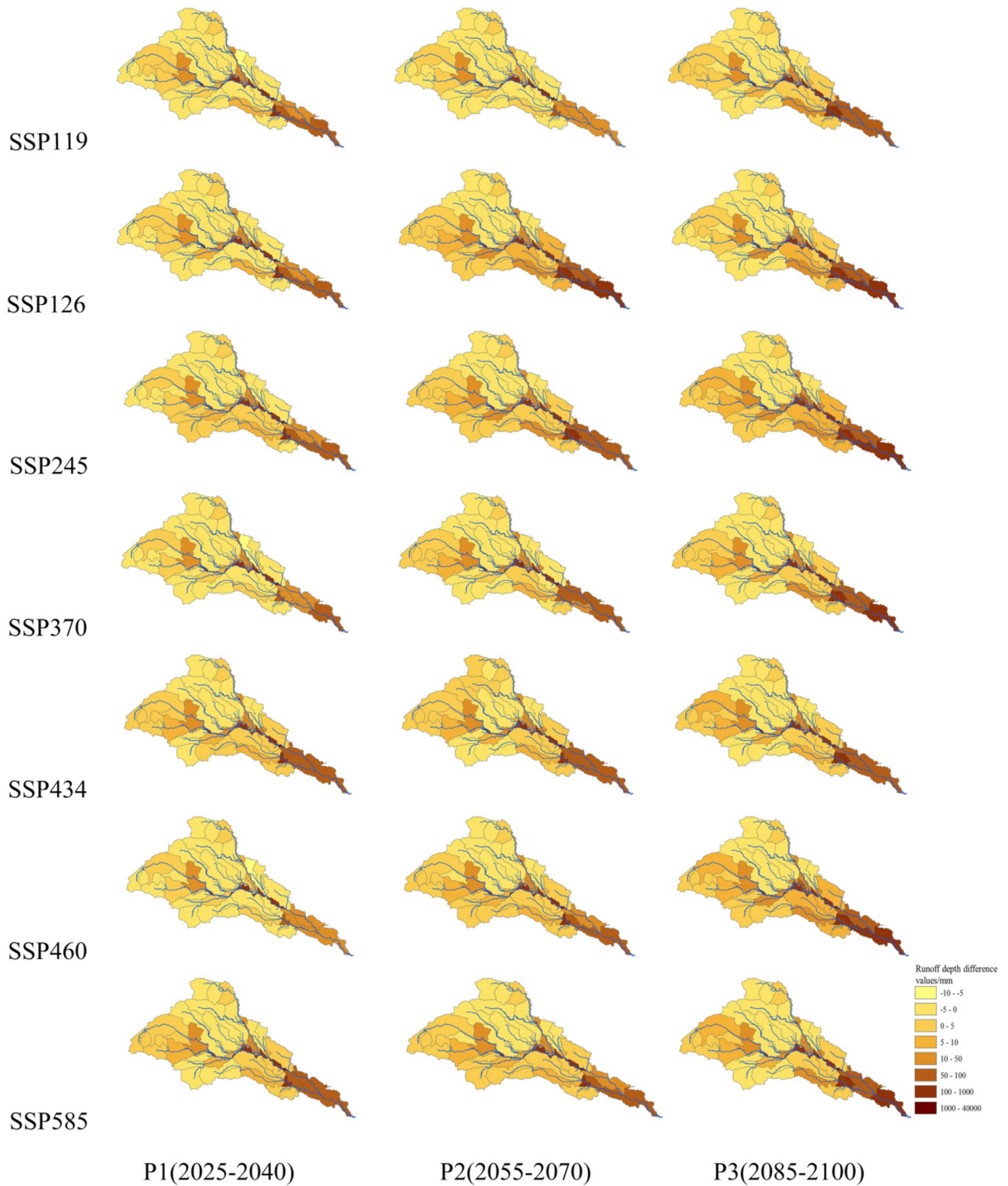
Fig. 8 Spatial variation in runoff depth change under seven SSP scenarios in the Shaying River Basin. Note: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, and SSP5-8.5 represent seven types of the shared socioeconomic pathway scenarios; P1, P2, and P3 represent short-, mid-, and long-terms, respectively

the predicted long-term change in runoff depth was more obvious. In the short-term, the predicted runoff depth under the SSP585 and SSP434 pathway scenarios changed more significantly than that under the other pathway scenarios, and the increase occurred mostly in the downstream region. In the mid-term, the change under the SSP126 pathway scenario was the most obvious, especially in the downstream region. In the long-term, the runoff under all seven pathway scenarios changed significantly when compared with that in the mid- and short-term simulations. Synthesizing the short-, mid-, and long-term situations, the areas with notable runoff changes were predicted to most likely be concentrated in the lower reaches of the Basin.

Discussion

Based on the historical meteorological and hydrological data in recent decades, this study applied the SWAT model to Shaying River Basin under the influence of gate dam discharge through the process of parameter surface perceptual analysis, calibration and verification. However, during modeling, only the discharge of large reservoirs and sluices with measured data was directly input into the model as reservoir flow data, neither considering the dispatching rule of reservoirs and sluice dams, nor processing the reservoirs without measured data. In order to better simulate the actual runoff process, it is necessary to further collect the relevant data of the dams and reservoirs in the basin, add them to the model. For different reservoirs without measured data, the scheduling rules that conform to their scheduling characteristics are set up and embedded in the SWAT reservoir module to further improve the simulation accuracy of the model and construct a SWAT model more suitable for the study basin.

The SWAT model showed an increasing trend of runoff under the influence of climate and land use changes in Shaying River Basin. The conversion of land use types has a great impact on water resource management and flood control. The increase of built-up area will increase the peak flow caused by rainstorm, advance the peak time and consequently increase the flooding risk, while the forest will function to intercept rainfalls, reduce the flood volume and thus slow down the flooding process (Prokesova et al. 2022; Tamm et al. 2018). In this paper, the reduction of agricultural land, forest land and grassland area and the increase of residential area all play an increasing role in runoff, which directly affect river ecosystems, water use and management.

In the response analysis of runoff to the future climate models, only precipitation and temperature were considered, while wind speed, humidity and sunshine hours and other climate factors were not considered. These climate factors are important for the water cycle, and their absence would reduce the accuracy of runoff simulation. And considering them will improve the accuracy of the simulation. Therefore, adding more climate factors that affect runoff simulation under future climate conditions, as well as considering government planning for land use, is the direction that needs further research.

Conclusions

1. R^2 and NSE in calibration and verification periods were 0.80, 0.83 and 0.77, 0.73 respectively, and PBIAS was within $\pm 25\%$. Therefore, the SWAT hydrological model was fitted well to on runoff simulation in Shaying River Basin.

2. During the historical period, the runoff depths under the four scenarios S1, S2, S3 and S4 were 257 mm, 298 mm, 259 mm and 301 mm respectively. The combined effects of land use and climate changes increased the average annual runoff depth by 44 mm, while land use changes (i.e., decrease in agricultural land and the increase in built-up area) reduced the average annual runoff depth by 2 mm and 3 mm, and precipitation and temperature changes increased the average annual runoff depth by 41 mm and 42 mm, respectively. The impacts of land use and climate changes on the average annual runoff of the Shaying River Basin accounted for 0.9% and 16.1%, that is, the impacts of climate change on the runoff was more obvious than land use change.

3. The greater the variation of precipitation and temperature, the greater the amplitude of runoff. The simulated annual average flow under the scenario ($\Delta T = -4$ °C, $\Delta P = +20\%$) was the largest with the maximum of 81.9% higher than the baseline period. Under the scenario ($\Delta T = 4$ °C, $\Delta P = -20\%$), the maximum annual average flow decreased by 70.9% compared with the baseline period.

4. In the future climate scenarios, the precipitation will be the main controlling factor affecting runoff. Toward the end of twenty-first century, the runoff will increase and advance, and the runoff depth in the main stream area of the basin will increase, while the runoff depth in the non-main stream area will decrease. The runoff changes in the lower reaches of the Shaying River basin will be the most significant in the future.

Data availability The data are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Compliance with ethical standards.

Consent to participate Not applicable.

Consent to publish All the authors have approved the submission and consented for the publication.

References

Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Klove B (2015) A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. J Hydrol 524:733–752. https://doi.org/10.1016/j.jhydrol.2015.03.027

Bennour A, Jia L, Menenti M, Zheng C, Zeng Y, Asenso BB, Jiang M (2022) Calibration and validation of SWAT model by using hydrological remote sensing observables in the Lake Chad Basin. Remote Sens 14:31. https://doi.org/10.3390/rs14061511

Brouziyne Y, De Girolamo AM, Aboubdillah A, Benaabidate L, Bouchaou L, Chehbouni A (2021) Modeling alterations in flow regimes under changing climate in a Mediterranean watershed: an analysis of ecologically-relevant hydrological indicators. Eco Inform 61:1–17. https://doi.org/10.1016/j.ecoinf.2021.101219

Chawla I, Mujumdar PP (2015) Isolating the impacts of land use and climate change on streamflow. Hydrol Earth Syst Sci 19:3633–3651. https://doi.org/10.5194/hess-19-3633-2015

Chen Y, Li J, Xu H (2016) Improving flood forecasting capability of physically based distributed hydrological models by parameter optimization. Hydrol Earth Syst Sci 20:375–392. https://doi.org/10.5194/hess-20-375-2016

Chen Q, Chen H, Zhang J, Hou YK, Shen MX, Chen J, Xu CY (2020) Impacts of climate change and LULC change on runoff in the Jinsha River Basin. J Geogr Sci 30:85–102. https://doi.org/10.1007/s11442-020-1716-9

Chen L, Xu YZ, Li S, Wang WZ, Liu GW, Wang MJ, Shen ZY (2023) New method for scaling nonpoint source pollution by integrating the SWAT model and IHA-based indicators. J Environ Manag 325:11. https://doi.org/10.1016/j.jenvman.2022.116491

Chordia J, Panikkar UR, Srivastav R, Shaik RU (2022) Uncertainties in prediction of streamflows using SWAT model-role of remote sensing and precipitation sources. Remote Sens 14:1–24. https://doi.org/10.3390/rs14215385

Dai YQ, Shi P, Hu JW, Zhai SM, Xiao ZW, Chen YB, Chen XY, Wang JJ (2018) Effects of climate change and human activities on runoff : a case of Shaying River (in Chinese). J China Three Gorges Univ (Nat Sci) 40:15–19

De Girolamo AM, Barca E, Leone M, Lo Porto A (2022) Impact of long-term climate change on flow regime in a Mediterranean basin. J Hydrol-Reg Stud 41:19. https://doi.org/10.1016/j.ejrh.2022.101061

Dile YT, Daggupati P, George C, Srinivasan R, Arnold J (2016) Introducing a new open source GIS user interface for the SWAT model. Environ Model Softw 85:129–138. https://doi.org/10.1016/j.envsoft.2016.08.004

Eyring V, Bony S, Meehl GA, Senior C, Stevens B, Stouffer RJ, Taylor KE (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 9:1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Eyring V, Cox PM, Flato GM, Gleckler PJ, Abramowitz G, Caldwell P, Collins WD, Gier BK, Hall AD, Hoffman FM, Hurtt GC, Jahn A, Jones CD, Klein SA, Krasting JP, Kwiatkowski L, Ruth L, Maloney E, Meehl GA, Pendergrass AG, Pincus R, Ruane AC, Russell JL, Sanderson BM, Santer BD, Sherwood SC, Simpson IR, Stouffer RJ, Williamson MS (2019) Taking climate model evaluation to the next level. Nat Clim Chang 9:102–110. https://doi.org/10.1038/s41558-018-0355-y

Fan X, Qing YY, Gao X (2021) Interpretation of the Main conclusions and suggestions of IPCC AR6 Working Group I Report (in Chinese). Environ Prot 49:44–48

Gan R, Chen CZ (2021) Simulation of runoff process and variation characteristic in Shaying River basin (in Chinese). Southto-North Water Transf Water Sci Technol 19:83–91. https://doi.org/10.13476/j.cnki.nsbdqk.2021.0008

Gan R, Chen CZ, Tao J, Shi YQ (2021) Hydrological process simulation of sluice-controlled rivers in the Plains Area of China based on an improved SWAT model. Water Resour Manag 35:1817–1835. https://doi.org/10.1007/s11269-021-02814-6

Giri S, Lathrop RG, Obropta CC (2020) Climate change vulnerability assessment and adaptation strategies through best management practices. J Hydrol 580:19. https://doi.org/10.1016/j.jhydrol.2019.124311

Gu JT, Shan TL (2022) Causes analysis of the snowstorm occurring in the Shaying River Basin in 2017 (in Chinese). Meteorol Environ Sci 45:23–31

Han YP, Yue Y, Mu WB (2020) Analysis on evolution characteristics of water cycle influencing factors in Shaying River Basin (in Chinese). J North China Univ Water Resour Electr Power (Nat Sci Ed) 41:43–49

Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. Int J Climatol 34:623–642. https://doi.org/10.1002/joc.3711

Idrees M, Ahmad S, Khan MW, Dahri ZH, Ahmad K, Azmat M, Rana IA (2022) Estimation of water balance for anticipated land use in the Potohar Plateau of the Indus Basin using SWAT. Remote Sens 14:19. https://doi.org/10.3390/rs14215421

IPCC (2021) Climate Change 2021: the physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Ji GX, Lai ZZ, Xia HB, Liu H, Wang Z (2021) Future runoff variation and flood disaster prediction of the Yellow River Basin based on CA-Markov and SWAT. Land 10:19. https://doi.org/10.3390/land10040421

Jiang T, Lv YR, Huang JL, Wang YJ, Su BD, Tao H (2020) New scenarios of CMIP6 ModeI (SSP-RCP) and its application in the Huaihe River Basin (in Chinese). Adv Meteorol Sci Technol 10:102–109

Jiao YF, Liu J, Li CZ, Wang W, Yu FL, Wang YZ (2020) Quantitative attribution of runoff attenuation to climate change and human activity in typical mountainous areas: an enlightenment to water resource sustainable utilization and management in North China. Sustainability 12:19. https://doi.org/10.3390/su122410395

Jin X, Jin Y, Mao X (2019) Land use/cover change effects on river basiN hydrological processes based on a modified soil and water

assessment tool: a case study of the Heihe River Basin in Northwest China's Arid Region. Sustainability 11:18. https://doi.org/10.3390/su11041072

Khan N, Shahid S, Ismail T, Ahmed K, Nawaz N (2018) Trends in heat wave related indices in Pakistan. Stoch Environ Res Risk Assess 33:287–302. https://doi.org/10.1007/s00477-018-1605-2

Li D, Qu S, Shi P, Chen XQ, Xue F, Gou JF, Zhang WH (2018) Development and integration of sub-daily flood modelling capability within the SWAT model and a comparison with XAJ model. Water 10:17. https://doi.org/10.3390/w10091263

Lin BQ, Chen XW, Yao HX, Liu MB, Gao L, James A (2015) Analyses of landuse change impacts on catchment runoff using different time indicators based on SWAT model. Ecol Indic 58:55–63. https://doi.org/10.1016/j.ecolind.2015.05.031

Luo ZL, Zuo QT (2019) Evaluating the coordinated development of social economy, water, and ecology in a heavily disturbed basin based on the distributed hydrology model and the harmony theory. J Hydrol 574:226–241. https://doi.org/10.1016/j.jhydrol.2019.04.042

Lynn J, Peeva N (2021) Communications in the IPCC's Sixth Assessment Report cycle. Clim Chang 169:10. https://doi.org/10.1007/s10584-021-03233-7

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R, Vuuren DP (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim Chang 122:387–400. https://doi.org/10.1007/s10584-013-0905-2

Prestele R, Arneth A, Bondeau A, Noblet-Ducoudré ND, Pugh TAM, Sitch S, Stehfest E, Verburg PH (2017) Current challenges of implementing anthropogenic land-use and land-cover change in models contributing to climate change assessments. Earth Syst Dyn 8:369–386. https://doi.org/10.5194/esd-8-369-2017

Prokesova R, Horackova S, Snopkova Z (2022) Surface runoff response to long-term land use changes: Spatial rearrangement of runoff-generating areas reveals a shift in flash flood drivers. Sci Total Environ 815:17. https://doi.org/10.1016/j.scitotenv.2021.151591

Qi JY, Lee S, Zhang XS, Yang QC, McCarty GW, Moglen GE (2020) Effects of surface runoff and infiltration partition methods on hydrological modeling: a comparison of four schemes in two watersheds in the Northeastern US. J Hydrol 581:124415–124415

Rafee SAA, de Freitas ED, Martins JA, Machado CB, Uvo CB (2021) Hydrologic response to large-scale land use and cover changes in the Upper Paraná River Basin between 1985 and 2015. Reg Environ Change 21:14. https://doi.org/10.1007/s10113-021-01827-6

Ricci GF, D'Ambrosio E, Girolamo AMD, Gentile F (2022) Efficiency and feasibility of Best Management Practices to reduce nutrient loads in an agricultural river basin. Agric Water Manag 259:16. https://doi.org/10.1016/j.agwat.2021.107241

Ridwansyah I, Yulianti M, Apip OSI, Shimizu Y, Wibowo H, Fakhrudin M (2020) The impact of land use and climate change on surface runoff and groundwater in Cimanuk watershed, Indonesia. Limnology 21:487–498. https://doi.org/10.1007/s10201-020-00629-9

Sharma A, Patel PL, Sharma PJ (2022) Influence of climate and land-use changes on the sensitivity of SWAT model parameters and water availability in a semi-arid river basin. CATENA 215:20. https://doi.org/10.1016/j.catena.2022.106298

Siderius C, Biemans H, Wiltshire A, Rao S, Franssen WHP, Kumar P, Gosain AK, Vliet MTHV, Collins DN (2013) Snowmelt contributions to discharge of the Ganges. Sci Total Environ 468–469:S93–S101. https://doi.org/10.1016/j.scitotenv.2013.05.084

Tamm O, Maasikamae S, Padari A, Tamm T (2018) Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model. CATENA 167:78–89. https://doi.org/10.1016/j.catena.2018.04.029

Tankpa V, Wang L, Awotwi A, Singh L, Thapa S, Atanga RA, Guo XM (2020) Modeling the effects of historical and future land use/

land cover change dynamics on the hydrological response of Ashi watershed, northeastern China. Environ Dev Sustain 23:7883–7912. https://doi.org/10.1007/s10668-020-00952-2

Tian J, Guo SL, Deng LL, Yin JB, Pan ZK, He SK, Li QX (2021) Adaptive optimal allocation of water resources response to future water availability and water demand in the Han River basin, China. Sci Rep 11:18. https://doi.org/10.1038/s41598-021-86961-1

Wang R, Kalin L (2018) Combined and synergistic effects of climate change and urbanization on water quality in the Wolf Bay watershed, southern Alabama. J Environ Sci (China) 64:107–121. https://doi.org/10.1016/j.jes.2016.11.021

Wang RY, Kalin L, Kuang WH, Tian HQ (2014) Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama. Hydrol Process 28:5530–5546. https://doi.org/10.1002/hyp.10057

Wang YP, Wang S, Wang C, Zhao WW (2021) Runoff sensitivity increases with land use/cover change contributing to runoff decline across the middle reaches of the Yellow River basin. J Hydrol 600:1–13. https://doi.org/10.1016/j.jhydrol.2021.126536

Wu JW, Miao CY, Zhang XM, Yang TT, Duan QY (2017) Detecting the quantitative hydrological response to changes in climate and human activities. Sci Total Environ 586:328–337. https://doi.org/10.1016/j.scitotenv.2017.02.010

Wu LY, Zhang X, Hao FH, Wu YF, Li C, Xu Y (2020) Evaluating the contributions of climate change and human activities to runoff in typical semi-arid area, China. J Hydrol 590:11. https://doi.org/10.1016/j.jhydrol.2020.125555

Xia J, Liu CZ, Ren GY (2011) Opportunity and challenge of the climate change impact on the Water Resource of China (in Chinese). Adv Earth Sci 26:1–16

Xu JW, Gao YH, Chen DL, Xiao LH, Ou TH (2017) Evaluation of global climate models for downscaling applications centred over the Tibetan Plateau. Int J Climatol 37:657–671. https://doi.org/10.1002/joc.4731

Zhang L, Karthikeyan R, Bai Z, Srinivasan R (2017a) Analysis of streamflow responses to climate variability and land use change in the Loess Plateau region of China. CATENA 154:1–11. https://doi.org/10.1016/j.catena.2017.02.012

Zhang YY, Hua RX, Xia R (2017b) Impact analysis of climate change on water quantity and quality in the Huaihe River Basin. J Nat Resour 32:114–126

Zhang YQ, Qi JY, Pan DM, Marek GW, Zhang XL, Feng PY, Liu HP, Li BG, Ding BB, Brauer DK, Srinivasan R, Chen Y (2022) Development and testing of a dynamic CO2 input method in SWAT for simulating long-term climate change impacts across various climatic locations. J Hydrol 614:1–15. https://doi.org/10.1016/j.jhydrol.2022.128544

Zuo DP, Xu ZX, Yao WY, Jin SY, Xiao PQ, Ran DC (2016a) Assessing the effects of changes in land use and climate on runoff and sediment yields from a watershed in the Loess Plateau of China. Sci Total Environ 544:238–250. https://doi.org/10.1016/j.scitotenv.2015.11.060

Zuo QT, Luo ZL, Shi YQ, Gan R, Liu J, Chen H (2016b) Main parameters and physiographic characteristics of Shayinghe River Basin (in Chinese). Water Resour Hydropower Eng 47:66–72