RESEARCH ARTICLE

Study on hydrological response of runoff to land use change in the Jing River Basin, China

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Abstract

Land use change greatly affects the runoff characteristics of the basin, which in turn affects the distribution of surface water and groundwater in the region. Quantitative analyses of the hydrological response of watershed runoff to land use change are conducive to the formulation of sustainable water resource strategies. In this paper, the impact of land use change on runoff characteristics in the Jing River Basin was evaluated using the SWAT model, the land use pattern of the Jing River Basin in 2040 was predicted using CA-Markov model, and five land use change scenarios were set up in combination with the trend of land use transfer, and the response relationship between land use change and runoff hydrological characteristics in the basin was studied. The results show that the land use changes reduce runoff and change the hydrological cycle process of the basin. The hydrological response of different land use types varies significantly, but only has a less impact on annual runoff. Farmland has a promoting effect on production flow; woodland and grassland are not conducive to the formation of surface runoff and will increase underground runoff and evapotranspiration in the basin. The increase in vegetation coverage after returning farmland to woodlands and grasslands has reduced surface runoff, increased the recharge of groundwater, and played a positive role in ecological restoration in the river basin. The research results are of great significance for understanding the hydrological consequences of land use change and the rational planning of land use patterns in river basins.

Keywords Runoff response · Land use change · Surface runoff · Underground runoff · SWAT · CA-Markov

Introduction

As the main manifestation of subsurface change in river basins (Li et al. 2016), land use change has an impact on water balance in river basins, which is one of the important contents of hydrological research. With the increase of extreme weather and the intensification of human activities, land cover types have changed greatly, which is a key factor in changing the generation of surface runoff, which in turn has an impact on the hydrological cycle process (Ghaffari et al. 2010). At the same time, the irrational use of land by human beings has aggravated the shortage of water resources in the river basin, and its original ecological balance has also been damaged to a certain extent (Zhang et al. 2013). Therefore, it is of great significance to study the runoff response characteristics of different land use situations for in-depth understanding of the runoff evolution under future land use change conditions and also provides certain technical support and scientific basis for the rational planning of water resource management and land use pattern in river basins (Jiang et al. 2017).

The methods for studying the hydrological response of runoff to land use change mainly include the basin comparison experiment method, statistical analysis method, and model simulation method. The focus of the watershed experiment method is to study the hydrological effect of land use/land cover (LULC) on runoff in combination with sand production and soil and water conservation (Wang et al. 2014) and can only be applied to small watersheds with similar topography and geomorphology in the basin (Guo et al. 2014). The statistical analysis method analyzes the hydrological response results of different land use types through the evolution trend of mathematical statistical characteristic parameters, ignores the interaction between the variables,

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and cannot reflect the physical mechanism of runoff to land use response and the differences in the geospatial existence of watersheds. In model simulation method, through the abstract generalization of complex water cycle processes, the main features of simulating water cycle processes are the most widely used method for analyzing runoff changes caused by various drivers (Brath et al. 2006; Fan et al. 2010). The SWAT (soil and water assessment tool) model is a distributed hydrological model based on physical processes developed by the United States Department of Agriculture (USDA) (Havrylenko et al. 2016), which uses remote sensing and geospatial data to describe the spatial differences of hydrological elements at the watershed scale in a discrete manner, taking into account human processes such as urban expansion, land use change, and population increase, as well as natural processes such as climate change (Lai et al. 2012). Since its development, this model has been widely used in the simulation and prediction of different land use types and land management measures at the basin scale and the impact of climate change on the hydrology of the river basin (Guo et al. 2014), which can better simulate the natural runoff process and truly reflect the characteristics of runoff change in the basin (Cao et al. 2022), and is an effective tool for conducting research on the hydrological effects of land use change (Guo et al. 2021). Guo et al. (Guo et al. 2008) used SWAT models to study the hydrological responses of annual and seasonal runoff in the Xinjiang River Basin of Poyang Lake with land use change, and the results showed that land use change greatly changed the monsoon runoff. Gessesse et al. (Gessesse et al. 2015) simulated the temporal and spatial patterns of runoff generation and soil erosion in the Modjo watershed based on the SWAT model in response to land use changes in the watershed. The results showed that the reduction of forest and shrub area and the increase of wasteland area led to increased surface runoff and soil loss. In addition, Dunn and Mackay's (Dunn and Mackay 1995) study further reveals the important role of soil properties in regional water cycle changes caused by land use change. On the other hand, with the development of land use prediction models, many scholars have achieved good results in simulating the distribution patterns of future land use based on ecological and geographical theories, using models such as CLUE-S and CA-Markov. This demonstrates the applicability of these methods for simulating complex land use. Yulianto et al. (Yulianto et al. 2019) combined remote sensing data with the CA-Markov model to analyze land use change dynamics and predict land use changes in the coming year. However, most previous studies focused on analyzing the impact of changes in land use distribution patterns on runoff, while ignoring the fact that different land use types have varied impacts on runoff. This affects the characteristics of runoff changes, thus reducing the accuracy of runoff responses to land use changes. In fact, the impact of land use

on runoff is the combined result of various land use types. Revealing the influence of single land use types on runoff is the basis for analyzing the comprehensive impact. Therefore, it is necessary to combine different land use scenarios and future land use modes to study runoff responses to land use changes, in order to enhance the health of river ecosystems.

As the largest tributary of the Wei River, the Jing River is located in the typical arid and semi-arid area of northwest China, and in recent years, climate changes and high frequencies of extreme weather have further affected the uneven distribution of runoff during the year. At the same time, rapid population growth and intensive human activities have exacerbated water scarcity (Chen et al. 2016), and changes in land use patterns have directly changed the lower cushion environment of runoff streams in the basin. Therefore, it is necessary to understand the hydrological response of the Jing River to land use change in the basin. In this paper, the monthly runoff of three hydrological stations in the Jing River Basin was simulated by using five phases of land use data, and the response of runoff to land use change was quantitatively analyzed, and the runoff response characteristics of specific land use types were further simulated and studied on this basis. The results of the study will help improve the predictability of the hydrological consequences of land use change and provide theoretical basis and model support for the long-term planning of land use patterns in river basins.

Materials and methods

Description of the study area

Jing River is the largest tributary of the Wei River, a secondary tributary of the Yellow River, located in the middle of the Loess Plateau, located at 106° 14′~108° 42′ E, 34° 46′~37° 19′ N, with a total length of 455.1 km and a basin area of 45421 km^2; spanning Ningxia, Gansu, and Shaanxi, which are the three provinces, is an important water source of the lower Guanzhong Plain. The Jing River Basin has a typical temperate continental climate, with high temperature in the south and low in the north, rainfall as the main source of runoff replenishment, and annual precipitation between 350 and 600 mm, decreasing from south to north. The distribution of rainfall during the year is significantly different, with dry and cold winters and little rain and hot and rainy summers, and precipitation from June to September accounts for more than 70% of the whole year. The loess in the basin is widely distributed, and the structure is loose, which is typical of yellow cotton soil and black moat soil, and the problem of soil erosion is serious. In order to deeply study the impact of land use change on runoff in the basin in recent decades, Jingchuan Station and Yangjiaping Station located

in the middle reaches of the Jing River and Zhangjiashan Station as the total outlet hydrological measurement station of the basin are selected as hydrological stations, which can well represent the overall situation of runoff in the basin, as shown in Fig. 1.

Data sources

The input data of the distributed hydrological model of the Jing River Basin based on SWAT include spatial data and hydrometeorological data. Spatial data include soil data, DEM (digital elevation data), and land use data, of which the soil data is based on the Chinese soil dataset (v1.2) based on the World Soil Database (HWSD) with an accuracy of 1:1,000,000, provided by the National Tibetan Plateau Science Data Center (http://data.tpdc.ac.cn/zh-hans/data/844010ba-d359-4020-bf76-2b58806f9205/). The DEM data is derived from geospatial clouds (http://www.gscloud.cn/search) with a spatial resolution of 30 m, and the land use data is 30 m remote sensing monitoring data of land use provided by the Institute of Geographic Sciences and Resources Research of the Chinese Academy of Sciences. Hydrological data collected month-by-month runoff data from 2008 to 2018 at three hydrological stations in

Jingchuan, Yangjiaping, and Zhangjiashan in the study area were derived from the hydrological data of the Yellow River Basin in the Hydrological Yearbook of the People's Republic of China. The meteorological data selected from 1960 to 2020 from 6 meteorological stations in and around the Jing River Basin, including daily rainfall data, daily maximum and minimum temperature, and other data required to drive the SWAT model, and the meteorological data came from the China Meteorological Science Data Sharing Service Network.

The land use data reflects the coverage and hydrological characteristics of different land use types in the river basin, and the land use remote sensing image data of the five different periods in 1980, 1990, 2000, 2010, and 2018 is selected as the land use input data of the SWAT model, and it is reclassified with reference to the national standard of "Classification of Land Use Status" (GB/T 21010-2007) of China. According to the secondary type, it is divided into six categories: farmland, woodland, grassland, water, urban, and unused land, as shown in Fig. 2.

The soil physical property database required by SWAT model reflects the movement of water and gas in the soil profile, mainly involving the density, thickness, and hydrological properties of the soil, as well as the parameters of
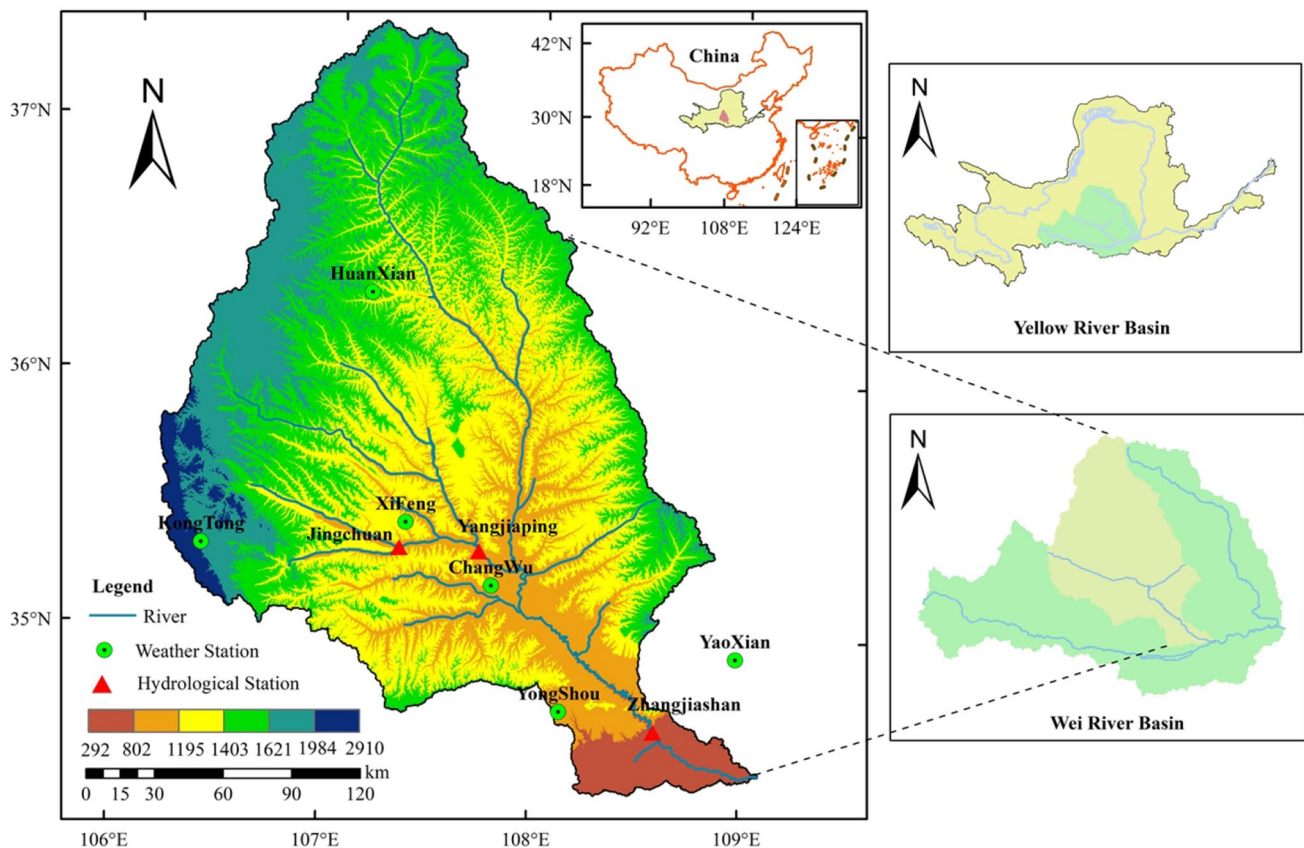

Fig. 1 Geographical location and distribution of hydrological sites in the Jing River Basin
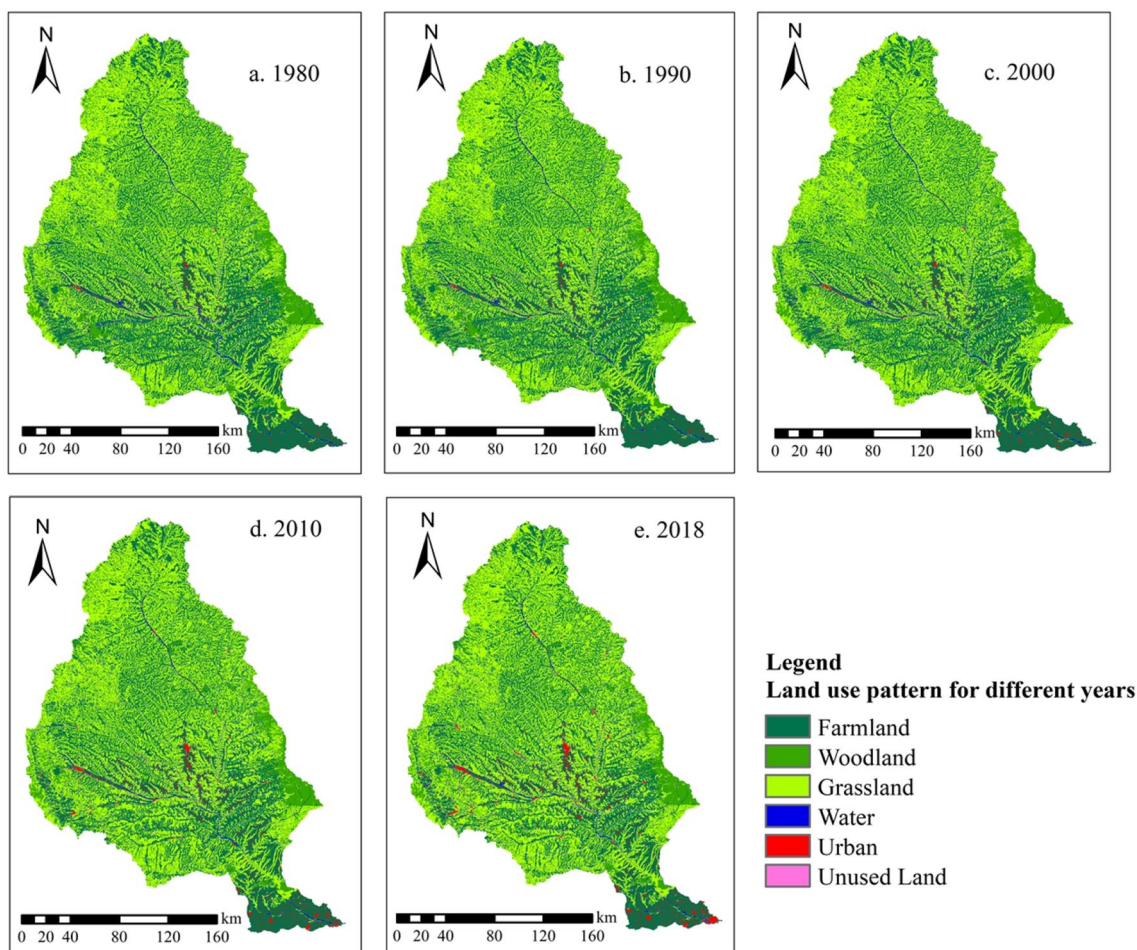
Fig. 2 Map of land use types in different periods of the Jing River Basin

effective moisture content, saturation permeability coefficient, conductivity, and soil erosion force factor of each layer of soil, which is an important data support for calculating the water cycle in the hydrological response unit. There are 39 soil types in the Jing River Basin, mainly calcareous rudimentary soils, accounting for 89.4% of the basin area, as shown in the Fig. 3.

Climate change is one of the important factors affecting the hydrological characteristics of runoff in the basin, and it is helpful to analyze the hydrological response characteristics of runoff to land use change by analyzing the changes of rainfall and average temperature in the Jing River Basin from 1960 to 2020, selecting a time period with relatively stable climatic conditions to reduce the impact of extreme weather. The Mann-Kendall nonparametric test statistical method was used to analyze the trend and abrupt changes of rainfall and temperature in the basin (Fig. 4), and the results showed that the multi-year average precipitation statistical value Z was −0.287, which failed the significance test of 95%, and showed an insignificant decrease, which occurred abruptly in 1968 and 2019. The statistical Z of

the multi-year average temperature is 5.479, which shows a significant increase trend through the significance test and suddenly changed in 1993.

The soil and water assessment tool

As a large-to-mesoscale watershed model, the SWAT model is mainly used to simulate and predict the hydrological and water quality responses of land management to runoff and sediment and agrochemicals in complex watersheds under different soil types, land use patterns, and management measures (Guo et al. 2008). Based on the physical mechanism, the model divides the watershed into sub-basins according to the differences in land use and soil attributes within the basin that are obvious enough to affect the hydrological process; uses hydrological response units (HRU) to analyze the spatial heterogeneity of land cover, soil type, and slope in the basin (Setegn et al. 2010); and finally converges at the outlet of the sub-basin to carry out slope convergence and river network confluence to
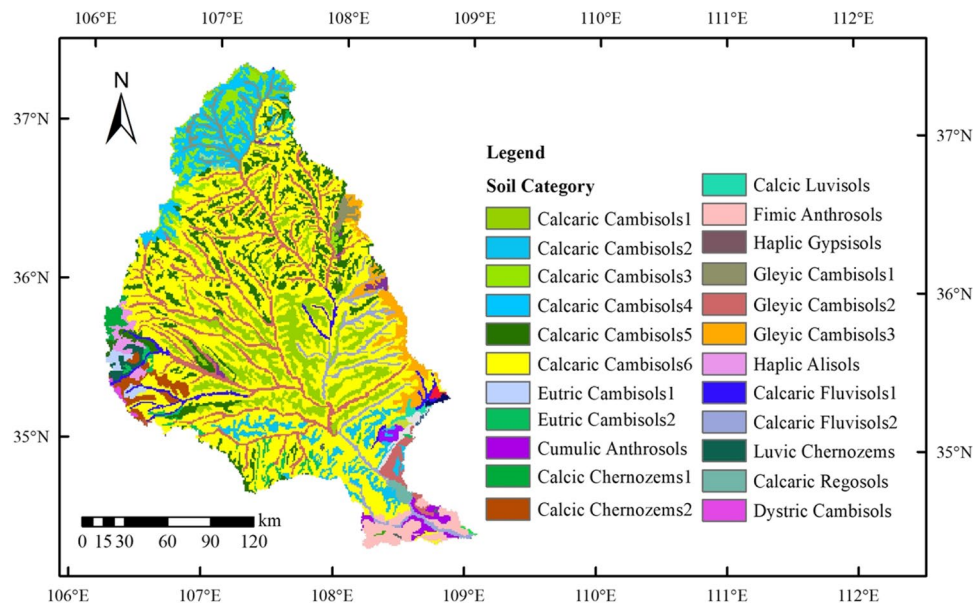
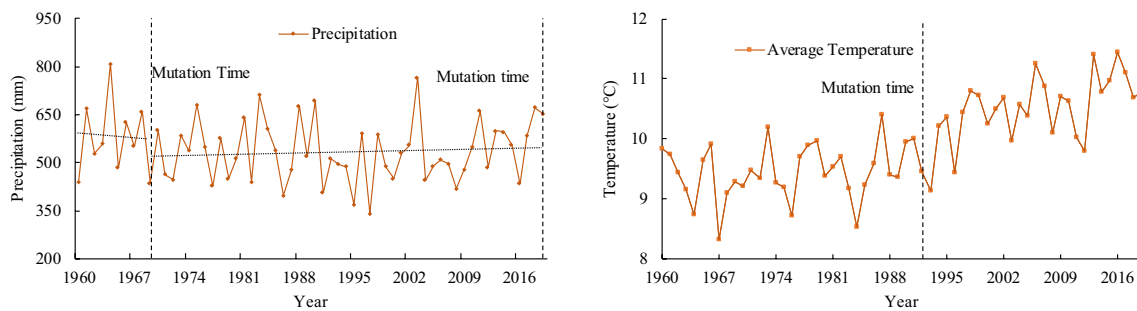**Fig. 3** Soil type map of the Jing River Basin

Fig. 4 Changes in rainfall and average temperature in the Jing River Basin from 1960 to 2020

obtain hydrological simulation results. The SWAT model simulates the hydrological cycle according to the following water balance equation:

$$SW_t = SW_0 + \sum_{n=1}^{t} \left(R_n - Q_n - E_n - W_n - T_n \right) \qquad (1)$$

where SW_t indicates the final moisture content of the soil (mm), SW_0 indicates the initial moisture content of the soil on the nth day (mm), t stands for time (d), R_n represents the total rainfall (mm) on day n, Q_n represents the total surface runoff (mm) on day n, E_n indicates the amount of evaporative transpiration on day n (mm), W_n indicates the amount of under filtration (mm) from the soil profile into the gas envelope on the nth day, and T_n represents the groundwater return flow (mm) on the nth day.

The SWAT model uses the rainfall of the daily time step; considers the temporal and spatial changes of hydrological conductivity, topographic slope, and surface water storage; calculates the surface runoff at the HRU level using the modified SCS-CN curve number method; and then summarizes the surface runoff released into the main channel of each sub-basin through the river network, which can quantify the relative effects of management, soil, and vegetation changes at the secondary basin level (Arnold and Allen 1996).

Cellular automata Markov

The cellular automata Markov (CA-Markov) model is a coupling model for the dual advantages of the integrated cell automata (CA) model to simulate the dynamic changes of complex space and the long-term prediction of the Markov model and is widely used in the simulation and prediction of dynamic changes of land use structure in long sequences. The cellular automata model is a discontinuous model of space-time dynamics characterized by discrete time, space, and state. A CA system is mainly composed of four parts: cells and their states, cell space, cell neighborhood, and transformation rules. In the cellular space, each cell has its own limited specific state, which is synchronously updated according to the defined local rules, and these local rules interact to form a dynamic evolutionary system (Fu et al. 2018; Guan et al. 2019; Yulianto et al. 2019). The CA model can be represented by the following equation:

$$S(t + 1) = f(S(t), N) \tag{2}$$

where S is the finite and discrete set of states of the cell, t and $t+1$ are different moments, N is the neighborhood of the cell, and f is the cell transformation rule of local space.

The Markov model is a long-term prediction method based on the state of an event in one period and predicting its state in the next period, where the key is to determine the probability of the event transferring. The land use changes under the Markov process are as follows:

$$X(t + 1) = X(t) * P \tag{3}$$

In the formula, $X(t+1)$ represents the state of the random event at $t+1$, that is, the result predicted by the Markov model, $X(t)$ is the state of a random event at moment t, and P is the transition probability matrix, which represents the transition probability between different states of this random event.

Statistical evaluation of the results

Due to the uncertainty of the hydrological model and the many parameters that affect runoff in the SWAT model and the degree of influence of different parameters which is significantly different, this paper uses the SUFI2 algorithm (sequential uncertainty fitting algorithm) in SWST-CUP (SWAT Calibration and Uncertainty Programs) to calibrate and analyze the model parameters. The SUFI2 algorithm adopts the Latin hypercube sampling algorithm, combines uncertainty analysis and optimization to iteratively process the parameters, and runs efficiently and simply. In order to comprehensively evaluate the applicability and fitting effect of the SWAP model in the

Jing River Basin, Nash efficiency coefficient NSE, decision coefficient R^2, and relative error Re are selected as accuracy evaluation indicators, and the calculation formula is as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{obs} - Q_{sim} \right)^2}{\sum_{i=1}^{n} \left(Q_{obs} - Q_{avg} \right)^2} \tag{4}$$

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

$$Re = \frac{Q_{sim} - Q_{obs}}{Q_{obs}} \times 100\% \tag{6}$$

where Q_{obs} is the measured runoff value, Q_{sim} is the simulated runoff value, Q_{avg} is the average of the measured runoff, $(\overline{Q_{sim}})$ is the average of the simulated runoff; and n is the number of samples. The value range of Nash efficiency coefficient NSE is $(-\infty, 1)$, which indicates the similarity of measured runoff and simulated runoff, and the closer the NSE value is to 1, the higher the model credibility. The value range of the coefficient R^2 is $(0, 1)$, which represents the level of consistency between the simulated runoff and the measured runoff trend; The relative error Re reflects the reliability of the simulation results. When the three indicators meet the NSE > 0.5, R^2 > 0.6, and |Re| > 20%, it was assumed that the simulation results were satisfactory and could be used to study the response of runoff within the basin to land use change.

The Kappa coefficient is often used to interpret remote sensing accuracy and evaluate the similarity of two spatial maps. In this study, the Kappa coefficient was used to verify the simulation accuracy of the CA-Markov model on the evolution of land use in the Jing River Basin. The Kappa coefficient is calculated as

$$Kappa = \frac{P_o - P_c}{P_p - P_c} \tag{7}$$

where P_o represents the raster scale for a correct simulation, P_c is the raster scale of the desired correct simulation, and P_p is the scale of the raster correctly simulated under the ideal classification. When Kappa $\leq$ 0.4, it means that the consistency of the two pictures is weak; 0.4< Kappa $\leq$ 0.6, indicating that the consistency of the two pictures is moderate; 0.6<Kappa$\leq$0.8, indicating that the consistency of the two pictures is significant; and 0.8< Kappa$\leq$1, indicating that the consistency of the two pictures is the best.

Land use dynamic degree

In order to explore the dynamic change characteristics of land use types in the non-use period in a specific time period in the study area, the land use dynamic model that can reflect the change amplitude and change rate of land use types is used for evaluation, including single land use dynamic degree and comprehensive land use dynamic degree, and the calculation formula is as follows:

$$K = \frac{S_i - S_j}{S_j} \times \frac{1}{T} \times 100\% \tag{8}$$

$$LU = \frac{\sum_{i=1}^{n} \Delta dS_{i-j}}{2 \sum_{i=1}^{n} \Delta dS_i} \times \frac{1}{T} \times 100\% \tag{9}$$

where i is a certain land use type; S_i and S_j are the area of a certain land use type at the end and early stage of the study, respectively; dS_i is the area of type i land use; ΔdS_{i-j} is the absolute value of the area of type i land use to the area of type i to non-type land use; T is the length of the study time; and n is the total number of land use types in the study area. The single land use dynamic degree K reflects the change in the area occupied by a certain land use type during the study period, representing the rate of change of land type. The comprehensive land use dynamic degree represents the annual rate of change in land use and reflects the rate of change for all land use types during the study period (Guo et al. 2021; Xiao et al. 2020).

Results

Sensitivity analysis

The calibration range and optimal values of runoff sensitivity parameters under different land use conditions of three hydrological stations in the Jing River Basin are shown in Table 1 by SUFI2 algorithm. Before model calibration and validation, more parameters are brought into the model, and the 13 parameters that respond most significantly to runoff within the control sub-basin are selected for iteration based on the results of the sensitivity analysis to improve the efficiency and reliability of model calibration.

It can be seen from Table 1 that the flow process of monthly runoff in the Jing River Basin is mainly closely related to the sensitive parameters of hydrological processes reflecting surface runoff (CN2), groundwater processes (ALPHA_BF, GW_DELAY, REVAPMN), soil moisture (SOL_AW, SOL_K, GWQMN), geomorphological characteristics (SLSUBBSN), and evapotranspiration (ESCO, CANMX), and the sensitivity of the same parameter to runoff in different sub-basins is different. This is related to the fact that the Jing River Basin is located in the middle of the Loess Plateau, the surface vegetation is sparse, the soil is mostly loose loess, the soil erosion is serious, and the water storage capacity is poor and other natural factors.

Model calibration and validation

Since the meteorological series in the hydrological model are all stable, in order to ensure the relative accuracy of the

Table 1 Sensitivity parameters and optimal values at three stations in the Jing River Basin

Type	Sensitivity parameter	Parameter definition	Range	Optimal value		
				Zhangjiashan	Yangjiaping	Jingchuan
r	CN2	SCS runoff curve coefficient	(−0.5, 0.5)	−0.09	−0.46	−0.44
r	SOL_AWC	Soil available water	(0, 1)	0.72	−0.01	−0.93
r	SOL_Z	Soil depth	(−1, 1)	0.06	0.41	0.15
v	ALPHA_BF	Groundwater recession factor	(−0.5, 0.5)	0.47	0.33	0.78
v	SOL_K	Saturated hydraulic conductivity	(−1, 0.8)	−0.86	−0.61	0.11
v	GWQMN	Compensation depth of shallow aquifer	(0, 5000)	2.16	/	/
v	ESCO	Soil evaporation compensation factor	(0, 1.2)	0.16	1.12	0.16
v	CH_K2	Channel effective hydraulic conductivity	(0, 150)	124.09	0.58	138.42
v	CH_N2	Manning's n value for main channel	(−0.3, 0.3)	0.22	0.13	0.22
v	REVAPMN	Threshold water depth in the shallow aquifer	(0, 500)	4.43	/	3.94
v	SLSUBBSN	Average slope length	(0, 150)	1.37	−1.29	1.29
v	CANMX	Maximum canopy storage	(0, 100)	2.52	2.88	2.41
v	GW_DELAY	Groundwater delay time	(0, 500)	331.08	538.63	/

r means the initial value multiplied by (1 + final value); v means that the initial value is directly replaced by the final value; "/" indicates that this parameter is not sensitive to runoff within the hydrological station control basin

SWAT model simulation results, the calibration period and verification period of the model should avoid the year when the meteorological sequence of the basin changes as much as possible and select the stage where the meteorological characteristics in the study area are relatively stable. Combining the results of the Mann-Kendall test on meteorological data, this paper selects the period 2008–2018 as the simulation period for the model. At the same time, in order to avoid the situation of empty values in the early stage of the simulation, under the same climatic conditions, the model preheating period of 2008 and the model rate of 2009–2015 are calibration, and the 2016–2018 is the result verification period, and the land use data of 2018 is selected as the initial construction data of the model, and the monthly runoff of the three hydrological stations in Zhangjiashan, Yangjiaping, and Jingchuan in the middle and lower reaches of the Jing River Basin is calibrated and verified, and the impact of land use data on runoff in different periods of the five phases is simulated.

As shown in Table 2 and Fig. 5, the simulated monthly flow process and the observed flow process of each hydrological station in the Jing River Basin have obtained excellent fitting effects, except for the calibration period of the Jingchuan Hydrological Station, the model applicability evaluation indicators NSE and R^2 are not less than 0.8, and the |Re| is less than 20%, indicating that the SWAT model is suitable for runoff simulation and prediction in the Jing River Basin. The simulation results of Jingchuan Station are not as good as the other two hydrological stations, probably because Jingchuan Hydrological Station is located on the tributaries of the middle reaches of the basin and controls a smaller basin area, while the SWAT model is more suitable for large and medium watersheds, so the fitting effect is relatively reduced. From the perspective of time scale, the overall fitting effect of the model verification period is better than the calibration period, which may be due to the fact that the 2018 land use data used in the model construction period is more reflective of the lower cushion surface of the actual monthly runoff process than the calibration period. From the point of view of fit, the SWAT model captures the rising, declining, and non-flood trough segments of runoff during the calibration and verification periods, but the model simulates the peak of the flood season slightly lower. Nevertheless, higher NSE and R^2 values and lower |Re| values indicate that the monthly runoff simulation values are in good agreement with the measured values, and the SWAT model can simulate the runoff process within the watershed with considerable accuracy.

CA-Markov model evaluation

In order to test the simulation accuracy of the CA-Markov model, the land use pattern of the basin in 2020 was simulated by taking the 2000 land use distribution map of the Jing River Basin as the starting year, combined with the 1980–2000 land transfer probability matrix and the land use suitability atlas. Based on the accuracy evaluation statistics of the simulated and actual land use data in 2020, the Kappa coefficient of the land use simulation in 2020 is 0.89, indicating that the CA-Markov model simulation achieves the best effect and can be used to predict the future land use scenario of the Jing River Basin. Therefore, taking the 2020 land use distribution map as the starting year, using the CA-Markov model, combined with the modified land use transfer probability matrix and land use suitability atlas, the number of cycles of the CA filter is set to 20, and the land use distribution pattern in the Jing River Basin in 2040 is simulated, as shown in Fig. 6c.

Land use change analysis

Statistical analysis of the distribution of land use types in 1980, 1990, 2000, 2010, and 2018 obtained from remote sensing data and the land use data for 2040 projected by the CA-Markov model yielded the area and percentage of each land use type in the six periods. It can be seen from Table 3 that farmland, woodland, and grassland are the main land use types in the Jing River Basin, accounting for more than 96% of the total area of the river basin, while the proportion of water, urban, and unused land is small. Judging from the changing trend of land use type area in different periods, the farmland area showed a decreasing trend year by year, with a year-on-year decrease of 4.56% from 1980 to 2018. The overall area of woodland showed an increasing trend, increasing by 2.45% in 2040 compared with 1980, and the area of grassland first increased and then decreased. The upward trend of urban and unused land is significant, which is related to the rapid growth of population and the rapid expansion of urbanization and the large amount of farmland occupied by urban construction.

Table 2 Evaluation results of simulated runoff in the Jing River Basin

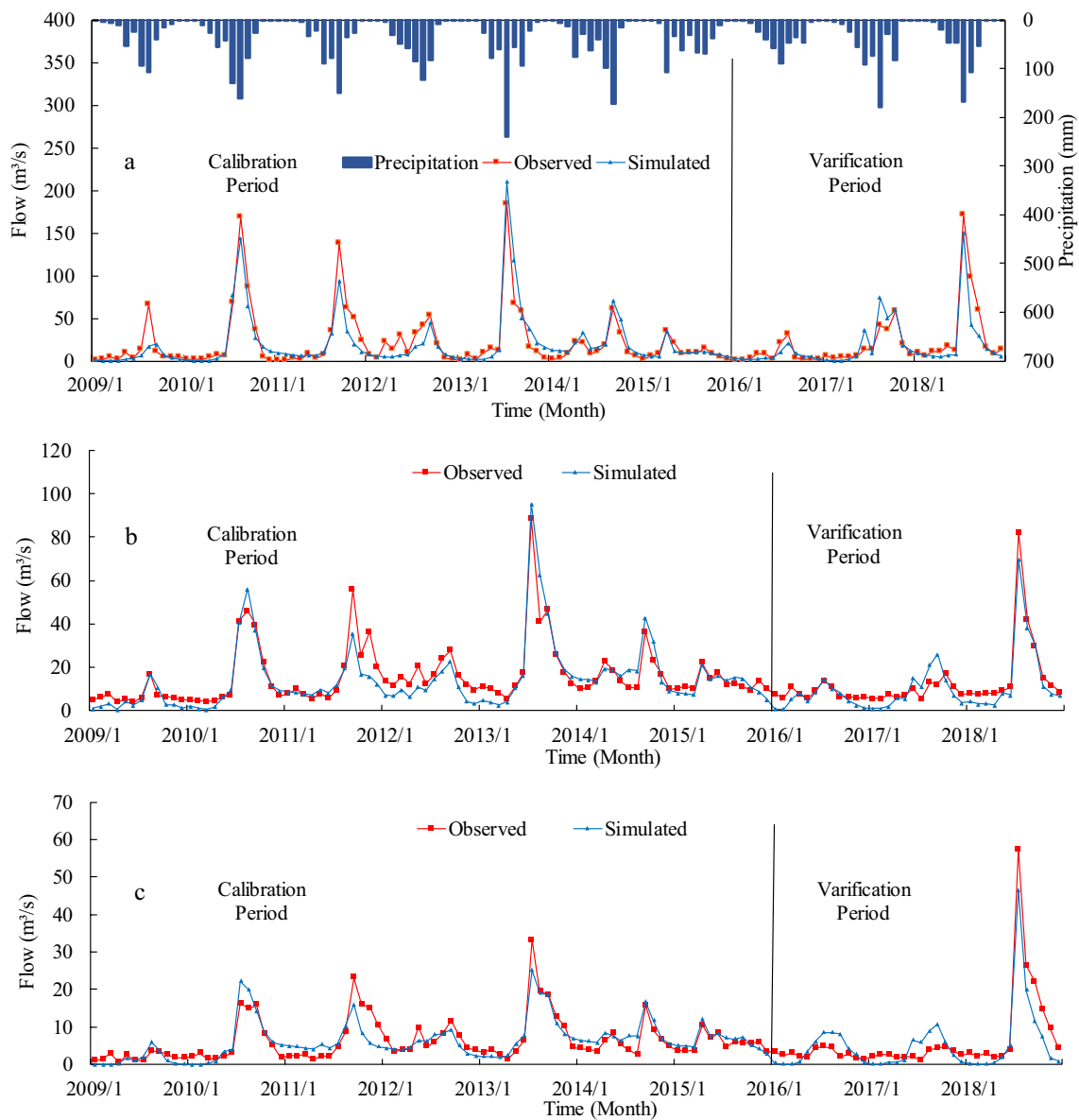| Hydrological station	Calibration period (2009–2015)			Verification period (2016–2018)		
	NSE	R^2	Re (%)	NSE	R^2	Re (%)
Zhangjiashan	0.83	0.84	−6.04	0.81	0.83	−14.98
Yangjiaping	0.81	0.86	−11.76	0.80	0.88	−16.09
Jingchuan	0.76	0.77	−0.03	0.82	0.84	−19.35

Fig. 5 Simulation and observation of monthly runoff at three hydrological stations in the Jing River Basin. **a** Zhangjiashan Station. **b** Yangjiaping Station. **c** Jingchuan Station

To further analyze land use transfer between different types in the Jing River Basin, this study utilized ArcGIS software to overlay remote sensing data of land use in 1980, 2018, and 2040 and extracted the vector change of the area of each land use type to obtain the land use transfer matrix. In order to display the transfer path and quantity between different land use types more intuitively, the form of Sankey diagrams is used to analyze the changes of land use circulation structure and rules in different periods by comparing the width of lines and calculate the land use dynamic degree (Table 4). It can be seen from Fig. 7 that the conversion of land use types in the Jing River Basin is reversible, and the

conversion of grassland to cultivated land is accompanied by the transfer of cultivated land and other land types to grassland. During the period 1980–2000, the lack of forest resource protection due to insufficient investment in forestry production led to the conversion of some woodland areas to grassland, coupled with the soil drying caused by climate change, which was not conducive to forest growth. Therefore, the transfer between land use types is mainly the conversion from forestland to grassland, and the conversion between other land use types is less. From 2000 to 2018, the implementation of natural woodland protection projects and the policy of returning farmland to woodland and grassland
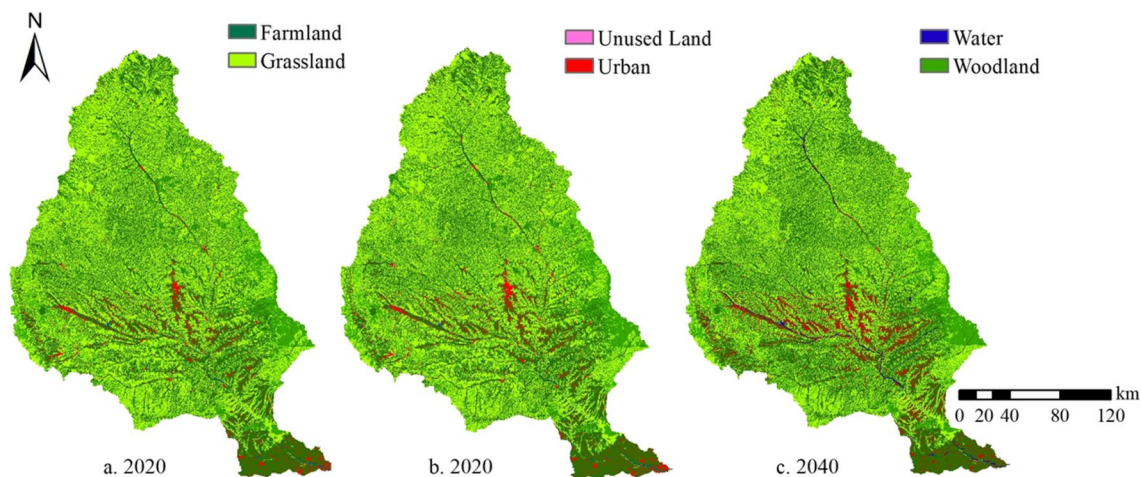
Fig. 6 Actual and simulation results of land use patterns in Jing River Basin. **a** Actual land use pattern in 2020. **b** Land use simulation pattern in 2020. **c** Land use simulation pattern in 2040

Table 3 Area distribution and proportion of five land use types in the Jing River Basin

Year	Items	Farmland	Woodland	Grassland	Water	Urban	Unused land
1980	Area (km^2)	19725.15	3646.98	20797.42	247.57	658.58	2.61
	Proportion (%)	43.76	8.09	46.14	0.55	1.46	0.01
1990	Area (km^2)	19641.10	3638.72	20760.38	201.09	656.27	2.54
	Proportion (%)	43.74	8.10	46.24	0.45	1.46	0.01
2000	Area (km^2)	19537.09	3496.39	20904.72	197.15	748.85	1.34
	Proportion (%)	43.53	7.79	46.57	0.44	1.67	0.00
2010	Area (km^2)	18308.78	3979.82	21411.40	182.16	965.59	11.35
	Proportion (%)	40.81	8.87	47.73	0.41	2.15	0.03
2018	Area (km^2)	17533.30	3945.10	21900.68	192.84	1128.37	26.56
	Proportion (%)	39.20	8.82	48.97	0.43	2.52	0.06
2040	Area (km^2)	17510.45	4721.79	20997.16	198.84	1325.64	28.76
	Proportion (%)	39.10	10.54	46.89	0.44	2.96	0.06

Table 4 Land use dynamic degree in the Jing River Basin from 1980 to 2018

Type	Single land use dynamic degree K (%)			Comprehensive land use dynamic degree LU (%)		
	1980–2000	2000–2018	1980–2018	1980–2000	2000–2018	1980–2018
Grassland	0.03	0.24	0.14	0.03	0.63	0.31
Farmland	−0.05	−0.51	−0.29			
Urban	0.69	2.53	1.88			
Woodland	−0.21	0.64	0.22			
Water	−1.02	−0.11	−0.58			
Unused land	−2.43	94.10	24.15			

promoted the conversion of farmland to woodland and grassland, and the mutual conversion among grassland, farmland, and woodland land increased significantly; as a result, a large number of farmland became grassland and woodland. At the same time, the continuous advancement of urbanization and the upgrading of industrial structure have increased the demand for construction land, resulting in the occupation of a large amount of arable land to expand urban boundaries (Liu et al. 2015). From the perspective of single land use dynamic attitude K, the K value of unused land was 94.1% during 2000–2018, indicating that the annual change rate of this land use type was fast, the change amplitude was large,
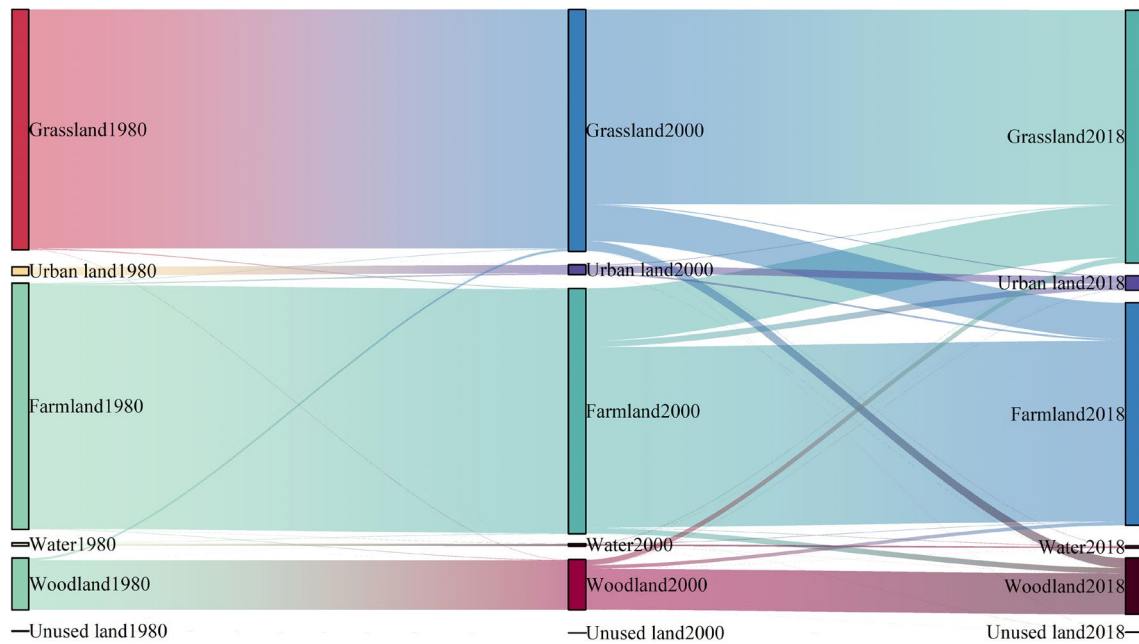
Fig. 7 Land use transfer in the Jing River Basin

and the area occupied by this land use type increased significantly during this period. The reason for this phenomenon is mainly due to the increase of extreme climate in recent years and the unreasonable development and utilization of land by human beings, which lead to the destruction of soil structure and the decline of soil quality, which is reflected in the continuous expansion of unused land area (Wang et al. 2019). On the whole, the dynamic attitude of comprehensive land use in the basin during 1980–2018 was 0.31%, and the LU value during 2000–2018 was 0.63%, indicating that the change rate of all land use types in the study period was relatively slow, the annual change rate of land use was relatively flat, and the main changes occurred after 2000.

Response analysis of runoff to land use change

According to the proportion of land use types in the six periods, it can be seen that the main land use methods in the Jing River Basin are farmland, grassland, and woodland, and the area occupied by farmland has changed sharply, especially since 2000. Meanwhile, the areas of grassland in 2018 and

woodland in 2040 have changed most significantly compared with those in 1980, although the area change rate of urban and unused land is greater, but the sum of the two areas only accounts for less than 3% of the area of the study area. Therefore, this paper selected remote sensing data of land use in 1980, 2018, and the next 2040 with the largest differences in land types and areas to be brought into the calibrated SWAT model, kept meteorological factors unchanged to simulate the monthly runoff from 2008 to 2018, and quantitatively analyze the impact of land use characteristic change on runoff.

From Table 5, it can be seen that compared with 1980, the annual average runoff change in 2018 and 2040 is small, which only decreased by 0.24 m^3/s and 0.32 m^3/s, while the surface runoff in 2018 and 2040 decreased by 14% and 16%, and the underground runoff increased by 55% and 88%, respectively. Meanwhile, the actual evapotranspiration also became larger. This may be related to the change of the area proportion of the main land use types in the three phase land use datasets. The decrease of farmland and the increase of grassland and woodland affect the water cycle process of

Table 5 Hydrological response of runoff to land use change

Year of land use	Average annual runoff (m^3/s)	Surface runoff (mm)	Underground runoff (mm)	Actual evapotranspiration (mm)
1980	20.35	24.96	3.12	353.85
2018	20.11	21.55	4.83	361.24
2040	20.03	21.08	5.85	367.73

runoff in the basin to a certain extent and greatly change the hydrological components of runoff but only have a small impact on the annual runoff. The main reason for this phenomenon is that grassland and forest surfaces are rougher than cropland, which generates greater flow resistance. This detention effect can slow down the conflux process of surface runoff, prolonging infiltration time and thus increasing rainfall infiltration into vegetation and soil. Meanwhile, grasslands and forests have more developed root systems, which helps maintain soil infiltration capacity and increases surface water percolation. Additionally, stems and trunks in grasslands and forests play a role in impeding exchanges between surface water and groundwater, raising groundwater levels, and reducing exchange rates, hence decreasing groundwater discharge to surface water. Moreover, different vegetation types have varied evapotranspiration effects. Forests and grasslands have stronger evapotranspiration than croplands. This enables soil moisture in deeper layers to be more readily absorbed into the atmosphere, increasing evapotranspiration in the watershed, which is also an important reason for changes in mean annual runoff.

Effects of main land use types on runoff

Scenario settings

Scenario analysis is a method that combines quantitative and qualitative analysis. According to the diversity of development trends, it designs a variety of possible scenarios through systematic analysis of problems related to internal and external factors of the system and describes and analyzes the development trend of the system on this basis. Setting different scenarios is beneficial to analyze the influence generated by specific factors. The change of runoff in the basin is caused by a combination of natural factors and human factors; natural factors are mainly climate changes, and human factors are manifested in changes in land use patterns and the construction of water conservancy projects. Due to the small rate of land use change in the Jing River Basin and the mutual conversion between multiple land use types during the study period, it is difficult to quantitatively analyze the impact of specific land use types on runoff. Based on this, this paper adopts the extreme scenario method; according to the current status of the main land use types in the river

basin, three extreme scenarios are set, and all the land use types in the basin are changed to single farmland, single woodland, and single grassland, and the impact of farmland, woodland, and grassland on runoff is specifically analyzed. At the same time, taking into account the changes in the layout and structural adjustment of land use by some ecological protection projects and policies such as returning farmland to woodlands and grasslands, two comprehensive scenarios are set up to increase the area of grassland and woodland, keep other existing land types and distribution unchanged, convert existing farmland into woodland and grassland, respectively, and explore the runoff response under future land use pattern changes (Table 6).

Monthly runoff response results

According to the scenario setting, the runoff characteristics under land use change in the Jing River Basin were quantitatively analyzed, and the monthly runoff process and hydrological response results are shown in Fig. 8 and Fig. 9: The multi-year average runoff and surface runoff under the three extreme scenarios were single farmland> single grassland > single woodland, the difference between woodland and farmland was obvious, and the average annual runoff was decreased by 9%, indicating that compared with woodland and grassland, farmland is conducive to the formation of production flow. The inherent reason is that the land surface of the farmland is more smooth, and the Jing River Basin is located in the Loess Plateau, the terrain is steep, and the water is easy to lose directly. At the same time, because the planting of crops breaks the soil structure, the arable layer close to the surface reduces the water seepage capacity and the interception effect of vegetation on rainwater and increases the surface saturation, resulting in the highly connected hydrological channels and the acceleration of the convergence speed. However, the rough surface of woodland and grassland and the poor connectivity of hydrological channels can prolong the infiltration time of rainwater, reduce the formation of surface runoff, and reduce the runoff volume in the basin. Underground runoff and actual evapotranspiration are manifested as single woodland > single grassland > single farmland, and the underground runoff and actual evapotranspiration of woodland were increased by 64% and 6%, respectively, reflecting that the interception of runoff between woodland and grassland promotes underground runoff

Table 6 Land use change scenarios of the Jing River Basin, China

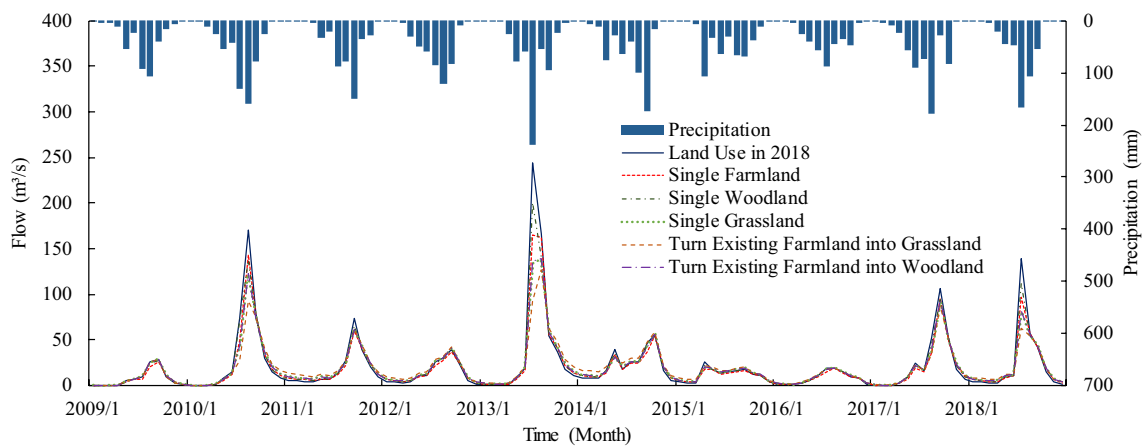| Scenario			Scenario description	Remarks
Extreme scenario		Scenario 1	Single farmland	
		Scenario 2	Single woodland	
		Scenario 3	Single grassland	
Integrated scenario		Scenario 4	Turn existing farmland into woodland	Return farmland to woodland
		Scenario 5	Turn existing farmland into grassland	Return farmland to grassland

Fig. 8 Comparison of monthly runoff processes under hypothetical scenarios in the Jing River Basin, China
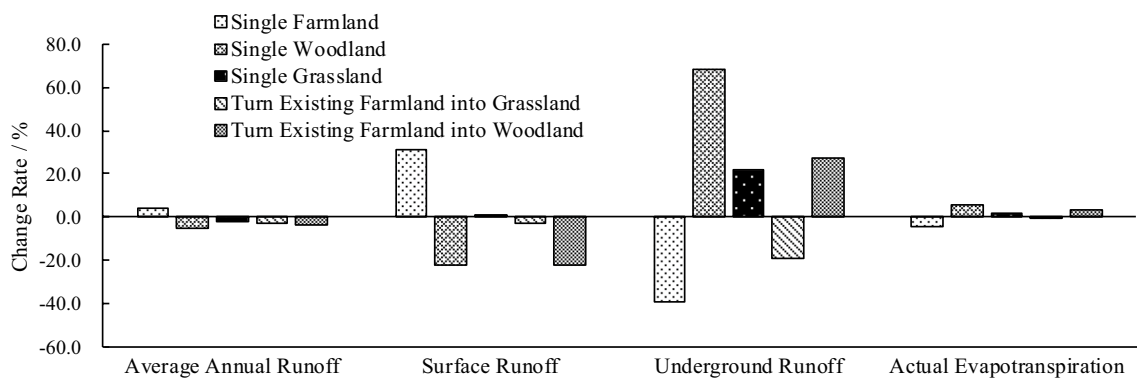

Fig. 9 Hydrological response under hypothetical scenarios in the Jing River Basin, China

and evapotranspiration in the basin. From the perspective of water balance, under the same rainfall conditions, the difference in water loss caused by evapotranspiration of different land use types and the difference in soil water consumption of different vegetation types are also indirect causes of runoff change. In order to qualitatively analyze the degree of inhibition of runoff between woodland and grassland, scenario 2 and scenario 3 were compared, and it was found that the average annual runoff reduction in the case of land use type single woodland was higher than that of single grassland land use type, and the actual evapotranspiration was also larger, indicating that the interception effect of woodland on runoff was more obvious than that of grassland, and the transpiration effect of woodland relative to grassland was larger.

Comparing scenario 4 with scenario 5, the response of runoff in the Jing River Basin to the change of land use pattern of returning farmland to woodlands and grasslands was further explored, and it can be seen that the runoff response trend of returning farmland to woodlands and grasslands is consistent, and compared with the basic

situation in 2018, both of which reduce runoff. However, the reduction of runoff is greater when all the existing farmland is converted to woodland, and the difference is mainly reflected in surface runoff and underground runoff, at which time the surface runoff decreases by 22% year-on-year, and the underground runoff increases by 21%, which is consistent with the runoff response in extreme scenarios. The reason is that forests have dense canopy structures that can effectively intercept precipitation, while grasslands rely solely on grass stems and thus have difficulty performing this function. Additionally, forests have multi-layered surface coverage, developed tree root systems, and rougher surfaces that can increase flow resistance during conflux, prolonging rainfall infiltration time. The tree root systems can then enhance soil infiltration capacity, enabling more conversion of surface runoff to groundwater runoff, indicating that changes in land use patterns affect the hydrological process of runoff.

Based on the runoff simulation results under different land use modes in 1980, 2018, 2040, and five scenario

modes, it is not difficult to find that with the increase of farmland in the study area, the watershed runoff gradually increased and the surface runoff also showed an increasing trend. As the area occupied by woodland and grassland increases, the watershed runoff gradually decreases, and with the exception of scenario 5 (conversion of existing farmland to grassland), underground runoff and actual evapotranspiration also increase. This result suggests that different land use types, through the interaction of vegetation with soil and surface runoff, can alter the hydrological processes of river runoff and exert strong biological control over the composition of runoff within the basin. For scenario 5, when grassland area increased, underground runoff and actual evapotranspiration did not increase compared to land use patterns in 2018, which may be related to the previous farmland being covered by various crops and also forming a continuous evapotranspiration amount leaving the surface, but the overall difference was small.

Discussion

In this paper, taking Jing River Basin as the research object, the CA-Markov model was used to simulate and predict the land use pattern in 2040. The monthly runoff of three hydrological stations in the Jing River Basin was simulated using the SWAT model, and the hydrological response under the influence of different land use types was analyzed. The results show that since 1980, the expansion of woodland, grassland, urban, and unused land area and the reduction of farmland and water area have changed the runoff size and various hydrological components in the basin, and the simulation results of the hypothetical land use scenario have verified the promotion effect of farmland on runoff and the inhibition effect of woodland and grassland on runoff, respectively. These conclusions are consistent with previous studies in other regions, such as Hernandez et al. (Hernandez et al. 2000) and Fohrer et al. (Fohrer et al. 2001) arguing that land use patterns directly affect the proportion of interception and transpiration within the watershed and that runoff from different land use types is different (Ghaffari et al. 2010), and Wang et al. (Wang et al. 2019) have also found that changes in woodland and grassland area are negatively correlated with changes in runoff and that farmland area is positively correlated with runoff changes.

Based on the simulated results for multiple different periods and hypothetical scenarios, this study validated that different land use types have varied impacts on the magnitude and composition of runoff, especially with farmland promoting runoff generation and woodland and grassland inhibiting the mechanism of runoff. This can enrich the research on the theoretical impact of land use change on water cycles in hydrology. Moreover, another specific finding of this study is

that land use change mainly has more significant influences on surface runoff and groundwater runoff, with only small impacts on annual runoff. Specifically, when woodland and grassland in the basin are destroyed and converted into large areas of farmland and bare unused land, the smoother ground surface cannot effectively intercept precipitation, resulting in faster conflux. Additionally, plowing of farmland loosens the topsoil and destroys the soil structure, reducing soil infiltration capacity. Coupled with the fact that major crops like wheat and corn in the Jing River Basin have weak root systems, it is difficult for rainwater to infiltrate into the soil, decreasing groundwater recharge and more readily forming surface runoff and exacerbating soil erosion in the basin. However, when woodland and grassland areas increase, their rougher surfaces and developed root systems can weaken the connectivity of hydrological channels, slow down the conflux process of rainfall, and increase infiltration to groundwater. The dense canopy structure and crowns of woodland can also intercept more rainwater, further reducing runoff. This finding further demonstrates that inappropriate guidance and changes in land use patterns will reduce water conservation functions and impact ecological environments. Policies like retiring farmland and restoring woodland and grasslands are beneficial for improving basin ecological environments and controlling soil erosion. Therefore, in future basin management, farmland areas and distributions should be rationally planned to prevent over-cultivation. Woodland and grassland can be interspersed in moderation to form ecological corridors, preserving green space while allowing other reasonable uses. This potential is more attractive for the Loess Plateau region in the temperate climate zone, because vegetation coverage is low, groundwater table burying depth is large, and soil erosion and water resource loss are serious in the Loess Plateau. Rational land use patterns can maximize land ecological system service functions and maintain ecological environment health while ensuring food security. In addition, it is worth noting that this paper only studies and analyzes the effects of different land use types on runoff; in fact, different vegetation types and coverage rates also affect the hydrological process of runoff to some extent. Therefore, in the follow-up study, it is necessary to further explore and verify the impact of vegetation cover.

Conclusion

Based on five periods of land use datasets in Jing River Basin, this paper simulated monthly runoff from 2008 to 2018 at three hydrological stations based on SWAT model and quantitatively analyzed the hydrological response of runoff to land use change in 2040 and five types of hypothetical land use scenarios. The main conclusions are as follows:

(1) Based on CA-Markov model, the land use pattern of Jing River Basin in 2020 was simulated and predicted, and the Kappa coefficient was 0.89, which could be used for the prediction of land use in 2040. The SWAT model has a good simulation accuracy for the monthly runoff process, which can be applied to study the impact of land use change on runoff in the watershed.

(2) The main land use types in the Jing River Basin are grassland, farmland, and woodland, which account for more than 96% of the total area of the river basin. The changes in land use types are mainly the conversion of large-scale farmland to woodland and grassland, as well as the rapid increase in the area of urban and unused land, but the overall change is not obvious.

(3) The land use mode in 2018 and 2040 slightly reduced the average annual runoff compared with 1980, which changed the water cycle process to a certain extent, increased underground runoff and actual evapotranspiration of the Jing River Basin, and reduced the surface runoff.

(4) Different types of land use runoff response characteristics are different, farmland is conducive to the formation of production streams, and woodland and grassland have an intercepting effect on surface runoff; while promoting underground runoff and watershed evapotranspiration, returning farmland to woodlands and grasslands has a reducing effect on surface runoff, which helps to improve the ecological environment in the basin.

Declarations

Ethics approval Not applicable.

Consent to participate All authors participated in this work.

Consent for publication All authors agree to publish.

Conflict of interest The authors declare no competing interests.

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