

Quantification of climate change and land cover/use transition impacts on runoff variations in the upper Hailar Basin, NE China

Yuhui Yan, Baolin Xue, Yinglan A, Wenchao Sun and Hanwen Zhang

ABSTRACT

Quantification of runoff change is vital for water resources management, especially in arid or semiarid areas. This study used the Soil and Water Assessment Tool (SWAT) distributed hydrological model to simulate runoff in the upper reaches of the Hailar Basin (NE China) and to analyze quantitatively the impacts of climate change and land-use change on runoff by setting different scenarios. Two periods, i.e., the reference period (before 1988) and the interference period (after 1988), were identified based on long-term runoff datasets. In comparison with the reference period, the contribution rates of both climate change and land-use change to runoff change in the Hailar Basin during the interference period were 83.58% and 16.42%, respectively. The simulation analysis of climate change scenarios with differential precipitation and temperature changes suggested that runoff changes are correlated positively with precipitation change and that the impact of precipitation change on runoff is stronger than that of temperature. Under different economic development scenarios adopted, land use was predicted to have a considerable impact on runoff. The expansion of forests within the basin might induce decreased runoff owing to enhanced evapotranspiration.

Key words | climate change, Hailar Basin, land cover/use change, runoff, SWAT model

INTRODUCTION

Water resources form the foundation of sustainable socio-economic development (Barnett *et al.* 2005). However, owing to continued global extreme climatic events and the negative influence of human activities, China is facing water resource problems that are becoming increasingly severe and that represent an important constraining factor on China's future sustainable socioeconomic development (Barnett *et al.* 2005; Piao *et al.* 2010; Voeroesmartly *et al.* 2010). In recent decades, under the influence of global climate change, the climate in northern China has shown an obvious trend of warming and drying (Fang *et al.* 2001;

Piao *et al.* 2009). The water cycle in many watersheds has been affected considerably, and runoff in major watersheds has shown a rapid decrease (Bao *et al.* 2012; Wang *et al.* 2018a). Human activities affect the hydrological cycle and the formation process of water resources by changing the mode of land use to varying degrees (Wheater & Evans 2009; Sterling *et al.* 2013), which can result in a series of problems such as wetland shrinkage and groundwater funneling (Kaushal *et al.* 2011; Sterling *et al.* 2013; Li *et al.* 2018). Therefore, it is of considerable scientific and practical importance to investigate the impact of climate change and land-use change on the hydrological cycle to resolve water resources problems in a changing environment.

Runoff is a vital link in the hydrological cycle that is also important in relation to the allocation of water resources

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Yuhui Yan
Baolin Xue (corresponding author)
Yinglan A
Wenchao Sun
Hanwen Zhang
College of Water Sciences,
Beijing Normal University,
Beijing 100875,
China
E-mail: xuebl@bnu.edu.cn

Baolin Xue
Yinglan A
Wenchao Sun
Beijing Key Laboratory of Urban Hydrological Cycle
and Sponge City Technology,
Beijing,
China

within a basin (Milly *et al.* 2005). Changes in runoff directly affect life and production activities in a basin (Piao *et al.* 2010). Therefore, it is of considerable importance to undertake quantitative research on the impact of climate and land-use changes on runoff. Methods commonly used for the quantitative analysis of the impact of environmental changes on runoff can be divided into three categories: comparative basin tests, statistical analysis methods, and hydrological model simulations (Mishra & Singh 2010). The comparative watershed method is used for the manual evaluation of the human impact on runoff by changing the natural geographical conditions (one or more watershed characteristics) of the test watershed. However, this approach is usually considered best for studying the effect of climate change in small watersheds but it is difficult to find two similar medium- or large-sized watersheds, and even the same watershed might undergo notable changes at different stages (Lorup *et al.* 1998). Statistical analysis can be used to analyze the trends of the change of hydrometeorological data, but it cannot consider the spatial heterogeneity of watersheds or the mechanisms via which land-use change and climate change might affect runoff change in watersheds (Gampe *et al.* 2016; Ishida *et al.* 2018). Therefore, comprehensive physically based tools are needed to obtain as much information as possible from limited existing data (Li *et al.* 2009). Hydrological models provide a framework for conceptualizing and studying relationships (Wang & Xu 2011). By linking model parameters directly with physically observable surface features, hydrological models can establish relationships among climate, human activities, and runoff (Leavesley 1994; Jothityangkoon *et al.* 2001). For example, Cuo *et al.* (2013) used the variable infiltration capacity hydrological model to analyze quantitatively the impact of climate change and land-use change on runoff in the upper reaches of the Yellow River Basin (China). Mango *et al.* (2011) used the Soil and Water Assessment Tool (SWAT) distributed hydrological model to analyze quantitatively the impact of climate change and land-use change on runoff in the Mala River Basin (Kenya). In hydrological model simulations, the mechanism of runoff formation is consistent with or without environmental change and no detailed data of human activities are needed (Legesse *et al.* 2003). Therefore, this study chose the hydrological model simulation method.

The impact of climate change and land-use change on runoff varies spatially, and therefore, research is usually conducted in specific watersheds (A *et al.* 2019a). Many studies have assessed the impact of climate change and land-use change on runoff in various watersheds in China. Research in an agricultural catchment of a tributary of the Jinghe River on the Loess Plateau highlighted that climate variability had greater influence than land-use change on the surface hydrological processes during 1981–2000 (Li *et al.* 2009). Results of a study in the Dongjiang River Basin indicated that climate variability and human activities each accounted for approximately 50% of the runoff change in the low-flow period (Zhou *et al.* 2018). Analysis in three main tributary subcatchments in the Yellow River Basin illustrated that climate change accounts for only 8% of the total decline in mean annual runoff, whereas human activities account for 92% (Li *et al.* 2020a). However, few studies have conducted relevant research on the Hailar Basin.

The Hailar Basin is a typical northern inland river basin in NE China. In recent years, it has encountered increasingly serious water shortage problems (Chi *et al.* 2018; Wang *et al.* 2019b). Therefore, it is of considerable urgency that research be conducted to alleviate the water shortage problems in this basin (Wang *et al.* 2019a). This study used the SWAT model to simulate runoff in the Hailar Basin, and the impact of climate change and land-use change on runoff was analyzed quantitatively. The main objectives of this study were as follows: (1) to determine abrupt change points in runoff according to runoff time series, (2) to analyze quantitatively the contribution rates of climate change and land-use change to runoff, and (3) to investigate runoff response under different climate change and land-use change scenarios. The ultimate aim was to provide support for strategic planning and allocation of water resources in the Hailar Basin.

STUDY AREA AND DATA

Study area

The Hailar Basin (47°38′–50°16′N, 117°43′–122°2′E) is located in the northeast of the Inner Mongolia Autonomous Region to the southwest of the city of Hulunbeier (Figure 1).

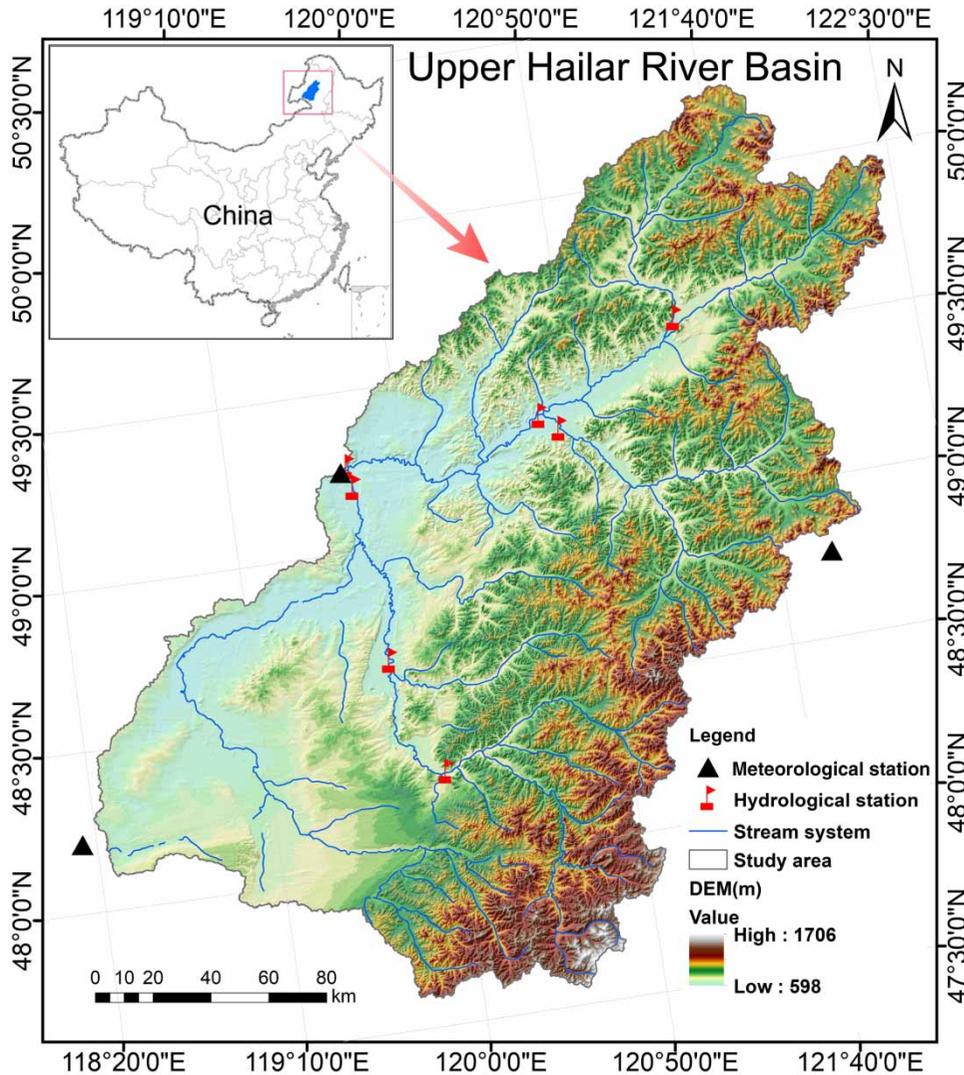


Figure 1 | Map showing location of the upper Hailar River Basin.

It has a temperate continental monsoon climate, and it covers an area of 54,500 km². The basin is located at the junction of the western slopes of the Daxing'anling mountains and the northeastern edge of the Inner Mongolia High Plain (Wang *et al.* 2018b). It is a fan-shaped basin that has large topographic fluctuation (Han *et al.* 2018a). The general trend of elevation (range: 536–1,706 m) is from low in the west to high in the east. The upper reaches of the Hailar Basin constitute the main area of the basin (Han *et al.* 2018b). There are two flood seasons annually: a spring flood season and a summer flood season. The spring flood season that usually occurs during March–May reaches its peak in May (Fang *et al.* 2018b). Runoff in this

period is derived primarily from snowmelt and precipitation. The summer flood season usually occurs during June–October, which is the period with the most concentrated precipitation (Xue *et al.* 2013b; A *et al.* 2019b).

Data sources

The data used in this study were divided into two parts. Part 1 data were used to analyze the water resources situation of the upper reaches of the Hailar Basin and to determine the relationship between runoff and climate factors. Part 2 were the input data required by the SWAT model. The input data of the SWAT model also included two main parts: spatial

data and attribute data. Spatial data mainly included digital elevation model data (90×90 m), land use/cover data ($1,000 \times 1,000$ m), soil distribution data, and spatial distribution data of the hydrological stations and meteorological stations. Attribute data mainly included soil type data, meteorological data, and hydrological data. Index tables of land-use type and soil type were established in the modeling process to ensure the required data in the model corresponded to each database.

Digital elevation model data: first, geometric correction was performed, and then clipping and projection transformation were undertaken using ArcGIS. Land use/cover data: first, the original data were downloaded from the Resources and Environment Science Data Center of the Chinese Academy of Sciences, and reclassification and projection transformation performed using ArcGIS. The data were divided into six categories: forest land, grassland, water area, urban land, unused land, and cultivated land, as shown in Figure 2(a). Soil type data and soil attribute data: these data were obtained from the Harmonized World Soil Database, which contains a large number of soil parameters. The data are presented in a gridded format using the WGS1984 coordinate system. The soil classification system adopted is mainly FAO-90. As the data provided in the database are international standards, the SPAW software was required to convert the data from international standards

to soil parameters of the United States Geological Survey standard. The soil distribution data in the Hailar Basin are shown in Figure 2(b). This study used daily meteorological and runoff data from 1980 to 2012. Meteorological data included daily precipitation, maximum and minimum temperature, humidity, and wind speed.

METHODOLOGY

Mutation analysis

Mann–Kendall mutation test

The Mann–Kendall (M-K) test is a widely used non-parametric test method recommended by the World Meteorological Organization. In recent years, many studies have adopted the M-K method to analyze the changes of trends in time series of precipitation, runoff, temperature, and water quality (Hamed & Rao 1998; Yue *et al.* 2002).

In this study, the M-K catastrophe test was used to analyze the catastrophe of the runoff time series. The M-K mutation test defines statistical variables by constructing order columns. Assuming time series $X = \{x_1, x_2, \dots, x_n\}$, r_i represents the cumulative number of the i th sample, and

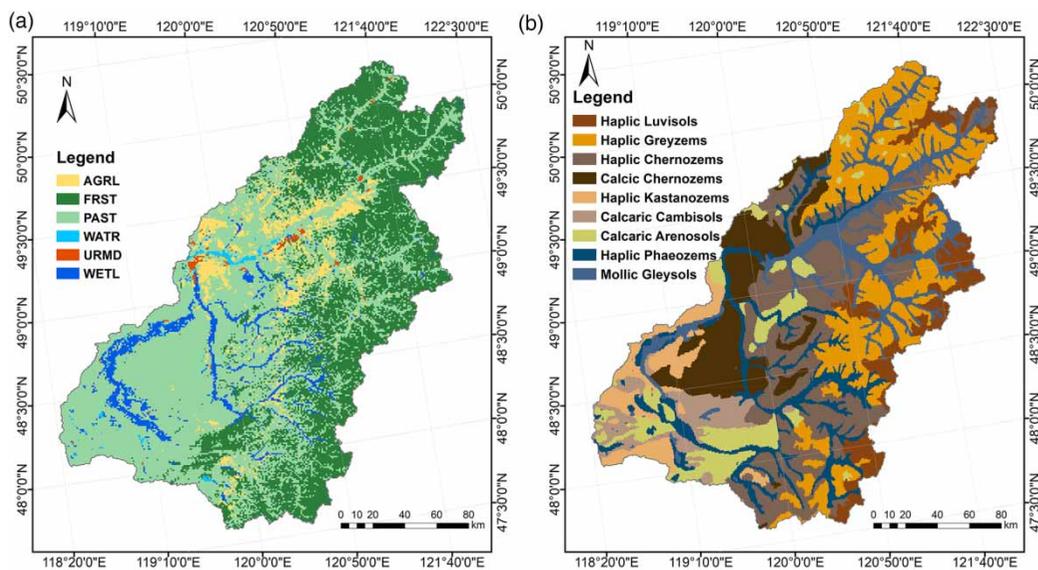


Figure 2 | (a) Distribution of land use/cover types and (b) distribution of soil types.

x_i is greater than x_j ($1 \leq j \leq i$), we have

$$s_k = \sum_{i=1}^k r_i \quad (k = 2, 3, 4, \dots, n) \tag{1}$$

$$r_i = \begin{cases} 1 & x_i > x_j \quad (j = 2, 3, \dots, i) \\ 0 & \text{other} \end{cases} \tag{2}$$

Under the assumption that the time series is random and independent, we have the following:

$$UF_k = \frac{s_k - E(s_k)}{\sqrt{\text{Var}(s_k)}} \quad (k = 1, 2, \dots, n) \tag{3}$$

When the elements x_1, x_2, \dots, x_n are independent of each other and continuously and uniformly distributed:

$$E(s_k) = k(k - 1)/4 \tag{4}$$

$$\text{Var}(s_k) = k(k - 1)(2k + 5)/72 \tag{5}$$

UF_i is a standard normal distribution. Given significance level α , if $|UF_i| > U$, there is an obvious trend change in the sequence, and the critical value of UF and UB is ± 1.96 . Arranging time series X in the reverse order and then performing the calculation according to the above equation, we have

$$\begin{cases} UB_k = -UF_k \\ k' = n + 1 - k \end{cases} \quad (k = 1, 2, \dots, n) \tag{6}$$

By analyzing the statistical sequences UF_k and UB_k , the trend change of sequence X can be analyzed further, which allows the mutation time to be defined and the mutation region to be identified. If the value of UF_k is >0 , it indicates that the sequence shows an upward trend and vice versa. When the value exceeds the critical line, it indicates that the upward or downward trend is significant. If the UF_k and UB_k curves have intersection points and the intersection points are between the critical straight lines, then the time corresponding to the intersection points is the time when the abrupt change is considered to start (Hamed 2008).

Sliding t -test technique

For a time series, the principle of the sliding t -test is to extract two subsequences of the main time series and then to test whether there is a significant difference between the average values of those two subsequences (Machiwal & Jha 2008). If there is a significant difference, the sequence is considered to have mutation (Zhao et al. 2008). Assuming time series $X = \{x_1, x_2, \dots, x_n\}$. Then, by taking a certain time in the series as a reference point and taking subsequence $X_1 = \{x_1, x_2, \dots, x_n\}$ and subsequence $X_2 = \{x_1, x_2, \dots, x_n\}$ forward and backward, respectively, based on the reference point, statistic t can be obtained based on the two subsequences as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{7}$$

In the above equation, $\bar{x}_1 = (1/n_1) \sum_{i=1}^{n_1} x_i$, $\bar{x}_2 = (1/n_2) \sum_{i=1}^{n_2} x_i$, and $s = \sqrt{(n_1 s_1^2 + n_2 s_2^2)/(n_1 + n_2 - 2)}$.

Then, statistic t obeys the t distribution with $n_1 + n_2 - 2$ degrees of freedom.

The specific steps of the sliding t -test for mutation are described in the following.

1. On the basis of the determination of the reference point, the lengths of subsequences n_1 and n_2 are determined. Normally, the lengths of the two subsequences are taken as the same, i.e., $n_1 = n_2$. Then, subsequences n_1 and n_2 are taken forward and backward, respectively.
2. By sliding the reference point backward in turn, taking out the corresponding subsequences, and calculating the corresponding statistics, the $n - (n_1 + n_2) + 1$ statistics can be obtained.
3. The obtained statistics are arranged in sequence to obtain the statistics sequence, the significance level ϑ is selected, and the corresponding standard statistics t_ϑ are obtained from a lookup table. The statistics sequence is drawn into a polyline graph. If $|t_i| > t_\vartheta$, the datum point can be adjudged the abrupt change point of the sequence (Dittmer 2013; Zhao et al. 2014b).

SWAT model

The SWAT model is a distributed hydrological model developed by the Agricultural Research Center of the United States Department of Agriculture (Arnold *et al.* 1998). The SWAT model is used widely for the simulation of hydrological cycle processes because its strong physical basis gives it the ability to simultaneously integrate the effects of topography, soil, land use, and weather (Yang *et al.* 2008). The model can simulate runoff change under different climate change conditions, land-use conditions, soil conditions, and watershed management conditions; thus, the SWAT model was selected for the runoff simulations conducted in this study (Moriassi *et al.* 2007). The model is calculated according to the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (8)$$

where SW_0 is the initial soil water content on the i th day, R_{day} is the precipitation on the i th day, Q_{surf} is the surface runoff on the i th day, E_a is the soil evaporation and plant transpiration on the i th day, W_{seep} is the seepage flow on the i th day, and Q_{gw} is the amount of groundwater on the i th day.

Model calibration and validation

In this study, the simulation of daily runoff was performed first. Then, the SWAT-CUP software was used to calibrate and verify the model. The data used included land-use data in 1980 and 2000 and meteorological data from 1980 to 2012. Based on runoff data recorded at the Bahou Station, the Latin Hypercube One factor At a Time (LH-OAT) method was used to analyze the sensitivity of the parameters, and those parameters with strong sensitivity were selected as adjustment parameters (van Griensven *et al.* 2006; Arnold *et al.* 2012). The SUFI-2 algorithm was used to determine the optimal ranges and values of the parameters through iterative calculation, and the optimal values of the parameters were introduced into the model through internal adjustment (Anoh *et al.* 2018). In this study, the effective evaluation method was used to evaluate the simulation accuracy of the SWAT model in the upper

reaches of the Hailar Basin based on three indices: the decision coefficient R^2 , Nash–Sutcliffe coefficient Ens , and relative error R_E (Bhatta *et al.* 2019). The expressions of the three indices are as follows:

$$R^2 = \frac{[\sum_{i=1}^n (Q_i^{obs} - Q_{ave}^{obs})(Q_i^{sim} - Q_{ave}^{sim})]^2}{\sum_{i=1}^n (Q_i^{obs} - Q_{ave}^{obs})^2 \sum_{i=1}^n (Q_i^{sim} - Q_{ave}^{sim})^2} \quad (9)$$

$$Ens = 1 - \left[\frac{\sum_{i=1}^n (Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^n (Q_i^{obs} - Q_{ave}^{obs})^2} \right] \quad (10)$$

$$R_E = \frac{\sum_{i=1}^n (Q_i^{obs} - Q_i^{sim})}{\sum_{i=1}^n Q_i^{obs}} \quad (11)$$

In the above equations, Q_i^{obs} is the measured runoff value, Q_i^{sim} is the simulated runoff value, Q_{ave}^{obs} is the measured average runoff value, and Q_{ave}^{sim} is the simulated average runoff value. The R^2 values (range: 0–1) represent the fitting degree between the simulated and measured values. The Nash–Sutcliffe coefficient (range: 0–1) is used to assess the quality of the hydrological model simulation results. Only when $Ens > 0.5$ can the simulation results be accepted. A value of Ens close to 1 indicates that the model simulation quality is good and its credibility is high. If the value of the relative error R_E is controlled to within 25%, the simulation results of the model can be considered within an acceptable range (Moriassi *et al.* 2007; Asl-Rousta *et al.* 2018).

Quantification of climate and land-use contributions to runoff change

Based on the SWAT model, this study used scenario analysis to separate the influences of various factors on runoff, i.e., assuming that climatic factors or human activity factors remain constant and that another factor changes accordingly, the contribution rate of this factor to runoff can be analyzed quantitatively.

This study used the M-K mutation test and sliding t -test to determine the time point of runoff mutation in the watershed. The year before the time point of abrupt change was defined as a period of natural runoff, i.e., runoff was assumed undisturbed by climate change and land-use change, whereas runoff after the time point of abrupt change was considered disturbed by both climate change

Table 1 | Model simulation scenario settings

Scenario	Land use/cover data	Meteorological data
1	1980s	1980–1988
2	1980s	1989–2012
3	2000s	1980–1988
4	2000s	1989–2012

and land-use change. To quantify the contributions of land-use change and climate change to runoff change, four scenarios were established (Table 1). A comparison of the simulated runoff under scenario 2 with that under scenario 1 allowed the analysis of the impact of climate change on runoff. Similarly, a comparison of the simulated runoff under scenario 3 with that under scenario 1 allowed the analysis of the impact of land-use change on runoff. A comparison of the runoff simulated under scenario 4 with that under scenario 1 allowed the analysis of the impact of both climate change and land-use change on runoff. Thus, the contribution rates of climate change and land-use change to runoff change were obtained.

In this study, Q_1 , Q_2 , Q_3 , and Q_4 were used to represent the average annual runoff simulated under scenarios 1, 2, 3, and 4, respectively. Thus, $Q_2 - Q_1$ represents the impact of climate change on runoff, $Q_3 - Q_1$ represents the impact of land use/cover change (land-use change) on runoff, and $Q_4 - Q_1$ represents the total change of runoff within the basin. In this paper, we define the following:

$$\omega_{cl} = \frac{Q_2 - Q_1}{Q_4 - Q_1} \quad (12)$$

$$\omega_h = \frac{Q_3 - Q_1}{Q_4 - Q_1} \quad (13)$$

Scenario setting and model analysis

To investigate the impact of climate change on runoff in the upper reaches of the Hailar Basin, the change values of precipitation and temperature were determined according to the possible range of future climate change. In simulating runoff in the upper reaches of the Hailar Basin, 25 different climate change combination programs were considered

based on the following scenarios: current precipitation unchanged, 10% and 20% increase in precipitation, 10% and 20% decrease in precipitation, current temperature unchanged, 1 °C and 2 °C increase in temperature, and 1 °C and 2 °C decrease in temperature.

To explore the influence of land use on runoff, this study used the cellular automata–Markov (CA–Markov) model to simulate land-use development scenarios based on existing land-use datasets of the Hailar Basin. Land use in the upper reaches of the Hailar Basin was simulated for 2030 and 2050, and the associated runoff was investigated according to historical development trends and existing problems within the Hailar Basin.

Land use/land cover prediction

This study used the CA–Markov model to predict future land use/land cover. The CA–Markov model is a powerful tool that combines the advantages of the Markov chain and cellular automata.

The CA–Markov model describes land-use change from one period to another, which allows predictions of the future trend of land-use change. The following formula can be used to predict land use:

$$S_{t+i} = P_{ij}S_t \quad (14)$$

where S_t and S_{t+i} are the states of the land-use structure at time t and $t + i$, respectively and P_{ij} is the state-transition matrix.

A cellular automaton represents a gridded dynamics model with strong spatial computing capability. The CA–Markov model can be expressed as follows:

$$S_{t+i} = f(S_t, N) \quad (15)$$

where S is a finite discrete state set element, N is a cellular neighborhood, t and $t + i$ are different moments, and f is the cell transformation rule in local space.

The model can simulate the temporal and spatial evolutions of complex systems, and it has been used widely in many studies (Mitsova *et al.* 2011; Sang *et al.* 2011). The detailed parameters and steps of land-use prediction using

the CA–Markov model are as follows. (1) Data format conversion and reclassification are performed to obtain fixed land-use types. (2) A state-transition probability matrix and a transition area matrix are obtained using the CA–Markov module. (3) A transitional fitness image set is established. (4) The CA filter and number of cycles are determined. (5) The accuracy of the predicted image is evaluated according to the actual image. In this study, a map of land use in 2000 was used as the basic image, and an assembly transition probability matrix of land-use maps in 2005 and 2015 was used to predict the land-use situation in 2030 and 2050.

RESULTS

Runoff trend analysis

The linear analysis and 5-year moving average curve of runoff during 1980–2012 at the Bahou Station at the outlet of the upper reaches of the Hailar Basin are shown in Figure 3. In the past 30 years, annual runoff at the Bahou Station has fluctuated but generally diminished with a rate that has become more obvious since 1990. Annual runoff at the Bahou Station has ranged from a maximum value of $69.82 \times 10^8 \text{ m}^3$ in 1984 to a minimum value of $10.28 \times 10^8 \text{ m}^3$ in 2007 with a trend of $-0.24 \times 10^8 \text{ m}^3/\text{a}$.

In this study, the M-K method and sliding t -test method were used to test for catastrophe in the runoff sequence. UF_k values >0 indicate that the sequence shows an upward trend and vice versa. When the values exceed the critical line, the

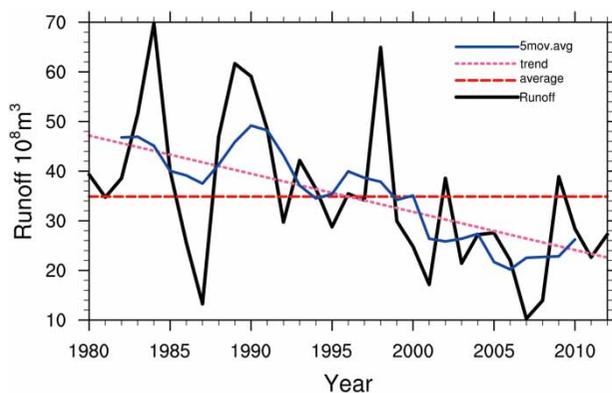


Figure 3 | Results of the trend analysis of runoff at the Bahou Station.

upward or downward trend is considered significant. The range beyond the critical line is determined as the time zone in which the abrupt change occurs. If there is an intersection point between the UF_k and UB_k curves and that intersection point lies between the critical lines, the time corresponding to the intersection point is the time at which the abrupt change starts. As shown in Figure 4(a), the UF_k value after 1995 is <0 , which indicates that the runoff sequence at the Bahou station began to decline continuously after 1995. In 2003, the UF_k value was lower than -1.96 , indicating that runoff had a significant decreasing trend based on the significance level test of 0.05. As shown in Figure 4(a), during 1980–1995, the UF_k and UB_k curves had intersection points between the critical lines at around 1980, 1982, 1986, 1988, and 1992. Therefore, the sliding t -test method was used to determine the mutation year in this study.

In this study, the sliding t -test method was also used to analyze the Bahou Station runoff time series. To avoid variable point drift caused by different subsequence lengths, the sliding length was changed repeatedly. Finally, it was determined that the length of the two sliding sequences should be 4, i.e., $n_1 = n_2 = 4$, and 33 statistics relating to the Bahou Station formed the corresponding statistical sequence. If the significance level $\vartheta = 0.05$ were selected, the statistic $t-t(6)$ and the critical value were found to be $t_{0.05}(6) = 1.943$, and each statistical sequence and critical value are plotted on the graph for the mutation analysis. The analysis of Figure 4(b) reveals that for the annual runoff series, the t statistics of the Bahou Station exceed the critical values in two places: 1987 and 1988, both of which are possible abrupt years. As the M-K mutation test identified 1988 as the intersection point of the UF_k and UB_k curves, it can be considered that mutation occurred in the annual runoff at the Bahou Station in 1988. As water resources are affected by various climate change factors, e.g., rising temperature and extreme weather, runoff of the major rivers in northern China currently shows an overall downward trend. Therefore, the identified sudden change is probably attributable to climate change because temperature rise leads to increased evapotranspiration. Based on these two methods, the mutation point was set to 1988, and the study period was divided into the reference period (before 1988) and the interference period (after 1988).

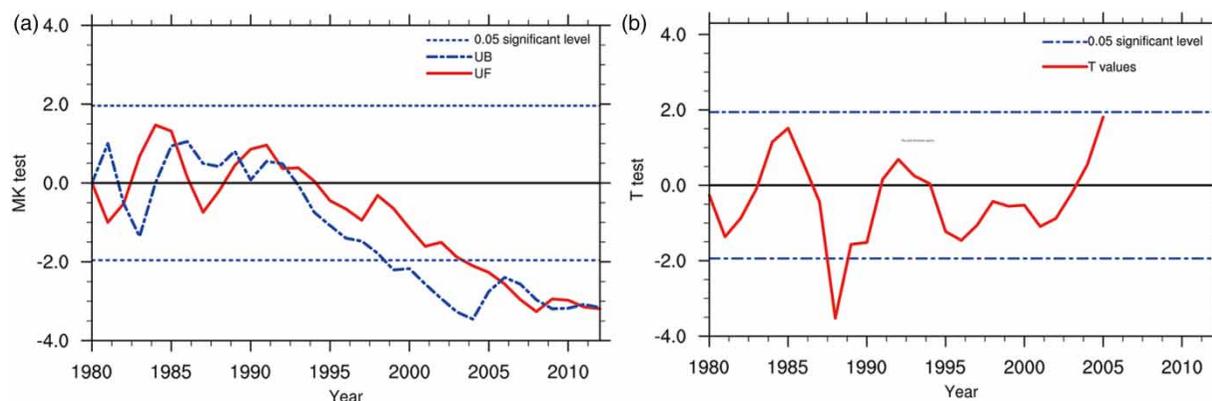


Figure 4 | Results of (a) the M-K mutation test and (b) the moving t -test.

Model calibration and validation

Parameter sensitivity analysis and model calibration are closely linked, and both are essential processes for runoff simulation using hydrological models. The SWAT-CUP software can be used to perform sensitivity analysis and calibration on relevant parameters for a runoff simulation. Combined with the actual situation of the basin, the LH-OAT method provided in SWAT-CUP was used in this study to select parameters related to runoff simulation in the northern region for sensitivity analysis and calibration, as shown in Table 2.

Through the sensitivity analysis of the SWAT model, 11 parameters with high sensitivity were selected to calibrate and verify the model (Table 2). In this study, the preheating period of the model was taken as 1988–1989, 1990–2006 was taken as the calibration period, and 2007–2012 was taken as the validation period. The SWAT-CUP software was used to calibrate the model parameters, and the monthly runoff at the Bahou Station was used to calibrate and verify the model.

In the calibration period, the R^2 , Ens , and R_E values of the simulated monthly runoff at the Bahou Station were 0.75, 0.71, and 20.8%, respectively, while the corresponding values in the validation period were 0.74, 0.70, and 20.3%, respectively, proving the suitability of the SWAT model for runoff simulation in the upper reaches of the Hailar Basin. The simulation results are shown in Figures 5 and 6.

Table 2 | Parameter sensitivity analysis

Parameter name	Variable name	Rank	Ranges	The most suitable value
GW_DELAY	Groundwater delay factor	1	(30,450)	45.75
ALPHA_BF	Base-flow recession constant	2	(0,1)	0.90
SMFMN	Snowmelt coefficient on December 21	3	(-10,10)	-2.42
CANMX	Maximum canopy storage	4	(0,100)	76.25
SOL_AWC	Available water capacity of the soil layer	5	(0,1)	0.15
SMFMX	Snowmelt coefficient on June 21	6	(-10,10)	6.75
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	7	(0,2)	0.96
CN2	Curve number	8	(20,100)	46
SMTMP	Snow melting	9	(-10,10)	-2.75
ESCO	Soil evaporation compensation coefficient	10	(0.01,1)	0.46
SFTMP	Snow temperature	11	(-10,10)	-3.63

Contribution of land use and climate change to runoff variation

According to the abrupt change years, the study period was divided into the reference period (before 1988) and

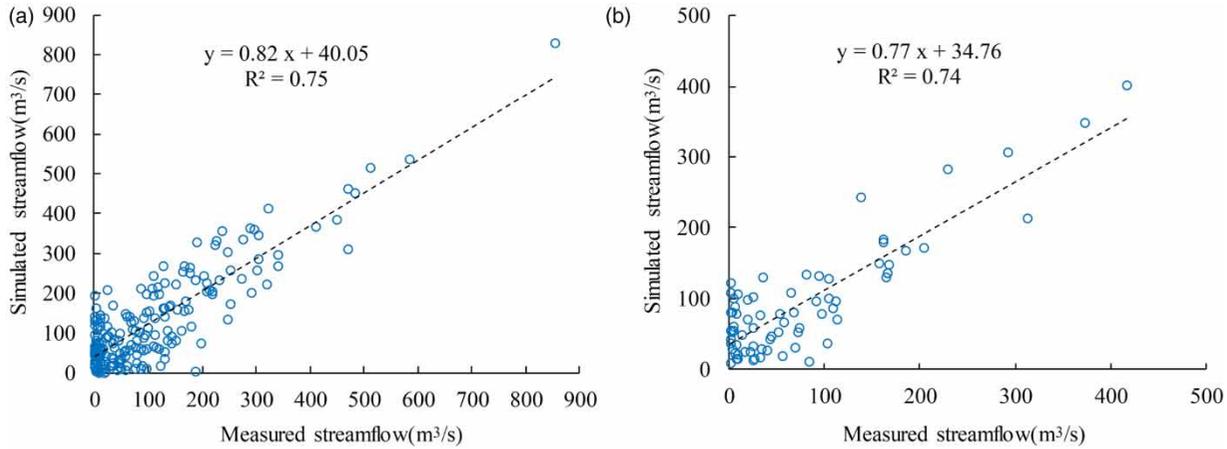


Figure 5 | Correlation between simulated and measured values of monthly streamflow at the Bahou Station: (a) calibration period and (b) validation period.

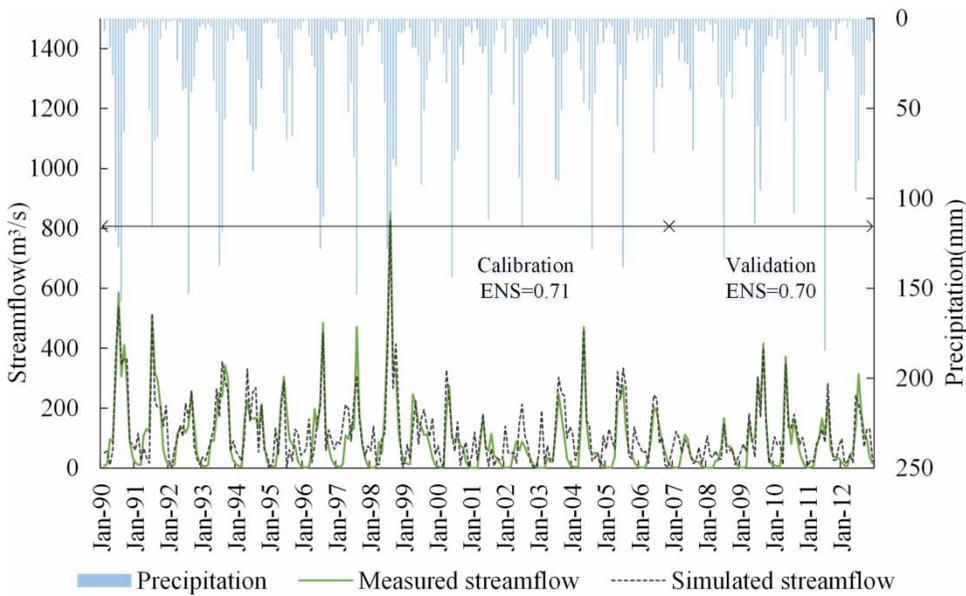


Figure 6 | Measured and simulated monthly streamflow graphs (Bahou Station) for the calibration period and the validation period.

interference period (after 1988). Using the meteorological data and land-use data of different periods and by establishing different scenarios, the contribution rates of land-use change and climate change to runoff in the upper reaches of the Hailar Basin were calculated. As shown in Tables 3 and 4, the average annual runoff simulated under scenarios 1–4 was 125.43, 104.05, 121.23, and 99.85 m³/s, respectively. The analysis of scenarios 1 and 2 suggests that under the influence of climate change, annual average runoff has decreased by 21.38 m³/s. The analysis of scenarios 1 and 3

Table 3 | Comprehensive scenario simulation results

Scenario	Annual average runoff (m ³ /s)	Influence of land-use change on runoff (m ³ /s)	Influence of climate change on runoff (m ³ /s)
1	125.43	–	–
2	104.05	–	–21.38
3	121.23	–4.2	–
4	99.85	–4.2	–21.38

suggests that under the influence of land-use change, annual average runoff has decreased by 4.2 m³/s. The

Table 4 | Simulated response of land-use change and climate change

Period	Time	Simulated annual average runoff (m ³ /s)	Varied runoff (m ³ /s)	Influence of land-use change on runoff (m ³ /s)	Influence of climate change on runoff (m ³ /s)
Reference period	1980–1988	125.43	–	–	–
Interference period	1989–2012	99.85	–25.58	–4.2(16.42%)	–21.38(83.58%)

analysis of scenarios 1 and 4 suggests that under the joint influence of climate change and land-use change, annual average runoff has decreased by 25.58 m³/s. Specifically, $Q_2 - Q_1 = 21.38 \text{ m}^3/\text{s}$, $Q_3 - Q_1 = 4.2 \text{ m}^3/\text{s}$, $Q_4 - Q_1 = 25.58 \text{ m}^3/\text{s}$, $\omega_{cl} = 83.58\%$, and $\omega_h = 16.42\%$. The contribution rate of climate change (land-use change) to runoff change in the basin is 83.58% (16.42%); consequently, it can be concluded that climate change has a greater impact than land-use change on runoff change in the basin.

Scenario simulation of climate change and land use/cover change

Climate change scenarios

As shown in Table 5, under the condition of constant basin temperature, surface runoff will increase with the increase of precipitation. Under the condition of unchanged precipitation, surface runoff will change with the change of temperature. In all temperature-drop scenarios, surface runoff shows an increasing trend, whereas in all temperature-rise scenarios, surface runoff shows a decreasing trend.

As shown in Table 6, values when $\Delta T = 0$ represent the response of runoff to changed precipitation at constant temperature. It can be seen that the increase of precipitation increases runoff, and the more precipitation increases, the

Table 5 | Relative variation of mean annual runoff for different scenarios (m³/s)

Variations in temperature	Variations in precipitation				
	P(1+20%)	P(1+10%)	P	P(1-10%)	P(1-20%)
T+2 °C	24.11	8.70	–8.82	–20.51	–42.20
T+1 °C	28.69	13.04	–7.91	–16.98	–37.57
T	31.99	16.23	0.00	–13.87	–33.56
T–1 °C	34.63	19.56	8.76	–11.49	–30.65
T–2 °C	36.23	22.36	15.16	–9.63	–28.15

Table 6 | Relative variation of mean annual runoff for different scenarios (%)

Variations in temperature	Variations in precipitation				
	$\Delta P = 20\%$	$\Delta P = 10\%$	$\Delta P = 0$	$\Delta P = -10\%$	$\Delta P = -20\%$
$\Delta T = +2$	19.82	7.15	–7.25	–16.86	–34.70
$\Delta T = +1$	23.59	10.72	–6.50	–13.96	–30.86
$\Delta T = 0$	26.30	13.34	0	–11.40	–27.59
$\Delta T = -1$	28.47	16.08	7.20	–9.45	–25.20
$\Delta T = -2$	29.79	18.38	12.46	–7.92	–23.14

greater the increase in runoff. Values when $\Delta P = 0$ indicate the response of runoff to temperature change when precipitation is constant. It can be seen that runoff decreases as temperature increases, and the more the temperature increases, the more runoff decreases. Values when neither ΔT nor ΔP are zero indicate the runoff response effect when both temperature and precipitation change. It can be seen that when temperature decreases and precipitation increases, the increase in runoff is greatest. When temperature increases and precipitation decreases, a decrease in runoff is greatest. When precipitation increases by more than 10%, runoff increases markedly, indicating that precipitation has a more significant impact on runoff.

Land-use change scenarios

According to the trend of land-use change in the Hailar Basin, and with reference to the problems encountered with current economic development and ecological protection in this region, this study simulated land-use scenarios in 2030 and 2050 using the CA–Markov model and analyzed the impact of future land-use change on watershed runoff. In simulating and predicting future land-use situations, three development models were established: natural development, ecological protection, and economic development. The distribution maps of land use in 2030 and 2050 under these three economic development models are shown in Figure 7.

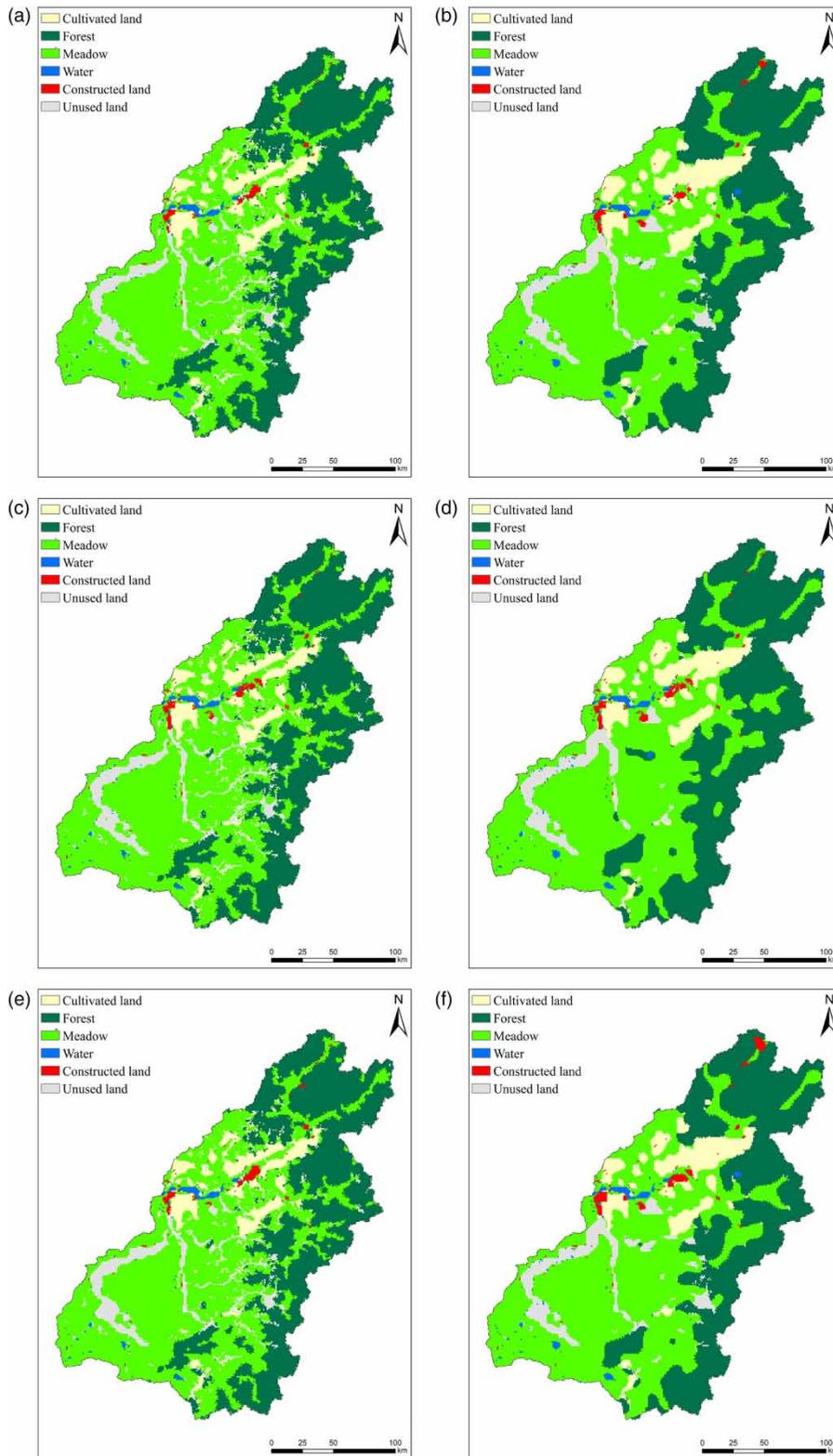


Figure 7 | Distribution of land-use types under different economic development scenarios: (a) natural growth scenario in 2030, (b) natural growth scenario in 2050, (c) ecological protection scenario in 2030, (d) ecological protection scenario in 2050, (e) economic development scenario in 2030, and (f) economic development scenario in 2050.

Table 7 | Proportion of land-use types in different scenarios (%)

Land-use type	Natural growth		Ecological protection		Economic development	
	2030 (%)	2050 (%)	2030 (%)	2050 (%)	2030 (%)	2050 (%)
Cultivated land	7.902	7.983	7.728	7.658	7.937	8.228
Forest	34.294	34.501	34.294	35.966	34.190	34.094
Meadow	50.456	50.027	50.560	50.108	50.454	49.864
Water	0.720	0.895	0.721	0.895	0.686	0.895
Constructed land	0.639	0.779	0.743	0.860	0.744	1.104
Unused land	5.989	5.815	5.954	4.513	5.989	5.815

It can be seen from Table 7 that future areas of various land-use types will increase or decrease to varying degrees. In the case of natural growth, from 2030 to 2050, the proportions of cultivated land, forest land, water areas, and construction land will increase, while the proportions of grassland and unused land will decrease. In the case of ecological protection, from 2030 to 2050, the proportions of forest land, water areas, and construction land will increase, while the proportions of cultivated land, grassland, and unused land will decrease. In the context of economic development, from 2030 to 2050, the proportions of cultivated land, water areas, and construction land will increase, while the proportions of forest land, grassland, and unused land will decrease.

The runoff simulation results under the different land-use scenarios are shown in Table 8. Under the natural growth scenario, ecological protection scenario, and economic development scenario, runoff shows a decreasing trend, but the degree of runoff reduction differs between the scenarios. Under the condition of natural growth, the proportion of the forest area will increase, the proportion of the grassland area will decrease, and runoff will decrease in 2030 and 2050. Under the condition of ecological protection, the proportion of the forest area will still increase and

the proportion of the grassland area will still decrease in 2030 and 2050; however, in comparison with the natural growth scenario, both an increase in the proportion of the forest area and a decrease in runoff will be greater. Under the condition of economic development, the proportion of the forest area will increase slightly in 2030 and 2050, the proportion of the grassland area will decrease greatly, and the proportion of cultivated land will increase markedly; however, runoff in the basin will still show a decreasing trend. This shows that the increase/decrease of the forest land area has a reasonably direct impact on the increase/decrease of runoff. Forest land can improve both the regional climate and the soil environment while reducing the surface temperature and direct evaporation of water to a certain extent, which can play a role in conserving water resources and intercepting runoff (Xue *et al.* 2015b). In future planning, the proportion of ecological land (e.g., forest land and grassland) should be adjusted appropriately to alleviate the trend of decreasing runoff within the basin.

DISCUSSION

According to the derived results, runoff in the Hailar Basin has shown a downward trend over the previous 30 years, with a more obvious downward trend since around 1990. A decrease in runoff in the basin is attributable to both decreased rainfall and changes of the underlying surface conditions (Xue *et al.* 2013a; Zhao *et al.* 2014a), e.g., increase of forest land and grassland areas, increase of forest land coverage rate, greater retention of surface runoff, and increase of surface evaporation in the basin (Wang *et al.* 2012). According to the results of the abrupt change test,

Table 8 | Change of runoff under different land-use scenarios

	Land-use change scenarios	Rate of change in runoff (%)
2030	Natural growth scenario	-0.515
	Ecological protection scenario	-0.704
	Economic development scenario	-0.371
2050	Natural growth scenario	-0.942
	Ecological protection scenario	-1.408
	Economic development scenario	-0.152

annual runoff in the basin experienced an abrupt change in 1988. According to the UF curve, runoff has shown a decreasing trend since 1988. Moreover, the UF curve exceeds the 0.05 critical line after 2003, indicating that the trend of decrease is very significant. The main reason might be that climate change has caused rainfall in the basin to change abruptly (Fang *et al.* 2018a). However, since China implemented the policy of returning farmland to forest in the 1990s, the rate of coverage of forest land in the basin has increased, which will have increased interception by vegetation and delayed runoff (Wang *et al.* 2015; Xue *et al.* 2017a).

Based on the determined catastrophe years, this study considered annual runoff data during 1980–2012 as the research object and divided the research period into the reference period (before 1988) and the interference period (after 1988). By setting different scenarios, it was established that the contribution rate of climate change (land-use change) to runoff change in the basin was 83.58% (16.42%). The main land-use types in the upper reaches of the Hailar Basin are grassland and forest land, and there has been little change in the underlying surface for many years. Moreover, the area is located in the grassland area of northern China, where the population density is low and there is little impact from human activities (Xue *et al.* 2013b; Wang *et al.* 2017). Consequently, given the global increase in temperature and regional decrease of precipitation, climate change can be considered the main reason for runoff change in the Hailar Basin.

In order to further explore the runoff variations under climate change and land-use change, this paper sets up different future scenarios for research based on the results of runoff variation attribution analysis. In this study, different scenarios were established to explore the changes of watershed runoff under the effects of both climate change and land-use change. The climate change scenarios showed that runoff in the basin will increase with the increase of precipitation. For every 10% increase in precipitation, the runoff will increase by 13.34% on average. Runoff in the basin will decrease with an increase in air temperature. For every 1 °C increase in air temperature, runoff will decrease by 6.5% on average. Overall, the influence on runoff of precipitation change is greater than that of temperature change. The main reason might be that runoff in this basin is replenished primarily by precipitation (A *et al.*

2018). Precipitation has a direct effect on runoff change, whereas the effect of temperature on runoff change is indirect (Fu *et al.* 2018; Li *et al.* 2020b). The simulation scenarios of land-use change showed that in 2030 and 2050, under the three different scenarios of natural development, ecological development, and economic development, runoff in the basin will show a decreasing trend to differing degrees. The main reason might be an increase in the proportion of the forest land area and a decrease in the proportion of the grassland area (Xue *et al.* 2015a). An increase in the forest land area has the functions of conserving water and fixing soil, which have a certain effect on intercepting runoff (Wang *et al.* 2014; Xu *et al.* 2014). Moreover, an increase in the forest land area leads to increased evapotranspiration, which can improve both the regional microclimate and the soil environment to a certain extent, reducing watershed runoff (Wang *et al.* 2012; El Kateb *et al.* 2013). Compared with land-use change, climate change has a more significant impact on runoff change in the Hailar Basin. To optimize water resources allocation in the basin, the layout of land use must be optimized to cope with the challenges brought by climate change (Fang *et al.* 2020). It will be important to consider changing the proportion of ecological land (e.g., forest land and grassland) to regulate and control runoff in the basin (Xue *et al.* 2017b; Zhang *et al.* 2017).

Certain problems encountered in this research should be resolved in future work. First, this study used only runoff data from 1980 to 2012 for the mutation analysis, and the time series was incomplete. The next step would be to collect a dataset that is more complete for specifying the mutation year. Second, the predictions of land use in 2030 and 2050 were based on the CA–Markov model and relied mainly on the transformation matrix derived using land-use maps from 2005 to 2015. However, the implementation of land-use management strategies by the Chinese government might change in the future, which would have a certain impact on the land use/coverage scenarios predicted in this study for 2030 and 2050. Third, different combinations of temperature and rainfall were used to drive the SWAT model. The climate change scenario was reasonably simple and did not start from actual conditions. In the next step, the climate forecast could be corrected based on actual local climate conditions to provide the improved simulation of future runoff.

CONCLUSIONS

This study employed the SWAT distributed hydrological model to assess the hydrological response of the Hailar Basin to climate change and land-use change, and to analyze its impact quantitatively. First, the runoff change trend at the Bahou Station on the upstream reaches of the Hailar Basin over the previous 30 years was analyzed, and the year of abrupt change in runoff was determined. The SWAT model was used to simulate runoff, and the contribution rates of climate change and land-use change to surface runoff were separated. Based on the principle of the water balance, the contributions of these two factors to runoff were calculated. Using combinations of different climate and land-use scenarios, the natural runoff under the influence of climate change and land-use change was simulated. The derived results are presented below:

- (1) Annual runoff at the Bahou Station generally showed a downward trend that exhibited diminishing volatility. The long-term runoff sequence changed abruptly in 1988. This study divided the runoff sequence into the reference period (before 1988) and the interference period (after 1988).
- (2) The SWAT model demonstrated satisfactory applicability to simulating runoff at the Bahou Station. The R^2 , Ens , and R_E values of the monthly runoff simulated in the calibration period were 0.75, 0.71, and 20.8%, respectively, while the corresponding values in the validation period were 0.74, 0.70, and 20.3%, respectively, proving that the model was suitable both for the calculation of the runoff contribution rate and for the simulation of runoff under different scenarios.
- (3) Compared with land-use change, climate change was found to have a more significant impact on runoff change in the river basin. The contribution rate of climate change (land-use change) to runoff change in the river basin was 83.58% (16.42%).
- (4) According to different combinations of temperature and rainfall change, temperature decrease will lead to evaporation and snowmelt runoff decrease, which will result in increased surface runoff in the watershed. A rise in temperature will increase both snowmelt runoff and evaporation; however, the amount of evaporation

will be greater than the amount of runoff derived from snowmelt, which will lead to an overall reduction in runoff. A significant positive correlation was found between the change in precipitation and runoff change. Moreover, it was found that when precipitation increases (decreases) and temperature decreases (increases), an increase (decrease) in runoff is greatest.

- (5) The projected impact of land use on runoff under different development scenarios was different. Runoff under the three development modes of natural development, ecological protection, and economic development showed a decreasing trend. In comparison with the natural development scenario, the reduction in runoff under ecological protection will be greater. Under the economic development scenario, runoff will still show a decreasing trend. It was established that forest land has a certain effect on decreasing runoff flow, i.e., an increase in the forest area will lead to decreased surface runoff. In future planning, the proportion of ecological land (e.g., forest land and grassland) should be adjusted appropriately to alleviate the trend of decreasing runoff within the basin.

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COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interest.

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