Vol 50 | Issue 1 | February 2019

NHF · British Hydrological Society · IWA PUBLISHING

Hydrology Research

ISSN 0029-1277
iwaponline.com/hr

Spatiotemporal impacts of land use land cover changes on hydrology from the mechanism perspective using SWAT model with time-varying parameters

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ABSTRACT

It is critically important to quantify the impact of land use land cover (LULC) changes on hydrology, and to understand the mechanism by which LULC changes affect the hydrological process in a river basin. To accurately simulate the hydrological process for a watershed like the Wei River Basin, where the surface characteristics are highly modified by human activities, we present an alternative approach of time-varying parameters in a hydrological model to reflect the changes in underlying land surfaces. The spatiotemporal impacts of LULC changes on watershed streamflow are quantified, and the mechanism that connects the changes in runoff generation and streamflow with LULC is explored. Results indicate the following: (1) time-varying parameters' calibration is effective to ensure model validity when dealing with significant changes in underlying land surfaces; (2) LULC changes have significant impacts on the watershed streamflow, especially on the streamflow during the dry season; (3) the expansion of cropland is the major contributor to the reduction of surface water, causing decline in annual and dry seasonal streamflow. However, the shrinkage of woodland is the main driving force that decreases the soil water, thus contributing to a small increase in streamflow during the dry season.

Key words | hydrological components, land use land cover changes, mechanism, Soil and Water Assessment Tool (SWAT) model, time-varying parameters

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INTRODUCTION

Land surface characteristics can have significant influences on the hydrology of a watershed by affecting rainfall infiltration, runoff generation, overland and channel flows, and other hydrological processes. Changing the land use and land cover land use land cover (LULC) is thus one of the ways that human activities have altered the regional hydrological cycle in many places. A large body of literature has documented the contribution of LULC changes to runoff variability in many regions (e.g., Li *et al.* 2007; Zhang *et al.* 2010; Nie *et al.* 2011; Tang *et al.* 2011; Yan *et al.* 2013; Alvarenga *et al.* 2016), while many other studies have attempted to evaluate the hydrological responses to different LULC patterns (e.g., Wang *et al.* 2008; Mao & Cherkauer 2009; Gessesse *et al.* 2015; Li *et al.* 2015; Owuor *et al.* 2016; Visessri & McIntyre 2016; Woldesenbet *et al.* 2017).

The approaches for studying the impact of LULC changes on hydrological processes typically involve multivariate statistics and hydrological modeling. For example, Schilling *et al.* (2010) applied the Generalized Additive Model to quantify the impact of LULC changes on the discharge in the upper Mississippi River. Mango *et al.* (2011) used the Soil and Water Assessment Tool (SWAT) model to assess land use and climate change impacts on the hydrology of the upper Mara River basin, Kenya. Moiwo & Tao (2014) studied the effects of land use change on groundwater recharge and discharge in a semi-arid area in northeast China using an integrated recharge–discharge model. Eum *et al.* (2016) employed the VIC hydrological model to evaluate the comparative effects of climate and land cover changes on hydrological responses of the Muskeg River in Alberta, Canada. The use of physically based distributed hydrological models such as SWAT and VIC has been gaining popularity in recent years, and is considered as an effective way to simulate the complex hydrological processes and to quantify the impact of LULC changes on those processes.

These hydrological models are very useful tools for understanding the pathways that LULC affects streamflow, but they are still a very simplified representation of the real world. An important step in using hydrological models is to calibrate the models by adjusting model parameters so that the models can simulate observed hydrological quantities such as streamflow in a reasonably accurate way. Model calibration serves as a way to minimize model errors that might be associated with model structural uncertainty, model resolution, and the crude representation of physical processes in model parameterizations. It has been a regular practice for most if not all hydrological models. Because model errors can depend on many things, such as the watershed characteristics, hydrological models are often calibrated for each individual watershed. In this way, the calibrated parameters reflect all the unique characteristics of that watershed in an aggregated way. It is important to note that applying the model with calibrated parameters from one watershed to a different watershed can degrade the model performance and thus is not to be recommended.

However, studies on the impact of LULC changes on streamflow have not necessarily followed the same philosophy. Models are often calibrated and validated under one LULC scenario, then the calibrated model parameters are assumed to be time-invariant and suitable when simulating hydrological processes under different LULC scenarios (He *et al.* 2013; Zhang *et al.* 2014; Tan *et al.* 2015; Liu *et al.* 2017; Xia *et al.* 2017). This may be acceptable for watersheds that have not been significantly disturbed by human activities. But for watersheds that are highly modified by human activities resulting in significant alterations in watershed characteristics, it is implausible to assume the model parameters are still suitable under the new LULC condition (Deng *et al.* 2016). The calibrated model parameters, to a large extent, compensate the model deficiencies and errors to best fit the observations during the calibration period, thus their values are often dependent upon LULC patterns and land surface characteristics. To properly reflect the LULC changes and to ensure the model performance is not degraded, a new set of parameter values is desirable for the new LULC condition. We hypothesize that using time-invariant parameters during periods with different LULC conditions may cause models to run in an inferior stage and unable to properly simulate hydrological processes, thereby the impact of LULC changes on watershed hydrology could have been inaccurately estimated. In this study, we propose and test an alternative approach to examine the impact of LULC changes on regional hydrological processes by using time-varying parameters for periods with different LULC conditions.

The second motivation for this study is to better understand the mechanism that connects the changes in runoff generation and streamflow with LULC in a river basin. A number of studies have examined the impacts of LULC changes on runoff and streamflow variability (e.g., Nie *et al.* 2011; Lin *et al.* 2015; Woldesenbet *et al.* 2017), but they are more or less fragmented. Few efforts have been invested to improve our mechanistic understanding about the impacts including changes in runoff production and variation, changes in streamflow variability, and changes in hydrology–LULC interactions, and how the impacts vary with space and time. These are all important for understanding and predicting changes in water resources, thus having policy relevance to urban planning and water resources management. This study will attempt to address these issues in a more systematic way.

DATA AND METHODS

Study region

This study focuses on the Wei River Basin (WRB), which is the largest tributary of the Yellow River in China (Figure 1). It lies in the Loess Plateau of China (103.50–110.50° E, 33.50–37.50° N) with a total drainage area of 134,800 km². Its main stream originates from the mountains in Gansu Province and flows east through Shaanxi Province for about 818 km, eventually entering the Yellow River at Tongguan (Figure 1). The Jing River and Beiluo River are the two major tributaries in the WRB with drainage areas of 45,400 km² and 26,900 km².

The WRB belongs to a typical arid and semi-arid region, and it has a distinct seasonal cycle in precipitation and temperature. The average annual precipitation is approximately 600 mm, 80% of which falls during the wet season. The annual mean temperature ranges from 7.8 °C to 13.5 °C across the basin with its extreme minimum and maximum temperature of 28.1 °C in January and 42.8 °C

in July. The average annual streamflow is 10.4 billion m³, accounting for 17% of the total discharge of the Yellow River Basin.

The WRB is the major source for domestic and industrial water use in Shaanxi Province, and the basin acts as a key economic development zone and important agricultural production area. The WRB hosts 76 major cities with a total population of 22 million across Gansu, Ningxia, and Shaanxi provinces (Li et al. 2016a). Human activity has become increasingly extensive in this basin over the past several decades (Chang et al. 2015). For example, the amount of surface water withdrawal and groundwater exploitation have increased rapidly to meet increasing water demand as a result of rapid population growth. Especially in the 1990s, the land right reform motivated farmers to boost agricultural production by agricultural expansion (Wang et al. 2004). The change from natural vegetation to cropland inevitably led to change of land surface characteristics and resulted in changes in hydrological processes such as infiltration and overland flow. Additionally, approximately 130 reservoirs have been built along the
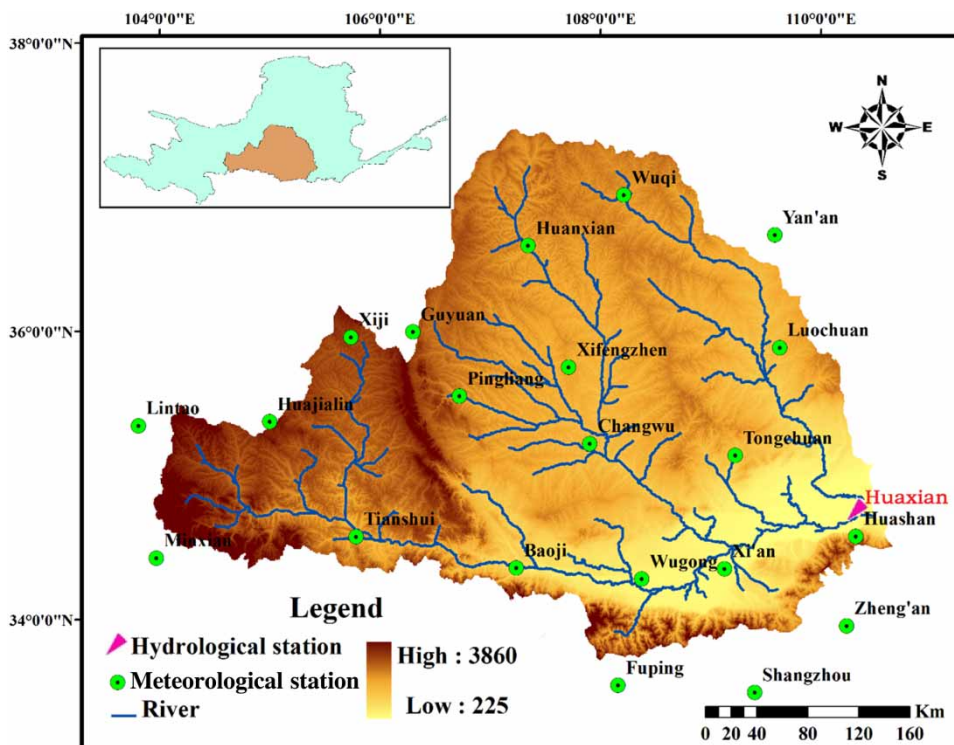
Figure 1 | Map of the WRB and locations of the meteorological and hydrological stations.

river, which can lead to increased evaporation and inter-annual variability of streamflow (Xing *et al.* 2007). The significant changes in the surface characteristics have made this basin an ideal place to study how such activities affect the hydrological process.

Hydrological modeling with SWAT

The SWAT, which is one of the most suitable models for simulating runoff process under land management scenarios (Woldesenbet *et al.* 2017), is applied in the WRB to assess the impacts of LULC changes on hydrological process. The SWAT model is a physically based distributed hydrological model that runs on a daily time step. It was developed to analyze the impacts of climate and land use management on hydrological process, sediment loading, and agricultural pollution transport in large, complex watersheds (Arnold *et al.* 1998). In this study, the SWAT 2009 version is used.

Based on topography and river channel network in the basin, the basin is divided into 111 subbasins. Then the subbasins are further divided into hydrological response units (HRUs) based on the dominant land use, soil type, and slope. Hydrological components (Figure 2) simulated by the SWAT model at each HRU mainly include surface runoff, evapotranspiration, percolation, groundwater, and soil water (Arnold *et al.* 1998). The overall water balance in the SWAT model can be expressed as:

$$SW_t = SW_{t-1} + P_t - SURQ_t - W_{seep,t} - ET_t - GWQ_t \tag{1}$$
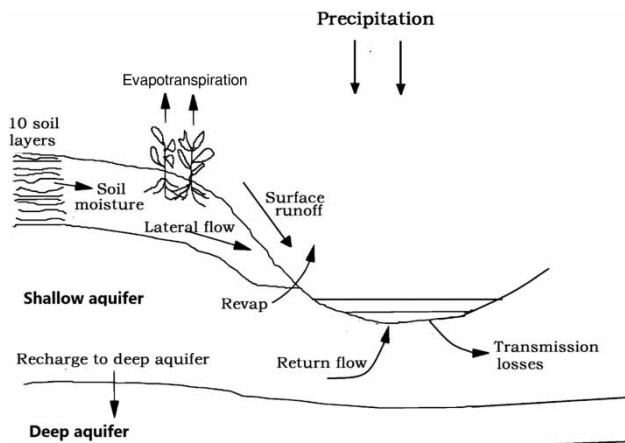
Figure 2 │ Schematic illustration of the components of the hydrologic balance simulated within a SWAT subbasin.

where SW_t is the soil water content (mm) at day t, SW_{t-1} is the initial soil water content on day t (mm), P_t, $SURQ_t$, $W_{seep,t}$, ET_t, and GWQ_t are the amount of precipitation (mm), surface runoff (mm), water entering the vadose zone from the soil profile (mm), evapotranspiration (mm), and groundwater return flow (mm) on day t, respectively.

The hydrological processes represented in the SWAT model can be categorized into two groups: runoff generation at the subbasin scale (Figure 2) and streamflow (channel flow) at the basin scale. The runoff generation is the process of net water yield (WYLD) which is individually calculated in each HRU and then aggregated at the corresponding subbasin as follows:

$$WYLD = SURQ + GWQ + LATQ - TLOSS \tag{2}$$

where *WYLD* is net WYLD (mm), *LATQ* is the lateral flow contributed to stream discharge (mm), and *TLOSS* is the transmission loss from the system (mm).

The streamflow is the process that net WYLD routes to the associated watershed outlet through the channel network and forms the streamflow, and the amount of streamflow at basin scale can be estimated as:

$$Streamflow = \sum_{i=1}^{n} WYLD \tag{3}$$

where *n* the number of subbasins.

Datasets

To support model calibration and simulations, a number of datasets are used in this study. The elevation data are extracted from NASAs Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a resolution of 30 m. The soil map (1:1,000,000) (Figure 3) and LULC data (1:1,000,000) for three periods (1980, 1995, and 2005) (Figure 3) were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn). The meteorological data that are used to drive the SWAT model, including daily maximum and minimum temperatures, precipitation, sunshine duration, humidity, and wind speed from 1960 to 2010 at 21 weather stations (Figure 1), are available from the National Climate
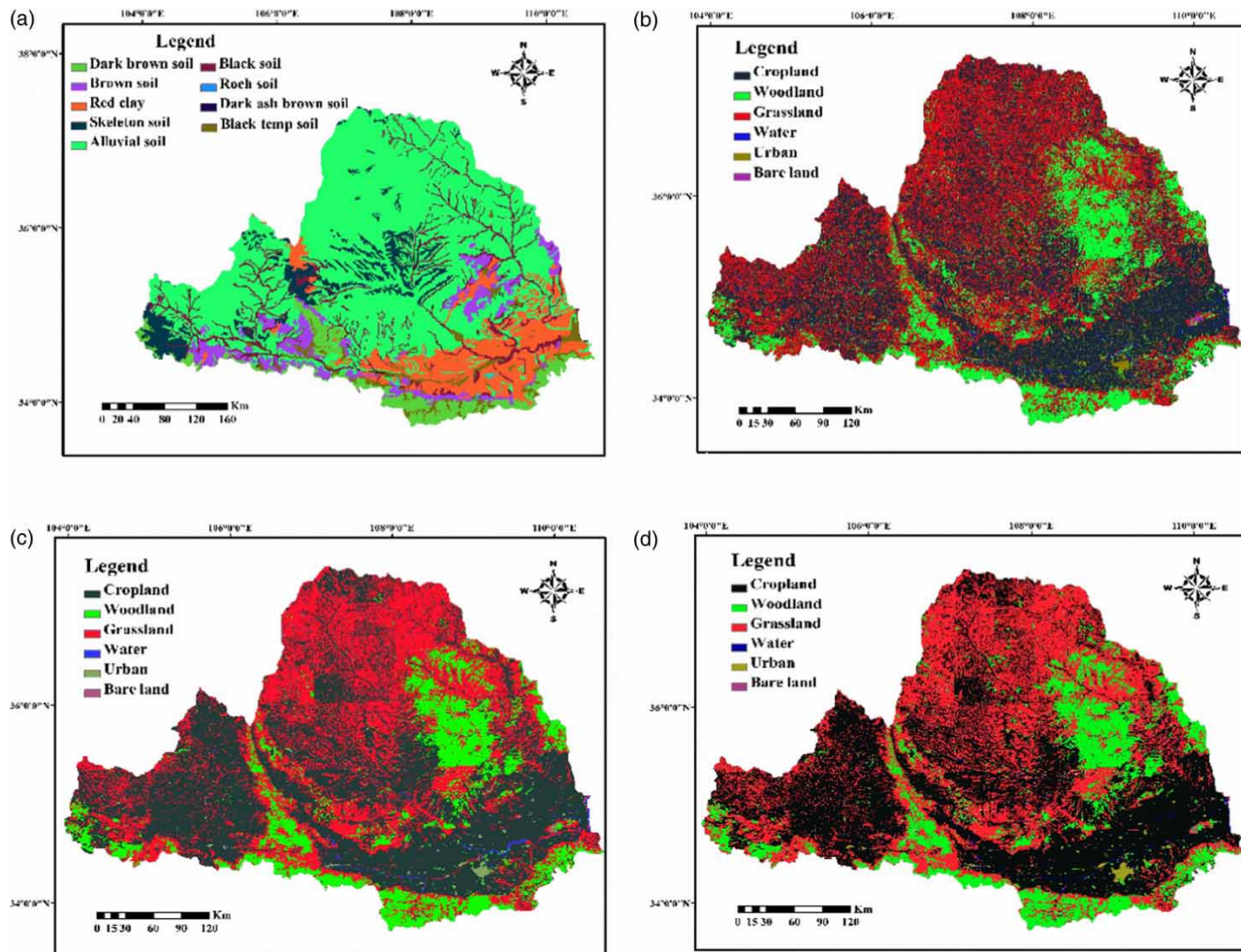
Figure 3 | Dominant soil types (a) and major land cover types in the WRB in 1980 (b), 1995 (c), and 2005 (d).

Centre of China. In this study, naturalized monthly stream-flow from 1960 to 2010 at Huaxian hydrological station (Figure 1) provided by the Yellow River Conservancy Commission is used to calibrate and validate the SWAT model. Huaxian station is a key hydrological station on the Wei River near its outlet, and it measures streamflow contributed by over 97% of the WRB. Although the Beiluo River basin could not be measured by the Huaxian station, the parameters calibrated by the Huaxian station can reflect the whole characteristics of the WRB. Here the naturalized streamflow refers to the streamflow that would have occurred if the influence from direct human activities, such as reservoir storage, irrigation, industrial, domestic and agricultural water consumption are eliminated.

Model calibration and validation with time-varying parameters

The main purpose of model calibration is to ensure that the hydrological model is optimized to simulate the hydrological processes with satisfactory accuracy. The meteorological inputs are used to drive the SWAT model, and the naturalized streamflow data from Huaxian station are used in model calibration. Model parameters are tuned during the calibration to maximize the Nash–Sutcliffe coefficient (NS) (Nash & Sutcliffe 1970) for streamflow at Huaxian station. Typically, a model is calibrated during the calibration (or training) period, and is validated against observations in a different validation period. Even in studies

that attempted to address the impact of LULC change, the same model parameter values are used in all periods once the model is calibrated for the calibration period under one LULC condition. Here, we take a different approach that allows for different sets of model parameter values during different periods when the underlying land surface characteristics change significantly between periods. Within a period when LULC experience relatively minor changes, we use a portion of that period for model calibration and the other portion for validation.

To analyze the impact of LULC change on the hydrology, we needed a baseline period when little LULC change had occurred during the period and an impact period when significant LULC changes have occurred within the period. The rationale for selecting these periods can be partially based on the changes in hydrological regime. Many studies have found that the modified Mann–Kendall (MMK) test method is more reliable in identifying abrupt change points in hydro-meteorological time series (Daufresne *et al.* 2009; Huang *et al.* 2015; Serinaldi & Kilsby 2016). Therefore, we conducted the change point analysis with the MMK test method on the naturalized annual streamflow from 1960 to 2010 at Huaxian hydrological station. The detailed procedures for MMK can be found in Li *et al.* (2016b).

The change point in the hydrological time series mostly indicates that the time series is not stationary, which is mainly due to the impact of environment changes including climate and human activities (Ngana *et al.* 2018). In this study, we conduct the change point of the naturalized annual streamflow, which has eliminated the influence from direct human activities, such as reservoir storage, irrigation, industrial, domestic and agricultural water consumption. Thus, the change point occurred in naturalized annual streamflow time series mainly due to the climate and LULC change. Figure 4 shows the results from the MMK test of the naturalized annual streamflow at Huaxian station. The time series is not stationary and there is one change point in the time series that occurred in 1990. Hence, in this study, the period before 1990 is referred to as the baseline period when both climate and LULC changes were still minimal. The period after 1990 is referred to as the impact period when both climate and LULC changes were significant enough to have altered the

hydrological cycle in the region. The impact period is further divided into two decades (1991–2000 and 2001–2010) as the characteristics of LULC changes are also different during these two decades. This difference will be facilitated and supported by the analysis of LULC change characteristics discussed later in the section 'LULC change characteristics analysis'.

The metrics that we use in this study to evaluate the model simulation include the NS, coefficient of determination (R^2), and percentage of bias (PBIAS) (Gupta *et al.* 1999). The NS is widely used in hydrology assessment to measure the goodness-of-fit between the observations and simulations. The performance of the SWAT model is considered satisfactory, adequate, and very good when the ranges are from 0.50 to 0.54, from 0.54 to 0.65, and larger than 0.65, respectively (Moriasi *et al.* 2007). The R^2 indicates the correlation between two series and ranges between 0 and 1 (Moriasi *et al.* 2007). The PBIAS represents the average deviation of the simulations from the observations. A negative (positive) PBIAS value suggests that the simulation underestimates (overestimates) the observation. Overall, according to Moriasi *et al.* (2007) and Li *et al.* (2016b), the performance of the SWAT model at the monthly scale can be considered satisfactory if NS > 0.50, R^2 > 0.60, and | PBIAS | <25.00%.

Modeling experiments

To demonstrate the performance of time-varying parameters in the SWAT model, two modeling experiments are conducted for the impact period. The setup of the two experiments are identical except that one (experiment T.V.) uses time-varying parameter values that are obtained from the calibration period within each decade while the other (experiment B.L.) uses the fixed parameter values that are obtained from the baseline calibration. The differences between these two experiments can provide some insights into the need for time-varying parameter values when dealing with significant changes in underlying land surfaces.

To assess the impacts of LULC changes on hydrological processes, we also conduct modeling experiments with the SWAT model for the baseline period with three different configurations, described below. The setup of the three experiments are identical except that the LULC map and
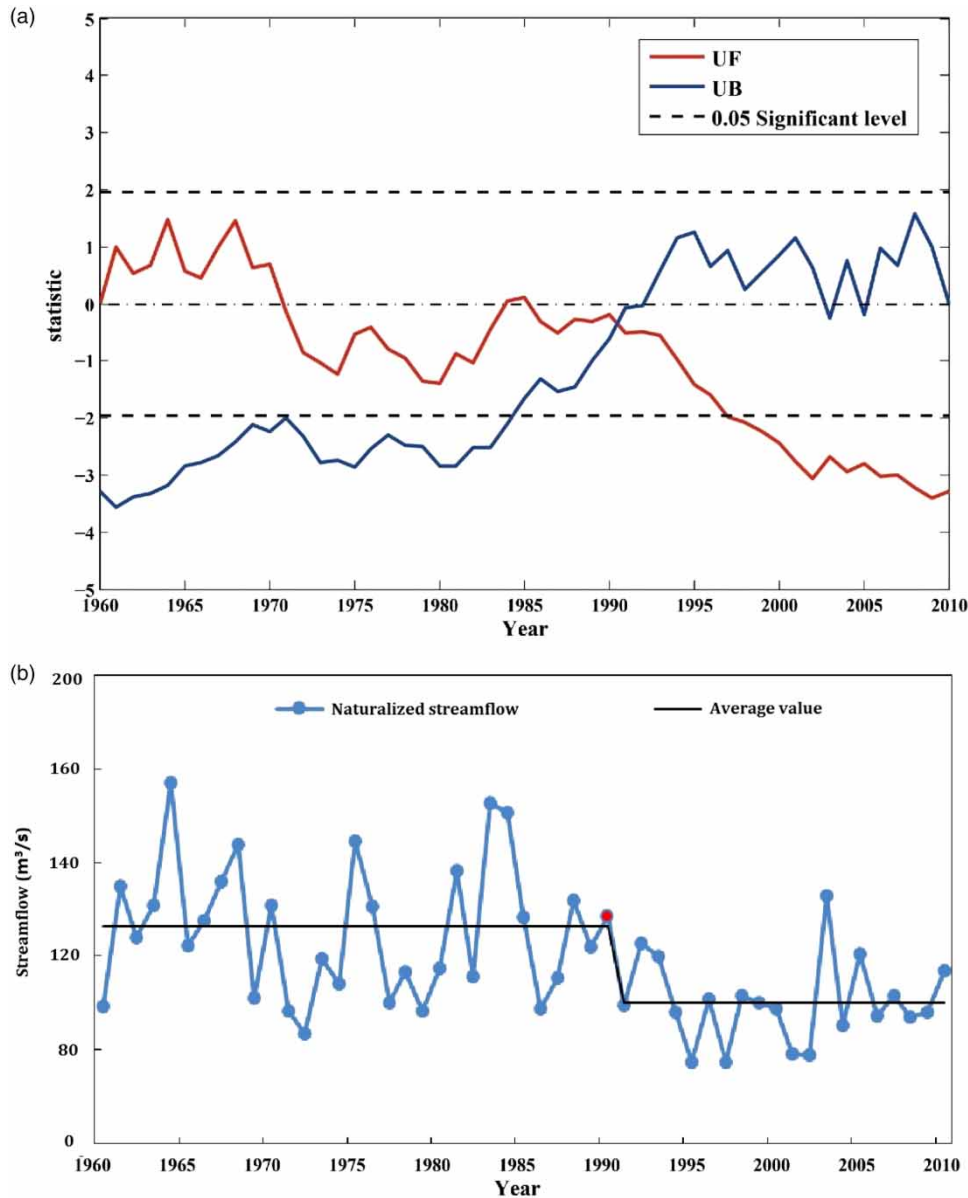
Figure 4 │ (a) Abrupt change point of the naturalized annual streamflow time series at the Huaxian hydrological station. UF is the conversion statistics of the naturalized annual streamflow time series, UB is the reverse time series of UF, and the crossover point of UF and UB is the abrupt change point. y-axes show the dimensionless values of UF and UB. (b) Change trend of the naturalized annual streamflow before and after the change point.

associated model parameter values are different. In the LC80, the LULC map from 1980 is used along with the model parameter values obtained during the baseline calibration period. The LC80 experiment serves as the baseline simulation. In the LC95, the LULC map from 1995 is provided to the model and the model parameters are obtained from the calibration in the first impact period. The LC05 is similar to LC95 except both LULC

map and parameters are from the second impact period. All other inputs such as DEM and soil data are kept fixed. By comparing the outputs of these modeling experiments, we can investigate how LULC changes affect the total streamflow in the WRB, and how they affect different hydrological components (e.g., runoff, evapotranspiration, etc.) at smaller subbasin scales that eventually help to explain the total changes in streamflow.

ANALYSIS AND RESULTS

LULC change characteristics analysis

We first examine multiple LULC maps over the WRB during the past few decades to provide a quantitative assessment on the changes of surface characteristics. Based on the distribution of land use types derived from the original Landsat data (TM/ETM), the area percentages of LULC types in 1980, 1995, and 2005 are obtained (Figure 5). It is easy to see that the dominant LULC types for the three time periods were cropland, woodland, and grassland, which together accounted for approximately 98% of the entire basin. The cropland maintained an increasing trend throughout the period of 1980–2005, while the grassland and woodland first decreased from 1980 to 1995 and then increased from 1995 to 2005.

We use the LULC transition matrix to quantify the spatial transformations that took place among different LULC types in the WRB during the past few decades. The LULC transition matrix has been widely applied to analyze and quantify LULC changes between different land use types (Wang *et al.* 2010). The matrix not only contains the static LULC information but also includes abundant dynamic change information in a certain period. The LULC transition matrix is usually presented as the following form.

$$\begin{pmatrix} a_{1,1} & \cdots & a_{1,j} \\ \vdots & \ddots & \vdots \\ a_{i,1} & \cdots & a_{i,j} \end{pmatrix}$$

where $a_{i,j}$ is the percentage of land cover type i that has been converted to land cover type j during the period of consideration; the detailed computational procedure can be found in Wang *et al.* (2010).

Using LULC maps from 1980, 1995, and 2005, the transition matrices are established between 1980 and 1995, and between 1995 and 2005, as shown in Table 1. Each value in the table is the percentage area of the land cover type labeled by the row being converted to the land cover type labeled by the column. It is not hard to see that the spatio-temporal changes of LULC types were bidirectional, i.e., conversion of one LULC type out to another was usually accompanied by conversions of some other types back into this type somewhere in the domain. During the period of 1980–1995, high frequency conversion occurred among cropland, woodland, and grassland within WRB. 21.68% of cropland was converted to grassland, and 19.13% of grassland was converted to woodland, while 11.17% of woodland was converted to cropland in the region. During the period of 1995–2005, 8.50% of the cropland was
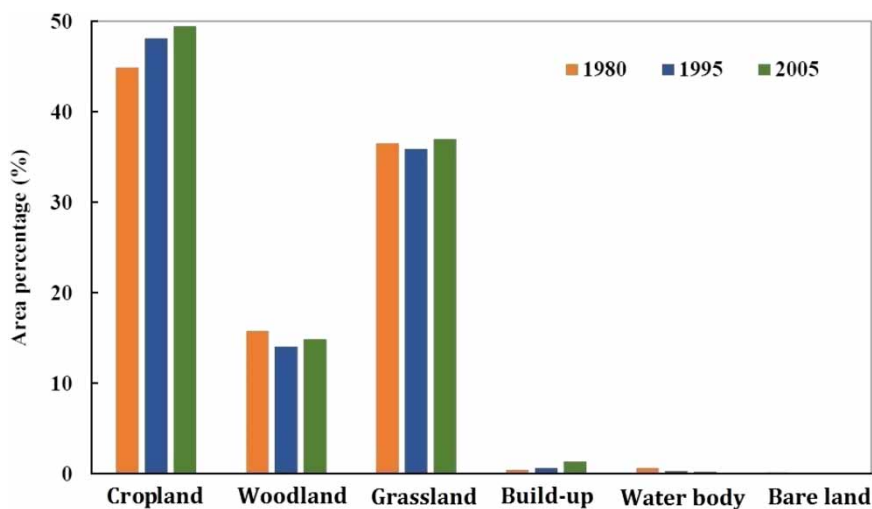

Figure 5 | Area percentages of LULC types in the WRB.

Table 1 | The percentages of LULC transition matrix in the Wei River Basin (%)

	Cropland	Woodland	Grassland	Water body	Build-up	Bare land
1980–1995						
Cropland	73.73	1.13	21.68	0.34	0.19	0.05
Woodland	11.17	57.62	7.54	0.11	0.09	0.06
Grassland	10.26	19.13	46.64	0.08	0.03	0.01
Water body	58.28	2.75	1.35	14.78	0.81	0.86
Build-up	34.17	1.11	0.38	0.64	58.01	0.34
Bare land	31.00	21.96	0.99	0.25	0.02	21.11
1995–2005						
Cropland	69.25	8.50	14.47	0.22	0.98	0.06
Woodland	4.79	81.35	8.94	00.05	0.07	0.02
Grassland	1.25	1.33	58.01	0.11	0.04	0.03
Water body	66.18	1.92	1.29	21.18	5.23	0.31
Build-up	25.10	2.12	0.00	0.12	69.44	0.00
Bare land	23.99	8.17	2.39	4.93	0.00	26.95

converted to woodland and 14.47% was converted to grassland. During both periods, water body, build-up, and bare land areas were largely converted into cropland.

LULC changes can reflect the interplay and dynamics of biophysical, social, and economic factors over time. As shown in Table 1, the cropland in the WRB kept increasing throughout the whole period, especially between 1980 and 1995, which is the result of land right reform that was vigorously prompted in the 1990s (Wang *et al.* 2004). The large area transfer from cropland to woodland and grassland between 1995 and 2005 corresponds to the implementation of soil and water conservation management in the 2000s (Li *et al.* 2016a). Based on these changes, we consider the LULC map for 1980 as a representation of LULC conditions before any significant changes, and LULC maps from 1995 and 2005 represent land surface characteristics during the 1990s (1991–2000) and the 2000s (2001–2010).

Model calibration and validation

The SWAT model is calibrated and validated for each of the periods separately. For the baseline period, the years of 1960–1965 are used to spin-up the model. The LULC map from 1980 is used throughout the period of 1966 to 1990,

and the model is calibrated using the naturalized monthly streamflow from Huaxian station between 1966 and 1980; the model performance is evaluated using monthly streamflow from the same station during 1981 to 1990. For the two decades during the impact period, the LULC maps for 1995 and 2005 are used to represent these two decades. Within each decade, the first half of the records is used for model calibration and the second half is used for model validation.

Since numerous parameters (totally 26 parameters) are associated with the hydrological process in the SWAT model and it is difficult and time-consuming to calibrate all parameters at the same time, the sensitivity analysis is first performed to optimally identify the most relevant parameters for better simulation and hence can simplify the procedure for model calibration.

Therefore, in this study, sensitivity analysis was performed for the monthly naturalized streamflow time series from 1965 to 2010 at Huanxian station using the method embedded in the SWAT interface, Latin Hypercube and One-factor-At-a-Time (LH-OAT). This analysis identified the key parameters influencing the model hydrological output. Based on the sensitivity analysis, the SUFI-2 algorithm in SWAT-CUP and an artificial trial-and-error method were both used to calibrate the key parameters for different

Table 2 | Key parameters and best fitted values in the three periods

Change type	Parameter	Description	Range	Periods Baseline	1990s	2000s
r	CN2.mgt	Curve number for moisture condition II	(−0.5, 0.5)	**0.35**	**0.29**	**0.14**
r	SOL_AWC.sol	Available water capacity of the soil layer	(−0.5, 0.5)	0.43	0.43	0.43
r	SOL_Z.sol	Soil depth	(−0.5, 0.5)	0.21	0.21	0.21
r	SOL_K.sol	Saturated hydraulic conductivity	(−0.8, 0.8)	−0.04	−0.04	−0.04
v	EPCO.hru	Vegetation transpiration compensation coefficient	(0.01, 1)	**0.99**	**0.62**	**0.69**
v	CANMX.hru	Maximum canopy storage	(0, 100)	**70.00**	**10.00**	**60.00**
v	SLSUBBSN.hru	Average slope length	(10, 150)	**26.00**	**12.00**	**15.00**
v	OV_N	Manning surface flowing coefficient	(0, 0.8)	**0.61**	**0.36**	**0.23**
v	CH_K2.rte	Main channel conductivity	(0, 150)	24.00	24.00	24.00
v	ALPHA_BF.gw	Base flow alpha factor	(0, 1)	0.52	0.52	0.52
v	REVAPMN.gw	Threshold of evaporation in shallow aquifer	(0, 500)	489.00	489.00	489.00
v	GW_DELAY.gw	Groundwater delay time	(0, 500)	**268.00**	**29.00**	**117.00**
v	GW_REVAP.gw	Groundwater 'revap' coefficient	(−0.02, 0.2)	0.10	0.10	0.10
v	RCHRG_DP.gw	Osmosis ratio in deep aquifer	(0, 1)	0.09	0.09	0.09
v	GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur	(0, 5000)	118.00	118.00	118.00

Notes: r indicates that the default parameter multiplies 1 + given value as a percentage; *v* indicates that the default parameter is replaced by the given value; the bold-faced numerical values are dynamical LULC parameters in each period.

periods with different LULC conditions. Table 2 shows the results of sensitivity analysis and their best fit values in the baseline and two impact periods (i.e., 1990s and 2000s) at Huaxian station.

Figure 6 shows the comparison of model simulated and observed monthly streamflow at the Huaxian hydrological station. Table 3 summarizes the performance using the three metrics. It is clearly observed that the simulated
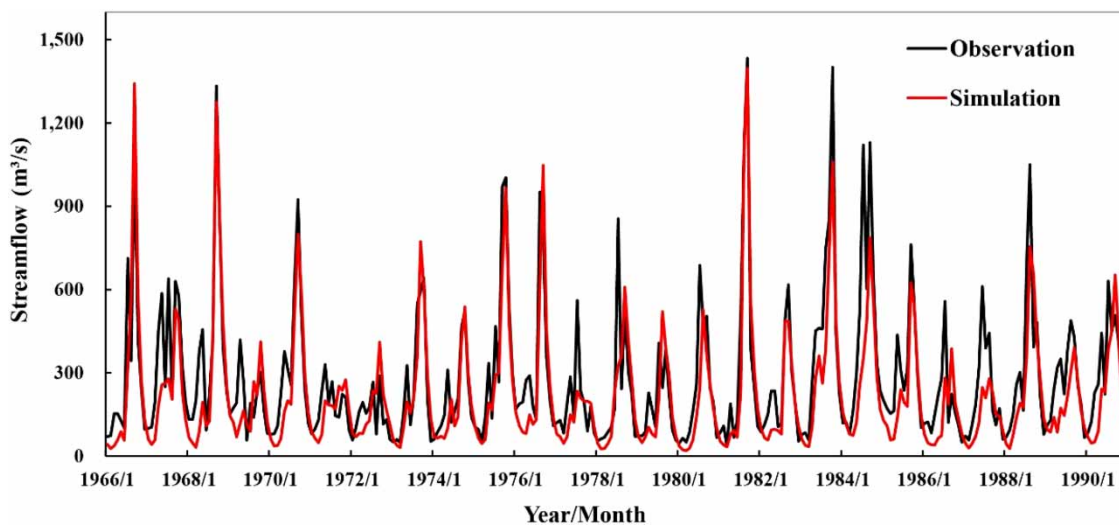
Figure 6 | Model simulated monthly streamflow compared to the observed naturalized monthly streamflow at the Huaxian hydrological station during the baseline period (1966–1990).

Table 3 │ Model performance measured by three metrics for different periods and using two sets of model parameters

| | Baseline period | | 1990s | | | | 2000s | | | |
| | | | Calibration | | Validation | | Calibration | | Validation | |
Metrics	Calibration	Validation	B.L.	T.V.	B.L.	T.V.	B.L.	T.V.	B.L.	T.V.
NS	0.70	0.70	**0.49**	0.63	0.55	0.66	0.52	0.79	**0.42**	0.62
R^2	0.73	0.78	**0.58**	0.77	**0.59**	0.80	**0.59**	0.83	0.79	0.82
PBIAS	16.21	24.49	19.50	16.05	1.45	4.23	9.22	9.23	−12.73	17.49

B.L. is the simulation that uses the parameters calibrated during the baseline calibration period. T.V. is the simulation that uses the parameters calibrated during the calibration portion of the impact period. The numbers in bold indicate that the metrics fail to reach the benchmark.

monthly streamflow is able to capture the seasonal cycle as well as the inter-annual variability of the streamflow, although the model has a hard time accurately simulating the peak flow during the wet season. The NS and R^2 values in both the calibration and validation periods are greater than or equal to 0.70, and the absolute values of PBIAS are within 25.00%, suggesting a satisfactory performance of SWAT model in the baseline period according to Moriasi *et al.* (2007).

Difference in model performance during the impact period with two sets of parameter values

Figure 7 shows the simulated monthly streamflow from the B.L. and T.V. simulations during the impact period with comparison to the observations. It is not surprising that the simulation with time-varying parameter values produces better performance. In many cases, the simulations with time-varying parameter values are able to better capture the peak flows and low flows during the two decades. This is further supported quantitatively by the three metrics as shown in Table 2. Note that each decade is further divided into the calibration period and validation period. During all periods, the NS and R^2 values are consistently higher in the T.V. simulation than in the B.L. simulation while the PBIAS values are mostly comparable.

What is more interesting in Table 2 is the comparison of these metrics between different periods within the simulation that uses the baseline parameter values. It is clear that the model performance is significantly degraded during the later two decades when the underlying land surface characteristics have undergone significant changes. The numbers in bold indicate that the metrics fail to reach the benchmark, suggesting that the SWAT model running with the baseline parameter values during the impact period has an inferior performance in simulating streamflow. While using the time-varying parameter values, the model performance is considerably better, with most NS and R^2 as high as 0.70 to 0.80. This highlights the issue that we raised earlier, that model performance can be significantly affected when the underlying land surface characteristics have changed, thus the estimate of impact of LULC change on regional hydrological process using the traditional approach may be severely degraded due to model deficiencies.

Figure 7 and Table 3 indicate that the time-varying parameter calibration is not only effective but also necessary to ensure the validity of the model when dealing with significant changes in underlying land surfaces. While model parameters obtained from the baseline period can degrade model performance during other periods, especially in late decades due to LULC changes. Thus, the SWAT model with time-varying parameters should be a better alternative approach to analyze the impacts of LULC changes on hydrology.

Spatiotemporal impacts of LULC changes on different hydrological processes

From the LULC change characteristics analysis, we know that the cropland, woodland, and grassland were the dominant LULC types over the past 30 years, and their spatial distributions have changed quite significantly. In this
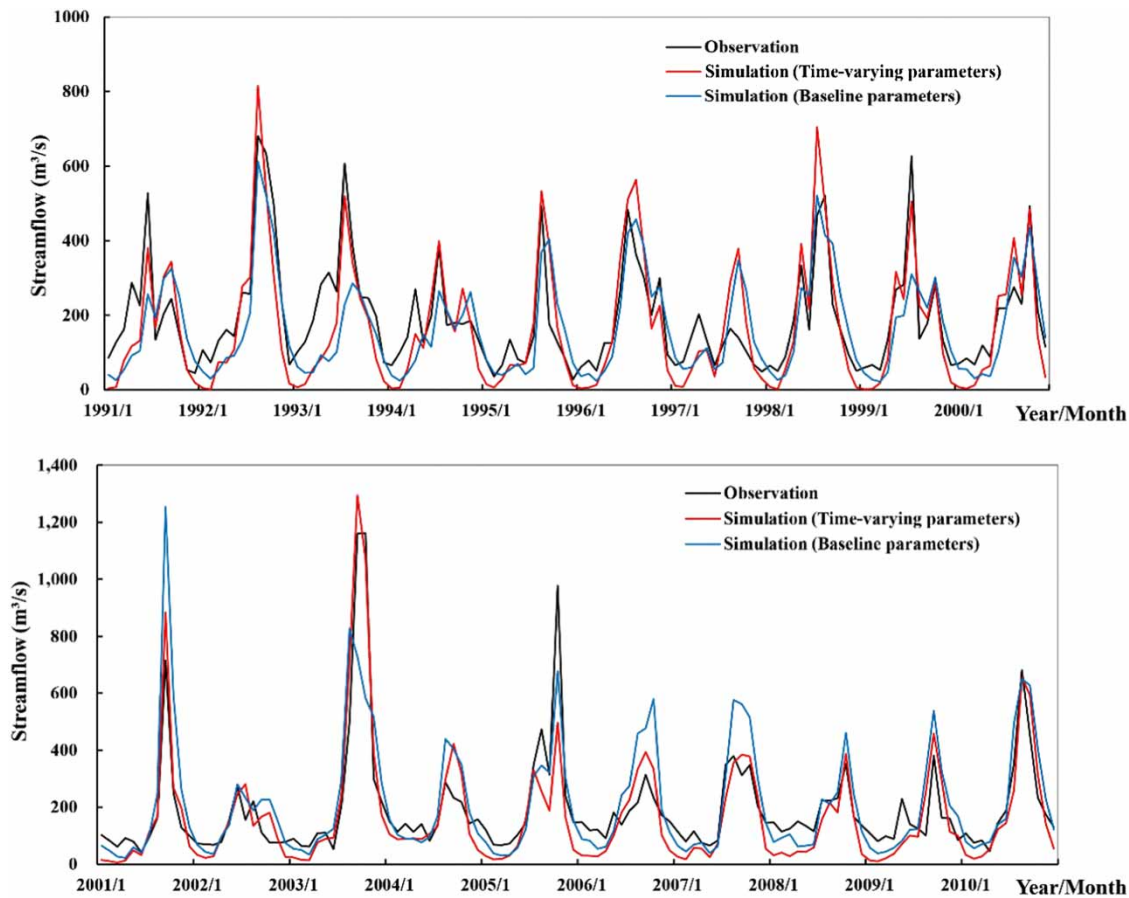
Figure 7 | Comparison of two model simulated streamflow time series and observed monthly streamflow time series at Huaxian hydrological station during the impact period (1991–2010).

section, we examine how such changes affect different hydrological processes in different parts of the WRB, and how they overall contribute to the changes in streamflow in the WRB. This is based on the three experiments (LC85, LC95, LC05) that use the same meteorological data during the baseline period (1966–1990) with different LULC maps and associated model parameter values. To thoroughly analyze the impact of LULC changes on the hydrological process, we first divide the entire WRB into five zones based on two large tributaries, the up-, middle-, and lower reaches of the main stream, and each zone covers a number of subbasins (Figure 8). We examine how the major LULC types have changed within each zone during the last few decades, then we will see how various hydrological components have changed in each zone that eventually help to explain the total changes in streamflow for the entire basin.

Impacts of LULC changes on watershed streamflow at different time scales

Based on the modeling experiments (LC80, LC95, and LC05), the impacts of LULC changes on watershed steamflow can be examined by comparing the streamflow outputs at annual and seasonal (wet season from June to September, and dry season from October to next May) scales. The results are summarized in Table 4.

Compared to the LC80, the annual and dry season streamflow in the LC95 and LC05 both decreased due to the LULC changes. The LULC changes have greater negative impact on the annual streamflow in the LC05 than in the LC95. During the dry season, the influence of LULC changes on the streamflow is larger in the LC95 than in the LC05. However, compared to the LC80, the streamflow in the wet season increased (about 10%) in the LC95 but
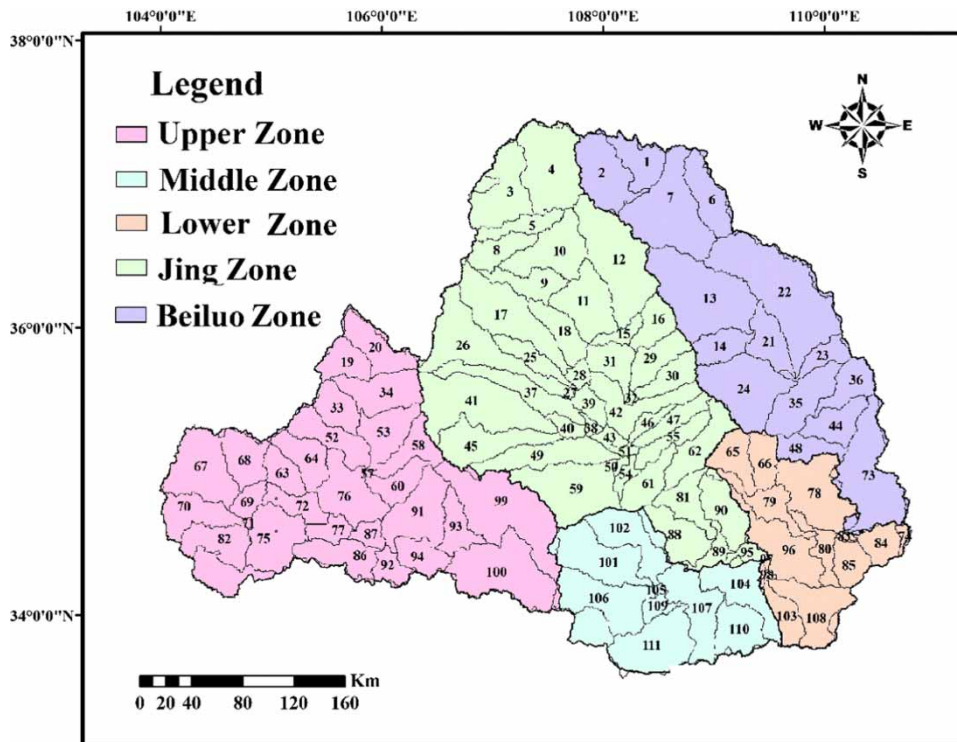
Figure 8 | The five zones and the subbasins in the WRB.

decreased (about 10%) in the LC05. Generally, the LULC changes in the LC95 and LC05 both have significantly negative impacts on the streamflow in the dry season. The fact that streamflow increased in the wet season but sharply decreased in the dry season indicates that the LULC changes have increased the risk of high-risk occurrences of hydrological extreme events, such as floods and droughts.

Mechanism of LULC changes affecting streamflow at the subbasin scale

To better understand the mechanism that connects changes in runoff generation and streamflow with LULC,

we first examined how the major LULC types have changed within each zone (Figure 9), and then the four hydrological components, surface runoff (SURQ), groundwater (GWQ), soil water (SW), and evapotranspiration (ET), which are closely related to the formation of streamflow (described in the section 'Hydrological modeling with SWAT'), are analyzed to detect LULC changes' impact in different zones. The hydrological components are obtained for each zone by summarizing the weighted average values of all subbasins accordingly for each of the three experiments (LC80, LC95, LC05). The percentage changes of SURQ, GWQ, ET, and SW components in each zone in the LC95 and LC05 at annual and seasonal

Table 4 | Contributions of LULC changes to watershed streamflow at annual and seasonal scales

|	Annual			Wet season			Dry season		
Experiment	Streamflow (m³/s)	Variation (m³/s)	Percentage (%)	Streamflow (m³/s)	Variation (m³/s)	Percentage (%)	Streamflow (m³/s)	Variation (m³/s)	Percentage (%)
LC80	227.11			374.97			118.54		
LC95	218.77	−8.34	−3.67	419.24	44.26	11.81	71.60	−46.94	−39.60
LC05	188.20	−38.90	−17.13	335.71	−39.26	−10.50	80.03	−38.51	−32.49
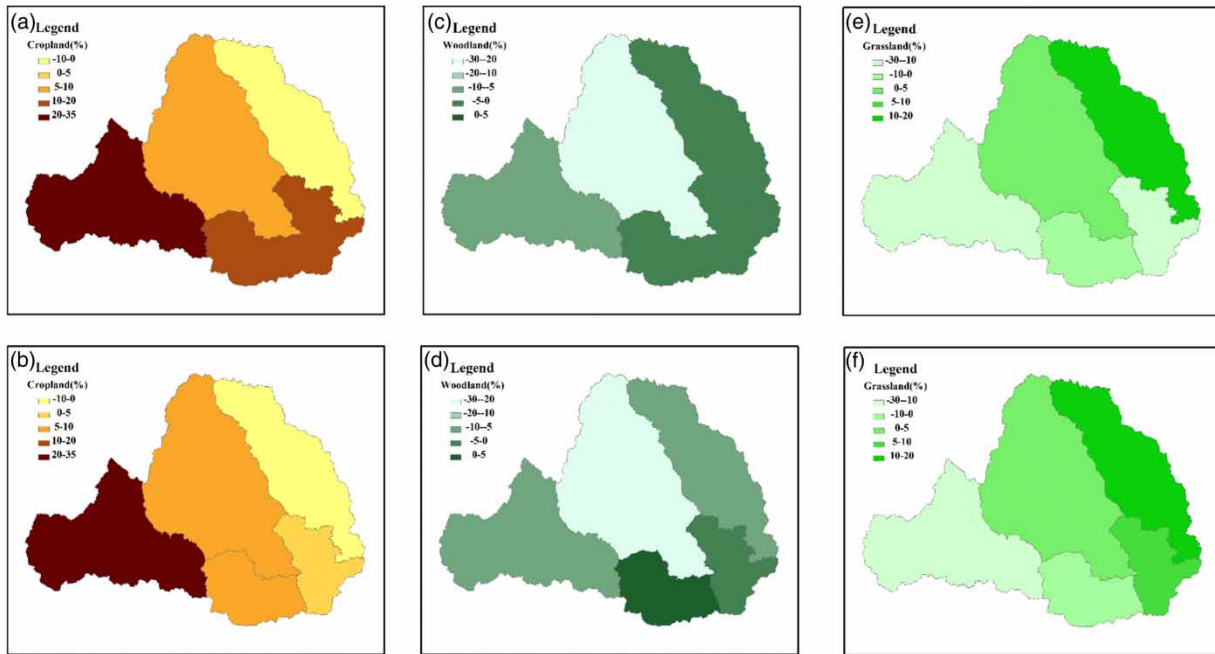
Figure 9 │ Percentage changes of main LULC types in each zone in the 1990s (top) and 2000s (bottom) compared to the baseline period: (a) and (b) are cropland change percentages in the 1990s and 2000s, respectively; (c) and (d) are woodland change percentages in the 1990s and 2000s, respectively; (e) and (f) are grassland change percentages in the 1990s and 2000s, respectively.

scales are obtained, and the results are shown in Figures 10–12, respectively.

The decreases of the streamflow at annual and dry seasonal scales in the LC95 and LC05, as well as its decrease in the wet season in the LC05, are largely due to the huge reduction of SURQ component in the process of runoff generation. From Figures 10–12, we can clearly see that SURQ decreased dramatically in both the LC95 and LC05
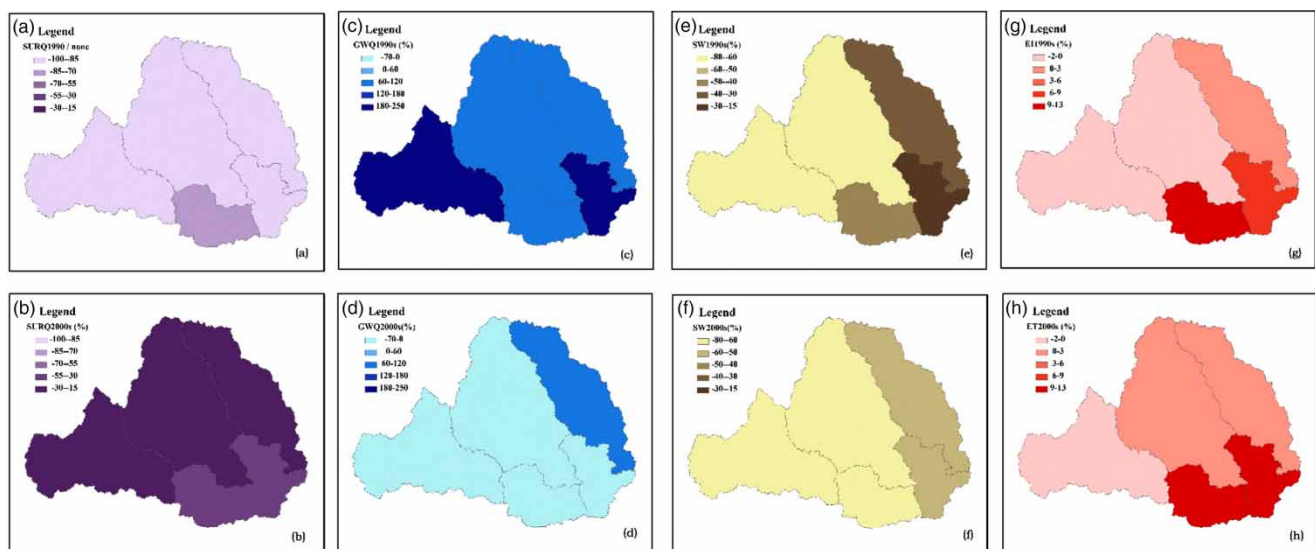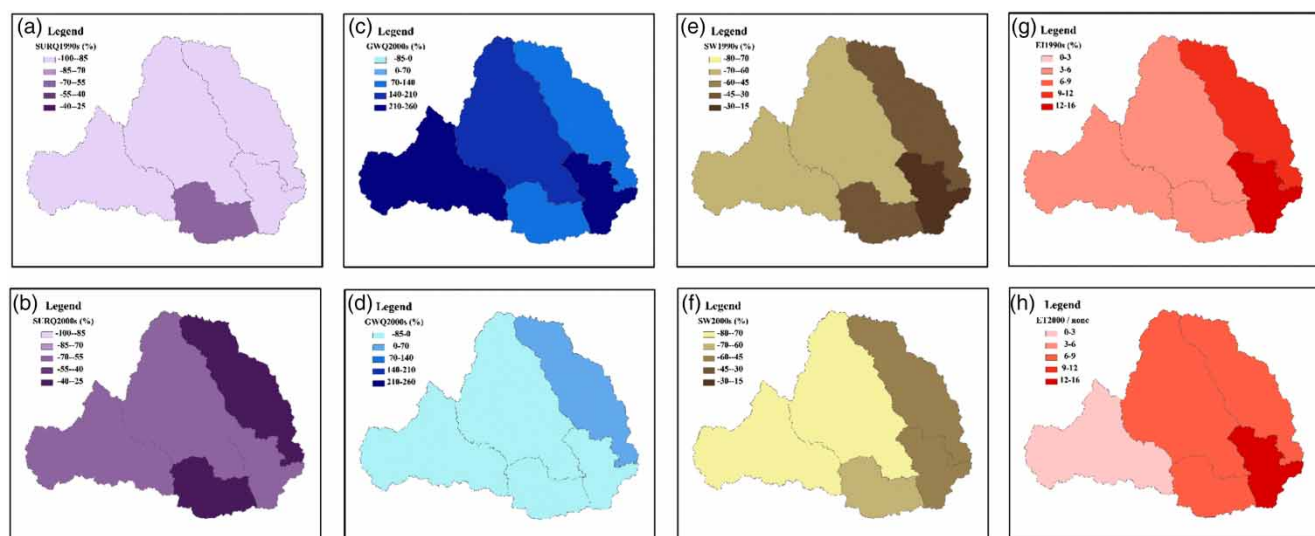

Figure 10 │ Change percentages of annual hydrological components in the LC95 (top) and LC05 (bottom) when compared to the LC80: (a) and (b) are SURQ change percentages in the LC95 and LC05, respectively; (c) and (d) are GWQ change percentages in the LC95 and LC05, respectively; (e) and (f) are SW change percentages in the LC95 and LC05, respectively; (g) and (h) are ET change percentages in the LC95 and LC05, respectively.
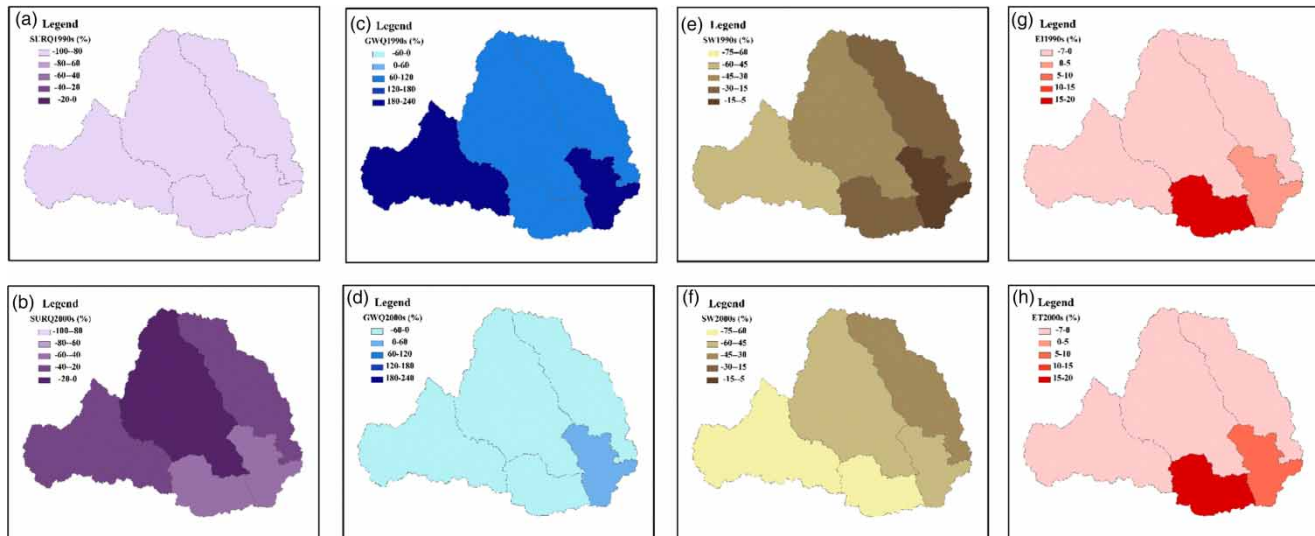
Figure 11 | Change percentages of hydrological components during the wet season in the LC95 (top) and LC05 (bottom) when compared to the LC80: (a) and (b) are SURQ change percentages in the LC95 and LC05, respectively; (c) and (d) are GWQ change percentages in the LC95 and LC05, respectively; (e) and (f) are SW change percentages in the LC95 and LC05, respectively; (g) and (h) are ET change percentages in the LC95 and LC05, respectively.

throughout the whole basin when compared to the LC80, especially in the LC95 with a large decrease of 80–100%. This phenomenon is mainly attributed to the expansions of the cropland in the Upper, Middle, Lower, and Jing zones (Figure 9), and the reason why SURQ decreased more in the LC95 is that the cropland experienced 10% more increasing areas in the Middle and Lower zones than that in the LC05. However, the streamflow increase in the wet season in the LC95 is closely related to the decrease in ET. From Figure 11, it is easy to observe that EI decreased in almost all zones by up to 7%, which is primarily due to the decrease of grassland in the Upper and Middle zones and the shrinkage of woodland over the entire basin, especially in the Upper and Jing zones where the area of the woodland decreased by 10–30%. Compared to the LC95, the decreased GWQ is the main reason that causes

Figure 12 | Change percentages of hydrological components during the dry season in the LC95 (top) and LC05 (bottom) when compared to the LC80: (a) and (b) are SURQ change percentages in the LC95 and LC05, respectively; (c) and (d) are GWQ change percentages in the LC95 and LC05, respectively; (e) and (f) are SW change percentages in the LC95 and LC05, respectively; (g) and (h) are ET change percentages in the LC95 and LC05, respectively.

the annual and dry seasonal streamflow to decrease more sharply in the LC05. For example, compared to the LC80, GWQ in the wet season increased by 60–240% over the entire basin, while it decreased by up to 60% in the LC05. That is to say, GWQ decreased almost four times from the LC95 to the LC05, thus leading to a large decrease in streamflow in the LC05. In contrast with other two time scales, the streamflow increased a little during the dry season from the LC95 to LC05, which is mainly attributed to the continuous decrease of SW. From Figure 12, we can clearly observe that SW decreased approximately 10–15% from the LC95 to LC05 throughout the entire basin, and these changes are primarily associated with the shrinkage of the woodland in the Beiluo and Lower Zones in the LC05.

CONCLUSIONS AND DISCUSSION

In this paper, we present an alternative approach to quantify the spatiotemporal impacts of LULC changes on hydrology in a case study of WRB, where the subsurface hydrology is highly influenced by human activities, using a SWAT model with time-varying parameters for periods with different LULC conditions. Based on these time-varying parameters, the watershed streamflow, as well as the hydrological components including surface runoff (SURQ), groundwater (GWQ), soil water (SW), and evapotranspiration (ET) in the 111 subbasins of the WRB are obtained from three modeling experiments that use the same meteorology over the baseline period (1966–1990) with different LULC patterns in 1980, 1995, and 2005. Then the contributions of LULC changes to watershed streamflow at annual, wet, and dry seasonal scales are quantified. Furthermore, to better understand the mechanism how LULC changes affect different hydrological components in the subbasins that eventually help to explain the total changes in streamflow, the interactions among LULC change, streamflow variation, and changes in hydrological components were investigated in the different parts of the WRB.

The results show that time-varying parameters' calibration is not only effective but also necessary to ensure the validity of the model when dealing with significant changes in underlying land surfaces, while models with fixed baseline parameters can degrade model performance during other periods. Generally, the LULC changes have significant impacts on the watershed streamflow at different time scales, especially on the streamflow during the dry season. Exploring its mechanism, the expansion of the cropland during the past 30 years is the major contributor to the large reduction of surface water in the runoff generation process, thus causing the decline in streamflow annually and streamflow during the dry season. However, the decreased groundwater is the main reason that causes the streamflow to decrease more sharply during the wet season, while the decreased soil water is associated with the little increase of the streamflow during the dry season, which is primarily due to the shrinkage of woodland from 1995 to 2005.

This paper mainly puts forward two new contributions: (1) the proposal of time-varying parameters to improve the performance of hydrological models when dealing with significant changes in underlying land surfaces; and (2) the analysis of changes in runoff generation and streamflow with LULC to better understand the mechanism by which the LULC changes affect the streamflow and water resources in a river basin. The results not only can help decision-makers to plan local LULC patterns reasonably and manage water resources efficiently, but also are crucial for the prevention and mitigation of hydrological extreme events. Despite this, it still has some limitations. The time-varying parameter approach could not be applied to deal with change in underlying surface in the future since the parameters need to be calibrated with observed streamflow. The period for time-varying parameters calibration is (relatively) long-term (e.g., ten years), which would miss some short-term LULC changes caused by factors, such as wild fire or tree mortality, and hence may not be sufficiently accurate to represent the dynamic underlying land surface characteristics over time. Also, this approach neglects the changes in climate, and would therefore affect the accuracy of hydrological process simulation and results in uncertainties. These issues will be pursued in our future study.

ACKNOWLEDGEMENTS

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