

Detecting the impact of the “Grain for Green” program on land use/land cover and hydrological regimes in a watershed of the Chinese Loess Plateau over the next 30 years

Haijie Yi^{a,b,c}, Xiaoping Zhang^{a,b,c,d,*}, Liang He^d, Jie He^d, Qilong Tian^{a,b,c}, Yadong Zou^d, Zefeng An^d

^a The Research Center of Soil and Water Conservation and Ecological Environment, Chinese Academy of Sciences and Ministry of Education, Yangling, Shaanxi 712100, China

^b Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China

^c University of Chinese Academy of Sciences, Beijing 100049, China

^d Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China

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ABSTRACT

To increase vegetation coverage and improve ecosystem services, the government has promulgated and implemented the “Grain for Green” policy since 1999. How and where vegetation cover increases and how land use/land cover (LULC) changes determine regional water resources and hydrological regimes. On the Chinese Loess Plateau (LP), an arid and semiarid area with fragmented topography and the transitional vegetation nature, accurately predicting LULC and vegetation change is particularly important. We employed a simple habitat analogy approach, and the Soil and Water Assessment Tool (SWAT) to predict potential vegetation restoration and LULC change and investigated their impact on the hydrological regime in a watershed of Liujiache. Results showed that the maximum recoverable vegetation cover of the Liujiache watershed is 71.1%, of which 9.2% still has potential for vegetation cover and 36.4% of the area vegetation continued to improve in the future. Future suitable afforestation areas are limited to 46.06 km², which will result in cropland will decrease by 47.4%, and grassland and forestland will increase by 15.8% and 0.7%, respectively. However, SWAT results showed that vegetation restoration between the 1980 s and 2020 s has already reduced the annual mean runoff and soil water content (SW) by 44.2% and 43.9%, respectively, while evapotranspiration (ET) has increased by 12.6%; LULC changes in the next 30 years will further reduce runoff and SW by 15.6% and 11.1% respectively, and increase ET by 1.2%. Overall, large-scale vegetation restoration has greatly affected hydrological regimes on the LP. The area still has potential for vegetation enhancement; however, considering the limited rainfall and water-carrying capacity, the vegetation restoration of this watershed should be based on natural restoration or low water consumption grasses and shrubs to avoid a water resource crisis. These results provide a perspective for modelling LULC changes in areas with fragmented terrain and highly influenced by human activities, and provide an important basis for sustainably managing natural resources on the LP under long-term ecological restoration.

1. Introduction

Land use/land cover (LULC) change is fundamentally important to the study of global environmental change (Chen et al., 2020) and is closely associated with the hydrological processes in watersheds in terms of canopy interception, infiltration and evapotranspiration (ET), which may eventually change the runoff volume, peak flow and flow

routing time (Laurance, 2007; Zhang et al., 2008a; Zhang et al., 2018; Chen et al., 2020; Obahoundje and Diedhiou, 2022). Therefore, understanding the future LULC and its impact on the hydrological regime is beneficial for the government to formulate ecological protection strategies, achieve sustainable management of land and water resources and improve ecosystem services (Qiu et al., 2017, Cao et al., 2009, Chen et al., 2020).

* Corresponding author at: Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China.
E-mail address: zhangxp@ms.iswc.ac.cn (X. Zhang).

The Chinese Loess Plateau (LP) has become one of the global hotspots of soil erosion due to a combination of fragmented topography, high-intensity precipitation, poor vegetation conditions and intense human activity over the centuries, and its erosion rate was once as high as 25,000 t t km⁻² y⁻¹ before the 1980s (Chen et al., 1988). To control soil erosion, many ecosystem restoration programs have been implemented since the 1950s (Liu et al., 2020; Yan, et al. 2018; Cao, et al. 2009); the most representative programs include the integrated soil conservation project of small watersheds, which has been implemented since the 1970 s (Yao, et al. 2005) and the GFG program, which was started in 1999 (Cao, et al. 2009). LULC has dramatically changed since these ecosystem restoration programs were initiated. The vegetation cover of the LP has increased from an estimate of approximately 56% in 2000 to approximately 77% in 2017 (Yang et al., 2020). At the same time, these ecosystem restoration programs have had considerable impacts on hydrological functioning (Hu et al., 2021). It has been estimated that the average streamflow across the Yellow River decreased from 42.6 billion m³ in 1919–1959 to nearly 30 billion m³ in 2010 (Liu et al., 2019). Therefore, prediction of the LULC and its impact on the hydrological regime is particularly important to the ecological protection and high-quality development of the LP.

Many researchers had developed LULC prediction models in recent decades. Markov chains was constructed by Andrey Markov in 1907 and have been applied to study land use dynamics since the 1970s (Iacono et al., 2015), and a system dynamics model (SD) was constructed by Jay W. Forrester in 1961 (Forrester, 1961). These models mainly predict the areas of various LULC types based on the average changing rates along time series, but it is difficult to connect LULC spatial distribution (Muller and Middleton, 1994; Michael et al., 2015; Qiao et al., 2022). In 1951, John von Neumann created the cellular automata (CA) model (von Neumann 1951). It relies on empirical statistics to simulate the spatial pattern of land use (Liu et al., 2017a; Liang et al., 2021). However, it cannot incorporate socioeconomic factors (El Yacoubi and El Jai, 2002; Qiao et al., 2022). Although the Conversion of land use and its Effects at Small regional extent (CLUE-S) model considers both natural and socioeconomic factors (by Peter H. Verburg in 2002) (Verburg et al., 2002), it is only valid for the dominant land use types (Verburg et al., 2002; Qiao et al., 2022), and its non-spatial module needs help of other models and has to ignore the interaction between different models (Liu et al., 2017b). Due to the fragmented topography, high impact of human activities, strong landscape heterogeneity and obvious transitional characteristics on the Loess Plateau (Chen et al., 1988), the above models were not able to precisely consider the complex characteristics of LULC in the region. It is important to develop a rational and practical method to predict the LULC of the Loess Plateau for future ecological restoration.

Afforestation has been recognized as a potential major LULC change for the LP in the coming decades (The Central Committee of the Communist Party of China and the State Council, 2021), which means that the impacts of afforestation on hydrological regimes should be considered in watershed management planning. To develop an effective watershed management plan, it is necessary to accurately predict hydrological responses using models. Numerous studies have studied variability in hydrologic regimes responses via hydrologic models (Park et al., 2013), such as the storm water management model (SWMM) (Huber and Dickinson, 2021), SWAT model (Arnold et al., 1998), and hydrological simulation program Fortran (HSPF) (Bicknell et al., 2001), which have been used to analyse the change in hydrologic responses under various physical conditions at different temporal and spatial scales. However, as far as the simulation accuracy is concerned, the SWAT model is relatively more suitable for long-term hydrological process simulation in small and medium-sized watersheds (Arnold et al., 2012; Rathjens et al., 2015), and is categorized as a semidistributed model with a physical basis, which can reflect the time-scale change and spatial distribution characteristics of hydrological processes in watersheds and describe the water balance, runoff and concentration mechanism and evapotranspiration of the underlying surface; furthermore, it

has a good simulation effect and stability. Therefore, the SWAT model is widely used in estimating the hydrological regimes response to LULC change (Kang et al., 2021; Yan et al., 2018).

The Liujiahe watershed is located in the center of the LP, which is a typical hilly and gully area with a fragmental landform. The fragmented terrain and extensive human activities in this region have caused very severe soil erosion, with an annual soil erosion modulus of 3000 ~ 20000 t/km²/a in most areas (Ni, 2008). This region is a source area of flood and coarse sediment in the middle reaches of the Yellow River, as well as one of the key areas for soil and water conservation (Ran, 2006). A deep understanding of future LULC and its impact on hydrology in the Liujiahe watershed can provide an important reference for future ecological restoration work on the entire LP. Therefore, the specific objectives of this study include (1) to analyse the potential vegetation restoration; (2) to map vegetation suitability and predict the LULC of selected watersheds; and (3) to simulate changes in runoff, soil water content (SW) and ET from the Liujiahe watershed due to future LULC change. Answers to these questions are important for regional ecosystem restoration and ecological protection of the LP.

2. Study area

The Liujiahe watershed (36°30′–37°19′N; 107°32′–108°11′E) is situated in the central LP, which is a typical hilly and gully area with an area of 7325 km² (Fig. 1). The mean annual precipitation of the watershed is 473 mm, with a mean annual ET₀ total of approximately 950 mm (Zhang et al., 2022). The main soil type is cultivated loessial soil with a poor anti-erosion capability, accounting for 90% of the entire watershed. The mean annual sediment load exceeded 15,000 t km⁻² before 1980 (Chen et al., 2016). To control severe soil erosion, integrated soil conservation projects have been implemented in the Liujiahe watershed since the 1970s, while the GFG program was implemented widely in the 1990s. The afforested area in the Liujiahe watershed increased from 4% in the 1970s to 40% in 2019 (Zou et al., 2021) through the GFG program. Although the area under trees in the Liujiahe watershed increased dramatically over the years, grassland typically dominated the landscape (Zou et al., 2021), with overall vegetation cover representing a mixture of forested land, grassland, and cropland. Hence, LULC changes in the Liujiahe watershed were predominantly determined by the GFG program, making the watershed particularly suitable for investigating future trends in vegetation cover, LULC and streamflow under continued vegetation restoration.

3. Data sources and methods

3.1. Data collection

3.1.1. Natural factors

Daily meteorological data, including precipitation, sunshine duration, air temperature, wind speed, and relative humidity, in the Liujiahe watershed from 1970 to 2020 were obtained from the National Climatic Center of the China Meteorological Administration (<https://cdc.nmic.cn/>) (Table 1). The potential evapotranspiration (ET₀) for each meteorological station was calculated on a daily scale using the P-M method (Allen, et al. 1998). The spatial distribution of annual ET₀ and precipitation within the Liujiahe watershed was obtained based on regional-scale point data interpolated by the collaborative kriging interpolation algorithm (Hohn, 1988). The drought index is a composite reflection of rainfall and evaporation in an area, and it was calculated using Equation (1) (Fig. 2a):

$$Dr = ET_0/P \quad (1)$$

where Dr is the drought index; ET₀ is the potential evapotranspiration (mm); and P is the precipitation (mm). According to the defined value of the traditional annual drought index and the principle of equal intervals

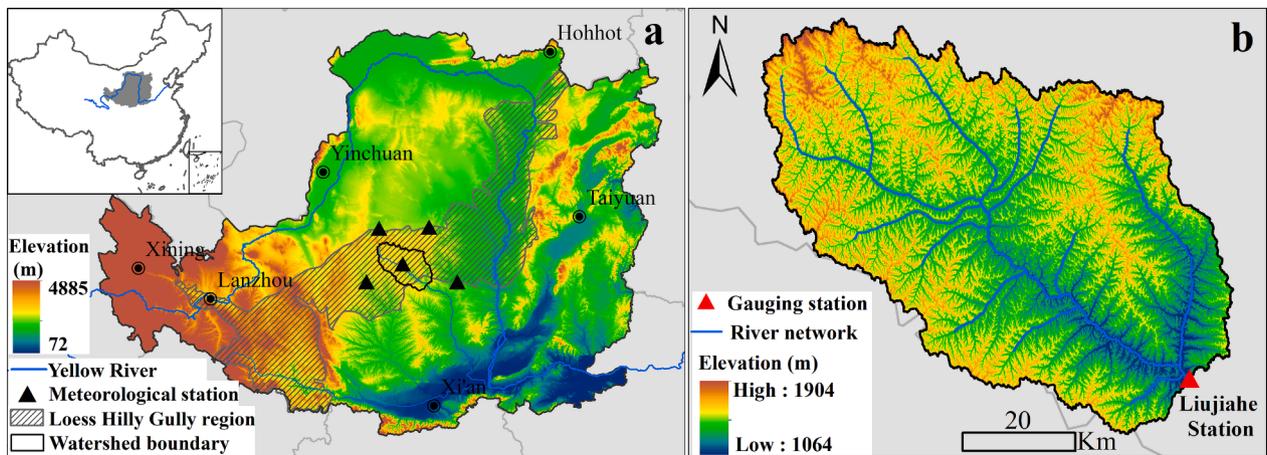


Fig. 1. Location of the Loess Plateau (a) and Liujiahe watershed (b).

Table 1
Description of the driving factors.

Category	Data	Data source	Spatial resolution	Reason for use
Climate	Daily precipitation, sunshine duration, air temperature, wind speed, and relative humidity	National Climatic Center of the China Meteorological Administration (https://cdc.nmic.cn/)	30 m	Construction of similar habitats area and SWAT model
	Potential Evapotranspiration data	P-M method and interpolated by the collaborative kriging interpolation algorithm	30 m	Construction of similar habitats area and SWAT model
	Drought index data	Calculated and interpolated by the collaborative kriging interpolation algorithm	30 m	Construction of similar habitats area
Terrain	DEM	Geospatial Data Cloud (https://www.gscloud.cn)	5 m	Suitability mapping of afforestation, construction of similar habitats area and SWAT model, LULC simulation
	Slope, Aspect and Hillslope shape	Using spatial analysis tools of ArcGIS10.2	5 m	Suitability mapping of afforestation, construction of similar habitats area and SWAT model, LULC simulation
Soil	Soil type data	Loess Plateau Science Data Center (https://loess.data.ac.cn/)	50 m	Construction of similar habitats area and SWAT model
	Soil property Data	Chinese Soil Database website: https://vdb3.soil.csdb.cn/ .	None	Construction of SWAT model
Vegetation	MODIS images	International Scientific Data Service Platform (https://datamirror.csdb.cn/)	500 m	Vegetation restoration potential analysis
	Vegetation zone	Loess Plateau Science Data Center (https://loess.data.ac.cn/)	30 m	Construction of similar habitats area and suitability mapping of afforestation
LULC	Landsat images	Google Earth Engine (GEE) platform.	30 m	LULC simulation and construction of SWAT model
Runoff	Daily runoff data	Hydrological Bureau of the Ministry of Water Resources of the People's Republic of China (http://www.mwr.gov.cn/)	None	Construction of SWAT model

Note: "None" indicates that the data type is point data and there is no accuracy or spatial resolution, "LULC" indicates that land use/land cover.

(Chen, 1974), the drought index was divided into five levels: [1.23–1.5], [1.5–1.75], [1.75–2.0], [2.0–2.25], and [2.25–2.5].

Digital elevation model (DEM) data (5 m × 5 m) were collected from the Geospatial Data Cloud (<https://www.gscloud.cn>) (Table 1). The terrain slope, aspect and hillslope shape of the Liujiahe watershed were obtained by the surface analysis tool in ArcToolbox in ArcGIS10.2 (Fig. 2b, c, d), and the slope was classified into seven classes [0°–3°, (3°–8°), (8°–15°), (15°–25°), (25°–35°), (35°–45°), and >45° (Tang et al., 2001) (Fig. 2b), classifying the aspect into north (0–22.5, 337.5–360], northeast (22.5–67.5], east (67.5–112.5], southeast (112.5–157.5], south (157.5–202.5], southwest (202.5–247.5], west (247.5–292.5], and northwest (292.5–337.5] (Fig. 2c). The hillslope shape was divided into concave and convex types according to the principle of curvature calculation (Fig. 2d).

The soil type map (1:500000) was derived from the Loess Plateau Science Data Center (<https://loess.data.ac.cn/>) (Table 1). The study area mainly includes five soil types: cultivated loessial soils, dark loessial soils, red earths, alluvial soils, and aeolian soils (Fig. 2e). The soil

property data for the soil types in the area were obtained from the Chinese Soil Database website: <https://vdb3.soil.csdb.cn/>.

The vegetation zone is a comprehensive reflection of macroclimate (precipitation, temperature, dryness, etc.), and the Loess Plateau vegetation zone data were obtained from the Loess Plateau Science Data Center (<https://loess.data.ac.cn/>) (Table 1). According to the vegetation zone division, the Liujiahe watershed spans from the forest steppe vegetation zone in the southeast to the typical grassland vegetation zone in the northwest (Fig. 2f).

3.1.2. Vegetation cover data

The vegetation cover data (2001 ~ 2020) were available from the MODIS data (MCD43A4, MOD09A1) derived from the International Scientific Data Service Platform (<https://datamirror.csdb.cn/>) with 500 m resolution. The corresponding vegetation coverage (annual maximum) was derived from the NDVI using the ternary linear mixed model (Guerschman et al., 2009). Based on a comparison with the ground truth data in 2020, the estimation accuracy (R2) was 0.83

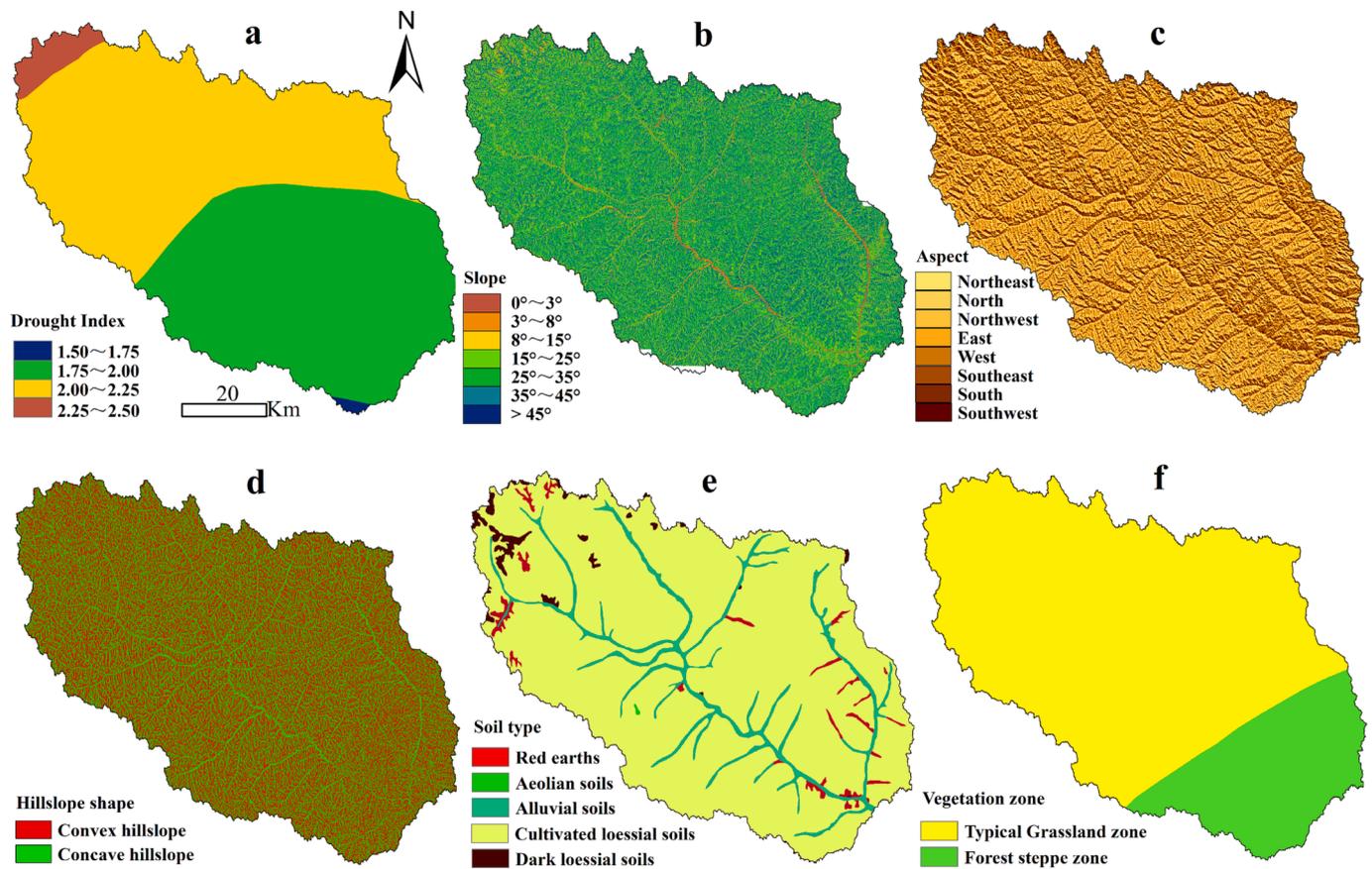


Fig. 2. Distribution of different elemental characteristics of the Liujiahe watershed (a: drought index; b: slope; c: aspect; d: hillslope shape; e: soil type; f: vegetation zone).

(Table 1) (He et al., 2020), which meets the research accuracy requirement.

3.1.3. LULC data

LULC affects the degree of vegetation restoration in the future and indirectly dominates the water cycle (Zhang et al., 2013). Landsat images with 30 m resolution covering the basin in approximately 2020 were collected from the Google Earth Engine (GEE) platform. According to the national land use classification system standard, the LULC map of the study area was obtained. To verify the accuracy of LULC interpretation, 981 points were randomly deployed in the study area and verified by high-resolution images in Google Earth software, and the verification results showed an overall correct rate of 92.85% and a Kappa coefficient of 0.90 (Table 1), with reliable classification results (Zou et al., 2021).

3.1.4. Runoff data

We collected observed daily runoff data for the Liujiahe gauging station (Fig. 1b) from the Hydrological Year Books (1970–2019) published by the Hydrological Bureau of the Ministry of Water Resources of the People's Republic of China (<https://www.mwr.gov.cn/>). Primary quality control was implemented to check the accuracy of the data before they were used. Annual runoff was derived by aggregating daily data.

3.2. Data processing methods and analysis framework

3.2.1. Analysis framework

The study aimed to analyse the potential for future vegetation restoration and suitable areas for afforestation and, on this basis, to predict the future changes in LULC and evaluate its impact on runoff.

Fig. 3 shows the framework of this research. After processing the acquired original data, the vegetation coverage, LULC, climate, terrain and vegetation zone data were used to analyse the potential vegetation restoration by the similar habitat method. Then, based on the LULC, topography, soil type and vegetation zone data, the spatial distribution of suitable afforestation areas was analyzed (Table 1). On this basis, the current land use status and China's vegetation restoration policy for the next 30 years were considered, and the results of the potential vegetation restoration and afforestation suitability analysis were used to predict future LULC. Finally, the runoff, LULC, slope and soil type data were used to construct and validate the SWAT model suitable for the Liujiahe watershed to quantitatively analyze and predict the impact of LULC change on the runoff, SW and ET (Table 1). Detailed explanations of each step are provided in the subsequent sections.

3.2.2. Construction of similar habitats

Vegetation growth is usually affected by climatic conditions (e.g., precipitation, temperature, ET0 and humidity), terrain conditions (e.g., elevation, slope, and aspect), and soil and geological conditions (e.g., soil type and landform) (Gao et al., 2017). Generally, under the same natural conditions, the vegetation coverage should be similar (Nauman et al., 2017; Zhao et al., 2021). If vegetation coverage differences exist within the same natural conditions, then there is potential for vegetation coverage to increase. On the basis of the above concepts, the drought index, topography, soil type and vegetation elements were divided into different classes and used to construct similar habitats (Fig. 2). Through the combination of these layers, 2083 similar habitats were formed in the whole study area. The average value of the vegetation cover within each habitat area from 2001 to 2020 was calculated, and to avoid statistical errors, the vegetation cover value at the 90% quantile was taken as the potential vegetation growth for a similar habitat area.

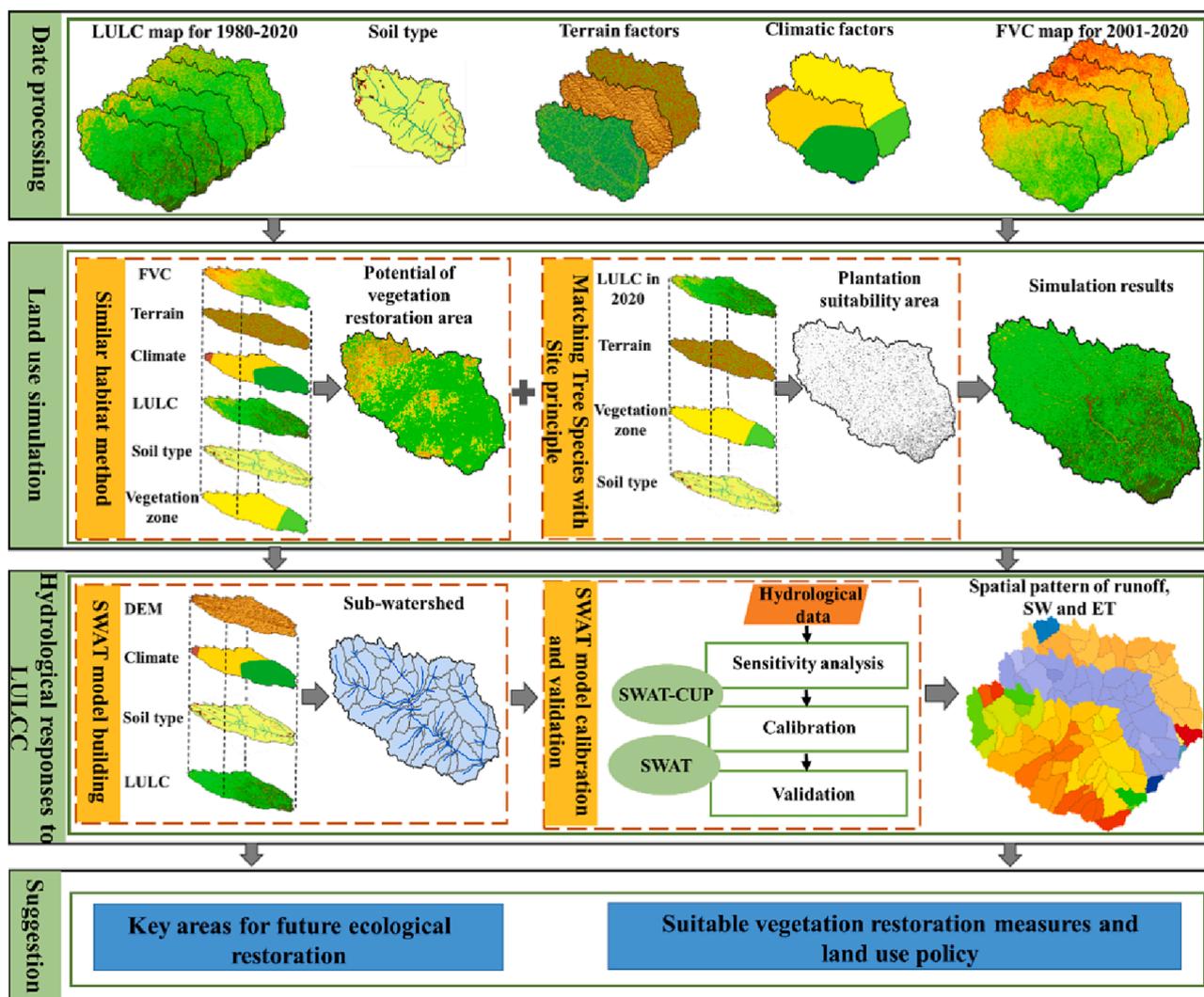


Fig. 3. Analysis framework of future LULC change and its impact on the hydrological regime (LULCC = land use/land cover change, FVC = vegetation coverage, SW = soil water content, ET = evapotranspiration).

To reflect the restoration potential of the Liujiahe watershed, the regional vegetation recovery potential index (I_{VCp} , 0–1) was calculated based on the current vegetation cover (VC , %) and the maximum recoverable vegetation cover (VC_m , %) in 2020:

$$I_{VCp} = (VC_m - VC) / VC_m \quad (2)$$

The closer the I_{VCp} is to 1, the greater the future vegetation recovery potential is, while the closer the I_{VCp} is to 0, the closer the vegetation restoration is to the upper limit of vegetation cover.

3.2.3. Plantation suitability and scenarios

Afforestation is an important part of ecological construction, and suitable afforestation is the key to reclaiming ecological functions. As the Liujiahe watershed is predominantly an arid and semiarid environment, the distribution of vegetation in the area is primarily influenced by precipitation and landforms, such as aspect, slope, and hillslope shape, as those factors affect the availability of soil moisture and incoming solar radiation (Yang and Shao, 2000; McVicar et al., 2007b; Zhang et al., 2008b).

The extent of soil moisture availability defined by local factors is dependent upon precipitation (Zhang et al., 2008b). Vegetation growth in forested vegetation zones is little affected by local factors because of relatively high precipitation. However, in a typical grassland vegetation zone with limited precipitation, vegetation suitability is determined by

local topography. Generally, there are obvious differences in soil moisture storage on different slopes, and the soil water content increases in the order of southwest face < south face < southeast face < west face < east face < northwest face < north face < northeast face in the Northern Hemisphere (Day et al., 1974). Concave hillslopes have a higher capacity for collecting and conserving water in soil than convex hillslopes (Jiang et al., 1987). In addition, the suitable slope gradient for afforestation is considered to be between 25 and 45° (Tang et al., 1998); however, due to the strong wind at the top of a mountain, the soil evaporation is strong, and the slope of the mountain receives external runoff recharge infiltration. The steeper the slope is, the higher the soil moisture content in the middle and at the bottom of the slope (Jiang et al., 1987). In addition, as the forest-steppe vegetation zone is between the forest vegetation zone and the typical steppe vegetation zone, it has typical transitional characteristics, i.e., the closer to the forest zone an area is, the weaker the influence of landforms on afforestation, and the closer to the typical steppe vegetation zone an area is, the stronger the control of landforms on afforestation. To reflect this transition, the forest-steppe zone was divided into 16 subzones according to the principle of equal spacing, and the influence of moisture on afforestation under the combination of landforms was considered according to the sequence of the slope direction, slope type and slope to show the difference in the influence of landforms on moisture and afforestation in the transition zone in a more uniform way; detailed screening rules are

$$RSR = \frac{\sqrt{\sum_{i=1}^n (oi - mi)^2}}{\sqrt{\sum_{i=1}^n (oi - \bar{o})^2}} \quad (6)$$

$$PBIAS = \frac{\sum_{i=1}^n (oi - mi) * (100)}{\sum_{i=1}^n (oi)} \quad (7)$$

where O_i is the measured data; m_i is the simulated data; \bar{O} is the mean of the measured data; \bar{m} is the mean of the simulated data; and n is the number of compared values.

Table 3 shows the general performance rating of the SWAT model according to the research evaluating model accuracy (Moriasi et al., 2007).

4. Results

4.1. Potential vegetation restoration in the Liujiahe watershed

Vegetation coverage inferred from the MODIS images taken in approximately 2001–2020 was used to investigate the current status of vegetation coverage and its restoration potential in the Liujiahe watershed.

The MODIS 2020 images showed that the average vegetation cover of the Liujiahe watershed in 2020 was 62.3% (Fig. 4a), while the results of vegetation recovery potential using the similar habitat method showed that the maximum vegetation cover in the hilly gully area was estimated to be 71.8%, with an improvement of approximately 9.2% in the future (Fig. 4b).

The vegetation restoration potential index (IVCp) in the Liujiahe watershed was calculated by Equation 2 to further analyse the spatial variation in vegetation restoration potential. Fig. 3c shows that there is a large spatial variation in vegetation restoration potential in the Liujiahe watershed in the future, and the high IVCp values (>0.1) are more concentrated in the northwest of the watershed, while low IVCp values (<0.1) are more likely to appear in the southeast of the watershed. Statistics from the whole watershed indicate that the vegetation in 36.4% of the area will continue to improve in the future, while the remaining area has relatively low vegetation restoration potential.

4.2. LULC scenario simulation

4.2.1. Suitability mapping of afforestation

To predict the future changes in forestland, suitability maps for afforestation were developed (Fig. 5) based on the threshold settings and the definition of suitable areas described in Section 2.2.2 and using the data shown in Fig. 2. Due to the dry climate and low precipitation rates in the Liujiahe watershed, the suitable areas for future afforestation are mainly distributed on scattered landforms with sufficient soil moisture and solar radiation conditions, and the statistics show that the area suitable for afforestation is only 46.06 km². The area suitable for afforestation becomes increasingly patchy and sparse from southeast to northwest, which indicates that less than 1% of the Liujiahe watershed

Table 3
SWAT model general performance rating.

Performance Rating	R2	NSE	RSR	PBIAS (%)
Very good	–	0.75 < NSE ≤ 1.00	0.00 ≤ RSR ≤ 0.50	PBIAS < ±10
Good	–	0.65 < NSE ≤ 0.75	0.50 < RSR ≤ 0.60	±10 ≤ PBIAS < ±15
Satisfactory	R2 > 0.6	0.50 < NSE ≤ 0.65	0.60 < RSR ≤ 0.70	±15 ≤ PBIAS < ±25
Unsatisfactory	R2 < 0.6	NSE ≤ 0.50	RSR > 0.70	PBIAS ≥ ±25

provides conditions that should be targeted for afforestation activity, and a large area of returned cropland in the hilly gully area is suitable for natural restoration or grassland.

4.2.2. LULC change in the future

Good knowledge of current LULC trends is important to understand future development. The major land cover units in the Liujiahe watershed include grassland, forestland, cropland, construction land and water bodies (Fig. 6a). Grassland is the dominant LULC type in the watershed, with an area of 3802.39 km², which accounted for more than 50% in 2020 (Table 4). The second most prominent types are forestland and cropland, and their areas are 2135.97 km² and 1302.78 km², accounting for 29.1% and 17.8% of the study area, respectively (Table 4). Smaller areas belong to construction land and water bodies, with areas of 80.18 km² and 3.67 km², accounting for 1.1% and 0.1% of the study area, respectively (Table 4).

According to the GFG policy implemented by the Chinese government and considering the results of afforestation suitability and the potential vegetation restoration area, the LULC was predicted. As shown in Fig. 6b, the grassland, forestland and cropland in the Liujiahe watershed are still the major land cover units in the future LULC structure, with areas of 4410.37 km², 2150.62 km² and 680.16 km², respectively (Table 4). Compared with 2020, the area of cropland decreases most significantly (decrease of 622.63 km², i.e., 47.8%) and is concentrated in the northwestern region of the study area, but owing to continuous conversion of sloping cropland with slopes that exceeded 25°, the expansion of grassland at a large scale is conspicuous, totalling 607.98 km². However, due to the dry climate and limited rainfall in the Liujiahe River region, the area suitable for afforestation is small, resulting in a small change in forestland in the future (Fig. 6c), increasing by only 0.7% compared with that in 2020 (Table 4).

4.3. Spatial patterns of hydrological regimes to LULC

4.3.1. Calibration and validation of the SWAT model

The SWAT model was used to simulate the impacts of regional hydrology under changing LULC conditions described in Section 3.2.2.

The sensitivity analysis using the SWAT-CUP program shows that the parameters CN2, SOL_AWC, HRU_SLP, SOL_K, ESCO, GW_REVAP, CH_K2, and ALPHA_BF are more sensitive to runoff than the other parameters. A general description and final values of the 8 parameters are shown in Table 5.

LULC data from the 1980s and 1990s were used for the calibration and validation of the SWAT model, respectively, because LULC was more stable during this period. Correspondingly, the runoff dataset from 1975 to 1994 was divided into two segments for calibration (1975–1984) and validation (1985–1994) of the model. A comparison of the observed and simulated runoff is shown in Fig. 7. The NSE and R2 values for the calibration and validation periods exceed 0.60 (Fig. 7), which indicates a good correlation between the simulated and observed runoff at the annual scale. In addition, the statistical parameters RSR and PBIAS indicate that the simulation produces “good” or even “very good” results (Fig. 7). The observed and simulated mean annual runoff depths for the calibration period were 30.7 mm and 31.4 mm, respectively, and the observed and simulated mean annual runoff depths for the validation period were 38.5 mm and 41.8 mm, respectively. Although the simulated annual runoff was slightly higher than the measured runoff (Fig. 7), overall, the calibrated model was reliable and acceptable in simulating the response of hydrology to LULC changes in the Liujiahe watershed.

4.3.2. Spatial pattern of hydrological responses to LULC

We fixed the input DEM, soil type and climate data (1970–2020) for the SWAT model and obtained the runoff results ET and soil water content (SW) for 1970–2020 (1970–1975 for the warm period) based on LULC data for six periods (1980, 1990, 2000, 2010, 2020 and future

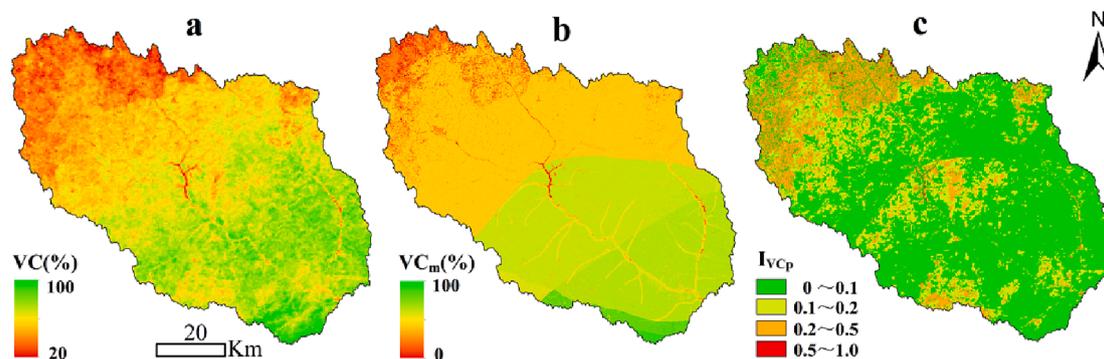


Fig. 4. Vegetation cover in 2020 (a, VC), maximum recoverable vegetation cover (b, VC_m) and its restoration potential index (c, I_{VCp}) in the Liujiahe watershed.

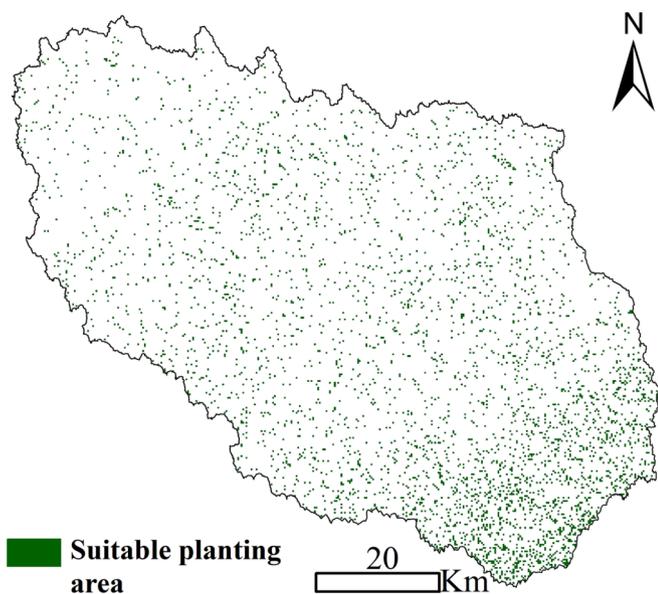


Fig. 5. The plantation suitability map of the Liujiahe watershed.

LULC scenarios) and further investigated the runoff response to LULC changes in the Liujiahe watershed.

Fig. 8a shows that the average annual runoff was 30.8, 42.5, 25.8, 19.1 and 17.8 mm in the 1980s, 1990s, 2000s, 2010s and 2020s, respectively. The spatial variation in runoff showed that the average runoff of all subwatersheds was high in the southeast and low in the northwest in the 1980s–2020s. However, it should be noted that for the

1990s, the situation was quite different, and the average runoff in all of the subwatersheds increased by 38% compared with 1980, though the increase mostly occurred in the northwest area of the watershed. Compared to the 1990s, the average runoff in the 2000s decreased by 39.2%, with the largest decrease occurring in the northwest at 78.1% and the smallest decrease in the southeast at 0.7%. However, the average runoff decreased by approximately 26.1% from the 2000s to 2010s throughout the entire watershed, and the runoff reduction rate in some subwatersheds in the northwest even reached 67.2%. In addition, compared to that in the 2010s, the average runoff in 2020s decreased by 6.5% with a maximum decreasing rate of 20.5% and a minimum of 3.2%.

Fig. 8b shows that the average ET of all subwatersheds generally increased from the 1980s to 2020s in the Liujiahe watershed, and the spatial distribution of the ET in the watershed formed a pattern of low in the southeast and high in the northwest. In the 1980s, the annual ET was 419.3 mm, with a minimum of 263.2 mm and a maximum of 488.5 mm. In the 1990s, the annual ET increased to 423.2 mm, an increase of 0.93% over the 1980s. Approximately 81.5% of all subwatersheds had ET in the

Table 4
Comparisons of current and future LULC areas in the Liujiahe watershed.

LULC	Cropland	Forestland	Grassland	Construction land	Water body
2020 / (km ²)	1302.78	2135.97	3802.39	80.18	3.67
LULC scenario simulation / (km ²)	680.16	2150.62	4410.37	80.18	3.67
Change / (km ²)	-622.63	14.65	607.98	0	0
Percentage / %	-47.79	0.69	15.99	0	0

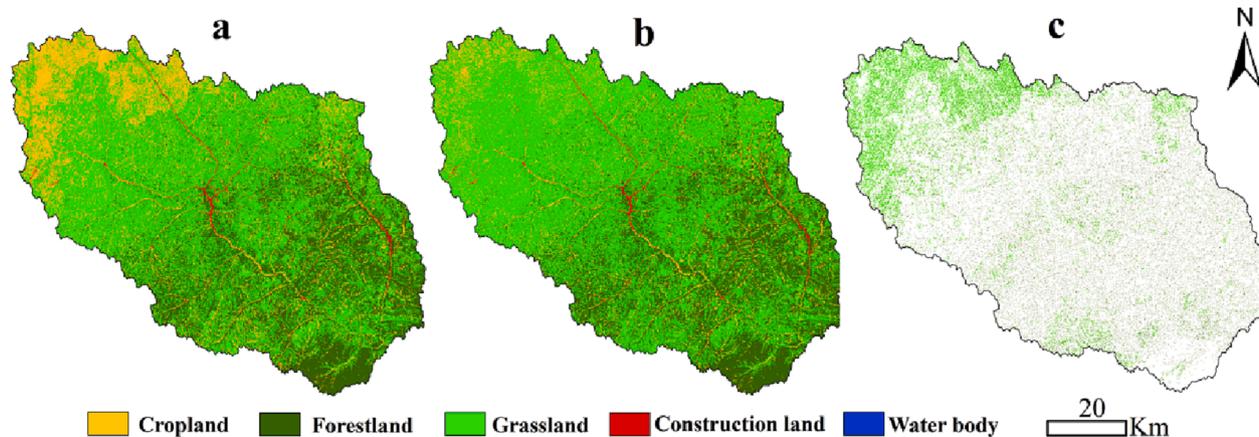


Fig. 6. LULC status (a), future LULC (b) and its change scenarios (c) in the Liujiahe watershed.

Table 5
Basic description, initial value range and final value of sensitive parameters.

Parameters	Description	Range	Fitted value
CN2.mgt	Soil conservation service (SCS) runoff curve number	-1-1	-0.03 r
SOL_AWC.sol	Soil available water capacity (mm/mm)	0-1	+0.28 r
HRU_SLP.hru	Average slope steepness (m/m)	-1-1	+0.30 r
SOL_K.sol	Soil saturated hydraulic conductivity (mm/h)	-3-3	+0.04 r
ESCO.hru	Soil evaporation compensation factor	0-1	0.42 v
GW_REVAP.gw	Groundwater delay time (day)	30-450	319.40 v
CH_K2.rte	Effective hydraulic conductivity (mm/h)	-0.01-500	322.34 v
ALPHA_BF.gw	Baseflow alpha factor (day)	0-1	0.22 v

Note: the superscripts “r” and “v” in the column of fitted value indicate the percent changes based on initial values and replaced parameter values, respectively.

range of 420–440 mm, and these areas were mainly located in the northwest; and central areas of the watershed. The ET increased rapidly with a growth rate of 3.7% during the 2000s of GFG implementation. Up to 86.2% of the total watershed had an annual average ET concentrated in the range of 430–450 mm and widespread throughout the watershed. After 2010, the ET increased to 456.2 mm, with the largest increase occurring in the southeast at 11.9%. From 2010s to 2020s, the average annual ET continued to increase and the change rate was 3.5% with a minimum of 395.9 mm and a maximum of 562.9 mm.

Similar to the spatial variation in ET, the average SW of all sub-watersheds showed a distribution of low in the southeast and high in the northwest in the 1980s–2020s (Fig. 8c). In the 1980s, the annual SW was 49.5 mm, with a minimum of 20.3 mm and a maximum of 88.8 mm. From the 1980s to 1990s, the average annual SW decreased by 11.7%, and the SW in approximately 66.9% of the watershed was concentrated in the range of 30–50 mm. Compared to the 1990s, the average annual ET decreased substantially by 15.5% in the 2000s. The areas with relatively low SW were distributed in the central and southeast regions of the study area, while areas with relatively high SW were mainly distributed in the northwest of the study area. With the continued implementation of reforestation, the average annual SW decreased to 32.4 mm with a change rate of 12.4% in the 2010s, with a minimum of 12.2 mm and a maximum of 83.7 mm, and the areas with the most significant reduction in ET were generally concentrated in the central

and southeast areas of the study area. In the 2020s, the average annual SW continued to decrease with a change rate of 14.1% and showed a similar pattern of spatial variability to that in the 2010s.

Fig. 4 shows that more than 36.4% of the Liujiahe watershed could be targeted for revegetation in the future, and extensive revegetation would affect the runoff, ET and SW in the Liujiahe watershed. The SWAT simulation results show that, compared to the 2020s, the average runoff in all the subwatersheds will decrease by 15.6% in the future, with a maximum decrease of 31.7% occurring in the southern part of the watershed and a minimum decrease of 1.3% prevailing throughout the watershed (Fig. 8a). The future ET showed a continuous decreasing trend from 472 mm in the 2020s to 480 mm, and the ET showed a spatial variation from high in the northwest to low in the southeast throughout the watershed (Fig. 8b). Correspondingly, the SW will decrease continuously with the increase in the area of the forestland and grassland, the average annual SW will be 24.7 mm with a decrease of 11.1% compared with the 2020s, and the areas with relatively low SW will be distributed in the central and southeast regions of the study area (Fig. 8c).

5. Discussion

5.1. Future vegetation restoration measures in the Liujiahe watershed

Water conditions are the main limiting factor for vegetation restoration on the LP (McVicar et al., 2010), and vegetation restoration measures should be “adapted to water conditions”. However, related studies showed that among the three major vegetation restoration measures of closure, grass planting and afforestation on the LP, afforestation measures accounted for 73.6% (Gao et al., 2017). Although revegetation areas on the LP initially led to active growth due to the exploitation of antecedent water stored in the soil matrix (Liu et al., 2005; McVicar et al., 2007a), this active growth usually precludes recharging of the soil stores and leads to the formation of dry soil layers 3 to 8 m deep (Jia et al., 2017). Not enough available water to maintain vegetation growth can lead to the death of vegetation or severely impede its normal growth rate, forming “little old man trees” (He et al., 2003; McVicar et al., 2007a).

In this paper, we simulated suitable areas for future tree planting, based on the availability of soil moisture. The results presented in Fig. 5 show that the suitable planting area in the Liujiahe watershed is 46.06 km² (Fig. 5), and the future grassland area will account for more than 60% of the regional area (Fig. 6 and Table 4), indicating that large areas of returning cropland in the hilly gully area are not suitable for afforestation, especially in the north of the watershed. Previous studies have

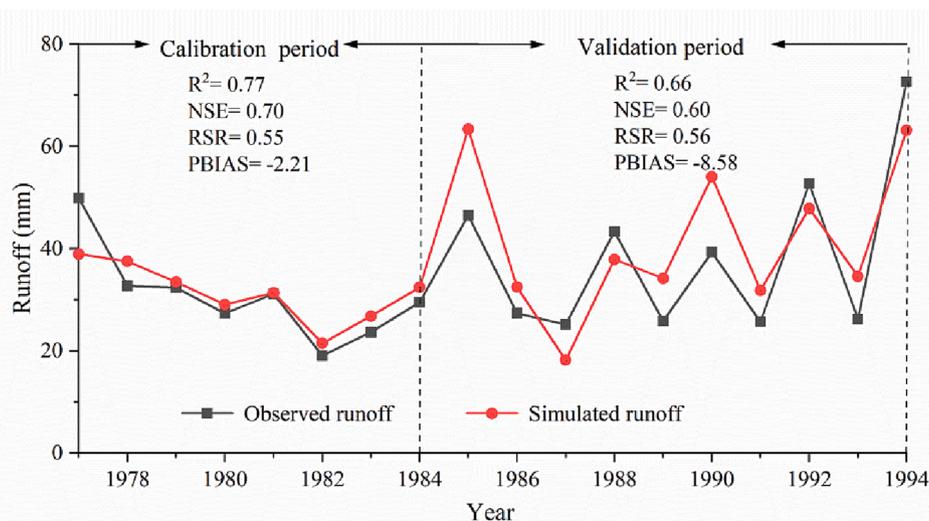


Fig. 7. Observed and simulated annual runoff of the Liujiahe watershed during the calibration (1975–1984) and validation (1985–1994) periods.

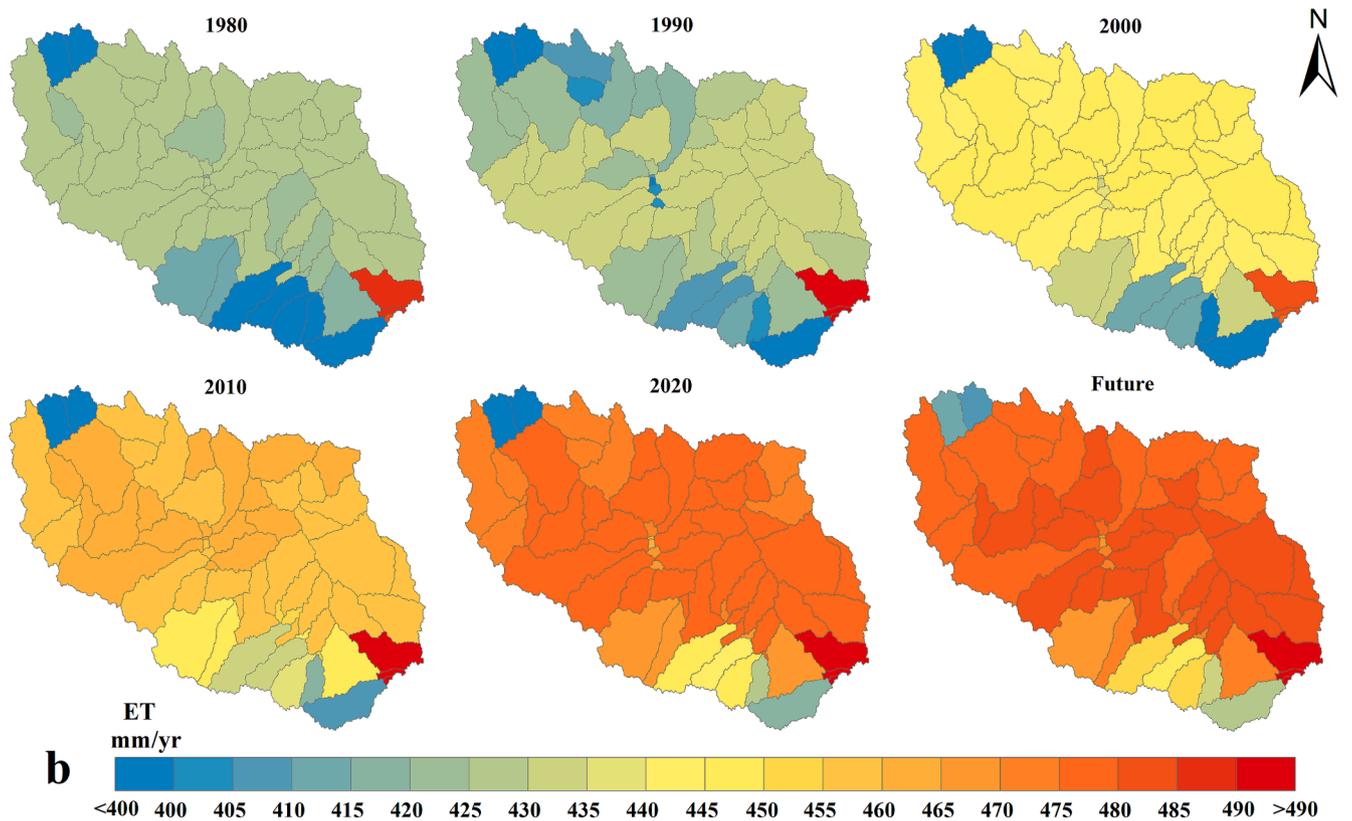
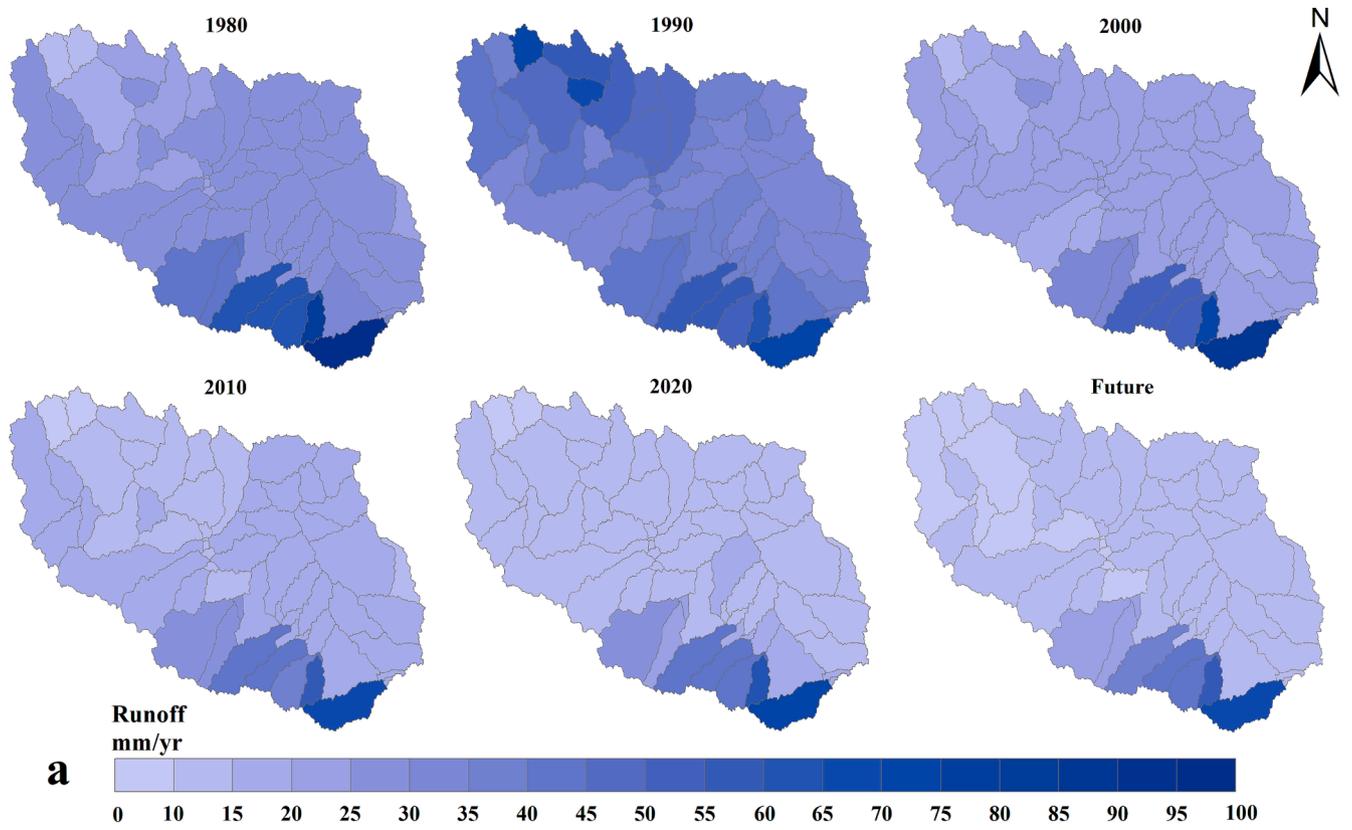


Fig. 8. Spatial patterns of the annual runoff (a), evapotranspiration (b) and soil water content (c) in the Liujiahe watershed in different years.

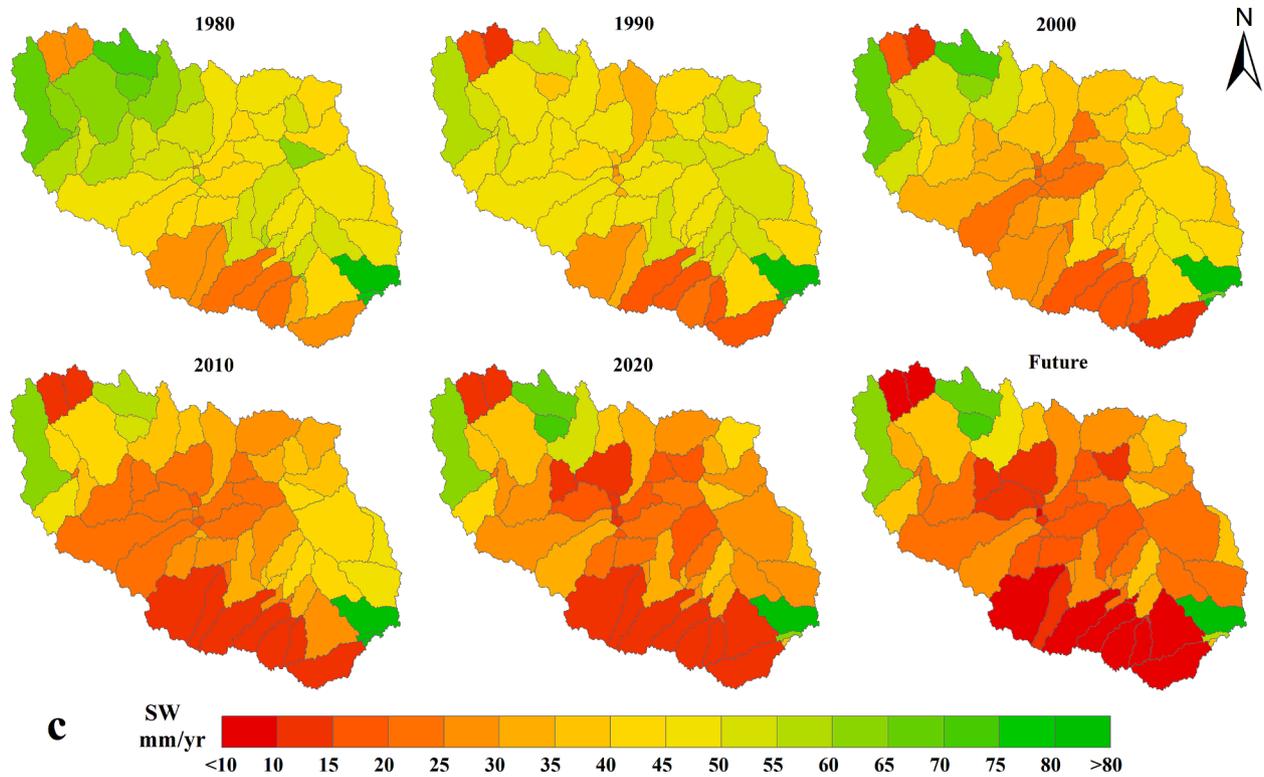


Fig. 8. (continued).

found that the region is more suitable for herbaceous plants due to its latitude and continental climate, resulting in deteriorating precipitation and temperature conditions (Zhang et al., 2006). Based on the above results, and considering that the Liujiahe watershed is an area with limited water resources where the annual potential evapotranspiration (947 mm y⁻¹) is greater than the annual precipitation (500 mm y⁻¹) (Zhang et al., 2022), we propose that future vegetation restoration in this watershed should be natural restoration or artificial restoration based on low-water-consuming grasses and shrubs.

5.2. Hydrological responses to the past LULC change

Our results showed that the annual runoff and SW demonstrated a decreasing trend while ET demonstrated an increasing trend over the study period in all subwatersheds of the Liujiahe watershed (Fig. 8). Zhang et al. (2022) found that there was no significant trend in annual precipitation in the Liujiahe watershed during 1958–2019, and Yan et al (2017) found that the spatial distribution and change patterns of runoff, SW and ET were closely associated with the land use in the northwestern area of the Liujiahe watershed, which suggests that the runoff, SW and ET changes could be mainly attributed to the change in LULC caused by human activities in the Liujiahe watershed. In the 1980s, the Chinese government implemented integrated small watershed management on the LP (Xu et al., 2004), while a larger-scale GFG program was initiated in 1999 (Zhang et al., 2017). The GFG project has converted large areas of cropland to forest and grassland; these ecological measures increased the vegetation cover of the Liujiahe watershed from 23% in 1970 to 70% in 2019 (He et al., 2020). However, the restored vegetation can intercept more precipitation and produce more evapotranspiration than farmland due to large forest canopies, large leaf areas and deep root systems (Li, 2001). In addition, the increase in vegetation creates a thick apoplastic cover and forest root system, which results in greater deadfall storage and water holding capacity than cropland, and helps to intercept surface runoff generated under high-intensity precipitation events and maintain precipitation in the soil profile (Marimon-Junior et al., 2019; Zhu et al.,

2020), thereby reducing runoff. Moreover, vegetation restoration affects soil physical properties, such as the water-stable aggregates, soil porosity and saturated hydraulic conductivity (Lyu et al. 2022; Qiu et al. 2022) and thus enhances soil permeability and water storage capacity (Gasch et al. 2014; Zhao et al. 2010), which may lead to a decrease in runoff and SW and an increase in ET in the Liujiahe watershed.

In addition, our results showed that the spatial pattern of the changes in the hydrological components presented a gradient from northwest to southeast in the Liujiahe watershed (Fig. 8). This result may be due in part to differences in LULC types between the northwest and southeast, and the LULC in the southeast is mainly forest, while the northwest is mainly grassland and cropland (Zou et al., 2021), and forests produce greater evapotranspiration than grasslands and cropland due to their large canopies, large leaf areas, and deep roots systems (Nepstad et al., 1994; Qubaja et al., 2020), which consume more soil water (Gates et al., 2011). On the other hand, the climatic differences between the northwest and southeast may be one of the possible reasons for the spatial distribution of hydrological component changes in the Liujiahe watershed, with the northwest being a typical grassland zone with little rainfall and the southeast having a relatively wet climate with some areas of forested grassland. Nevertheless, we cannot ignore the influence of extreme climate on the spatial pattern of hydrological components. For example, our results found that runoff was significantly higher in the 1990s than in other years (Fig. 8), which could be attributed to the 1000-year return period extreme precipitation event on August 30, 1994 in Wuqi counties in the upper reaches of the Liujiahe watershed, when 6-hour precipitation reached 251 mm (Ran, 2006), and the extreme precipitation caused fluctuations of the runoff in the Liujiahe watershed.

5.3. Comparison with other studies

Currently, many modeling tools and methods are used for LULC simulation, e.g., the CLUE-S model and CA model, which are widely used in the simulation of LULC spatial patterns (Qiao et al., 2022),

however, the CLUE-S model estimates the probability of occurrence of each LULC type separately, ignoring the competition between different LULC types (Verburg et al., 2002; Qiao et al., 2022). In addition, the CA model requires two sets of LULC data to fit the transition probabilities from one LULC type to another for the given driving factors, which inevitably introduces error propagation from multiple LULC classifications (Liu et al., 2017b). Moreover, the role of policies in long-term land use patterns is not well addressed in these models (Qiao et al., 2022). Other studies have focused on simulating LULC change under the influence of human activities (Gustafson et al., 2000; Li and Ren, 2012), and can only simulate individual LULC dynamics, while different LULC change processes occur simultaneously and interact with each other (Qiao et al., 2022). For the Liujiahe watershed, many previous studies have focused on the analysis of the processes of historical LULC change (Yan et al., 2018; Zou et al., 2021). However, few studies have considered the prediction of future LULC characteristics in the Liujiahe watershed.

In our study, we used the “similar habitat” method, which can characterize the complex geomorphological features of the LP by combining different influencing factors, and efficiently assess the future vegetation restoration potential by studying the growth state of vegetation in different habitats (Zhao et al., 2021). Based on the principle of “matching tree species with site”, the evaluation of the suitability of vegetation restoration takes into account the unique geomorphological and climatic characteristics of the LP, and can effectively identify the areas suitable for afforestation in the future (Mcvicar et al., 2010), based on which, combined with human influences such as the national policy of GFG in production, the scientific analysis of LULC change is accurate and reasonable. It is important to guide the future vegetation construction on the LP.

5.4. Accuracy, limitations and uncertainties of results

Data resolution affects the accuracy and resolution of LULC simulation results, for example, slope extracted from DEM data is a crucial terrain variable in land use simulation, especially in the LP with fragmented topography, and some studies found that the slope generated based on low-resolution DEM deviates from the actual slope (Tang et al., 2001), which will affect the simulation accuracy of LULC. In addition, the simulation results of LULC with coarser resolutions obtained from low-resolution data can seriously distort the spatial details of LULC type (Yu et al 2014; Li et al., 2022), thus limiting the application of LULC products. However, Li et al. (2022) found a logarithmic law between the spatial resolution of LULC products and the spatial details of the land use types, with a tipping point of the law around the 30 m resolution. Therefore, to ensure the resolution and accuracy of the LULC results, we used 30 m resolution data for the future LULC simulation. In particular, we used a 5 m resolution DEM, which is the ideal resolution scale to ensure the accuracy of topographic description of the LP (Tang et al., 2001), to extract topographic elements such as slope, aspect and hill-slope shape. In addition, the LULC results with 30 m resolution further ensure the accuracy of the simulation results for hydrological response to future LULC in our studies.

However, vegetation restoration potential, afforestation suitability, and LULC change are the result of a combination of environmental, social, and economic drivers, and the intricate interrelationships among these factors at different spatial and temporal scales constitute an extremely complex system, making the prediction results uncertain. Although the influence of climate and geographical factors, the national policy of returning cropland to forest (grassland), high-resolution remote sensing image data, reference materials and expert experience are considered in this paper, the results are still limited due to the multidimensional characteristics of the relationship between factors that influence the ecological system, the complexity of the Liujiahe watershed and the availability of data. When discussing the suitability analysis of afforestation, only biological measures are considered, but the

planning and construction of engineering measures such as terraces and check dams are less considered, which will have some influence on the predicted LULC results. In addition, the prediction of LULC change in this paper is based on the premise that there will be little change in construction land and water bodies in the future. Although the proportion of these two types of LULC in the Liujiahe watershed is small (Table 4), it will also bring some errors to the results. In addition, although the GFG program has been in operation in the Liujiahe watershed for nearly 20 years, the vegetation coverage in some habitat areas determined by the similar habitat method may not achieve the best state of vegetation restoration, which will underestimate the growth potential of vegetation in the habitat areas and impact the results. In future research, we should consider how to incorporate more potential influential factors into vegetation potential analysis and LULC prediction.

The calibration of models at a watershed scale is a challenging task due to possible uncertainties in the measured data and the error in the conceptual mode. Specifically, the regionalization of climate data such as precipitation and temperature data may introduce large errors (Abbaspour et al., 2007). On the other hand, the inherent drawbacks in the structure and conceptual design of the model determine that some simulations are biased (Abbaspour et al., 2007), including process simplifications and processes not accounted for by the model, which lead to reduced accuracy in the model results, such as the model ignoring the interaction between the surface and groundwater. In addition, some of the equations quoted in the SWAT model are empirical and may not be suitable for the LP region (Gao et al., 2020). Therefore, it is necessary to improve the existing theories or to develop new ones to construct hydrological models that can accurately simulate and are suitable for the LP.

6. Conclusion

The Liujiahe watershed, which is undergoing major conservation activities on the semiarid LP in northern China, was selected to investigate the potential vegetation restoration, LULC change and its impact on the hydrological regime using a habitat analogy approach and the SWAT model.

Despite more than 20 years of ecological restoration, there is still 9.2% potential for vegetation cover to increase, and the vegetation of 36.4% of the area is expected to continue improving in the future. However, the suitable planting area in the Liujiahe watershed is only 46.06 km², and a large area of returned cropland in the Liujiahe watershed is suitable for natural restoration or artificial restoration based on low-water-consuming grasses and shrubs, which will result in a 47.4% reduction in cropland and a 0.7% and 15.8% increase in forestland and grassland, respectively, in the next 30 years. In addition, due to the combined effects of climate, topography and human activities, runoff and SW form a spatial distribution pattern of low in the northwest and high in the northeast, and ET is high in the northwest and low in the northeast. Compared to values recorded in the 1980s at the start of watershed intervention, by the 2020s, average runoff and SW from the Liujiahe watershed were reduced on average by 44.2% and 43.9%, respectively. Conversely, the average ET increased by 12.6% during the corresponding periods. However, LULC changes over the next 30 years will reduce runoff and SW by 15.6% and 11.1%, respectively, and increase ET by 1.2%.

Our results suggest that ecological restoration on the LP has changed the LULC and hydrological regimes, and this change will continue in the future in the context of continued vegetation restoration, which can be a new challenge for water-scarce regions. Although the vegetation in the region still has potential for further improvement, considering the limitation of the precipitation and water-carrying capacity of this region, we propose that ecological measures should be adapted to local conditions to avoid soil dryness and water crises in future vegetation restoration on the LP. This study provides a valuable framework for

improving the rationality and accuracy of LULC simulation on the LP, and these results underpin the regional ecological health and sustainable management of water resources during long-term ecological restoration on the LP. Nevertheless, future studies can incorporate more factors to further improve the accuracy of the results.

CRedit authorship contribution statement

Haijie Yi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. **Xiaoping Zhang:** Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Liang He:** Conceptualization, Data curation, Investigation, Methodology, Visualization. **Jie He:** Conceptualization, Data curation, Investigation, Visualization. **Qilong Tian:** Methodology, Validation, Visualization, Writing – review & editing. **Yadong Zou:** Data curation, Methodology, Visualization. **Zefeng An:** Methodology, Software, Validation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request

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