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Effects of land use/land cover and climate changes on surface runoff in a semi-humid and semi-arid transition zone in Northwest China

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Abstract

Water resources, which are considerably affected by land use/land cover (LULC) and climate changes, are a key limiting factor in highly vulnerable ecosystems in arid and semi-arid regions. The impacts of LULC and climate changes on water resources must be assessed in these areas. However, conflicting results regarding the effects of LULC and climate changes on runoff have been reported in relatively large basins, such as the Jinghe River Basin (JRB), which is a typical catchment (> 45000 km^2) located in a semi-humid and arid transition zone on the central Loess Plateau, Northwest China. In this study, we focused on quantifying both the combined and isolated impacts of LULC and climate changes on surface runoff. We hypothesized that under climatic warming and drying conditions, LULC changes, which are primarily caused by intensive human activities such as the Grain for Green Program, will considerably alter runoff in the JRB. The Soil and Water Assessment Tool (SWAT) was adopted to perform simulations. The simulated results indicated that although runoff increased very little between the 1970s and the 2000s due to the combined effects of LULC and climate changes, LULC and climate changes affected surface runoff differently in each decade, e.g., runoff increased with increased precipitation between the 1970s and the 1980s (precipitation contributed to 88% of the runoff increase). Thereafter, runoff decreased and was increasingly influenced by LULC changes, which contributed to 44% of the runoff changes between the 1980s and 1990s and 71% of the runoff changes between the 1990s and 2000s. Our findings revealed that large-scale LULC under the Grain for Green Program has had an important effect on the hydrological cycle since the late 1990s. Additionally, the

conflicting findings regarding the effects of LULC and climate changes on runoff in relatively large basins are likely caused by uncertainties in hydrological simulations.

Keywords: SWAT; climate change; land use/land cover; streamflow; Jinghe River Basin.

1 Introduction

Both climate and land use/land cover (LULC) changes are key factors that can modify flow regimes and water availability (Oki and Kanae, 2006; Piao et al., 2007; Sherwood and Fu, 2014; Wang et al., 2014a). Since the 20th century, climate variability is believed to have led to changes in global precipitation patterns (IPCC 2007), thereby changing the global water cycle and resulting in the temporal and spatial redistribution of water resources (Milly et al., 2005; Murray et al., 2012). LULC changes are primarily caused by human activities (Foley et al., 2005; Liu and Li, 2008) and affect the partitioning of water among various hydrological pathways, including interception, evapotranspiration, infiltration, and runoff (Sterling et al., 2012). The influences of climate and LULC changes on hydrological processes and water resources will likely continue to increase, especially in arid and semi-arid regions characterized as vulnerable (Fu, 2003; Vorosmarty et al., 2010).

The impacts of LULC and climate changes on runoff can generally be identified by using hydrological models (Praskievicz and Chang, 2009). These models provide valuable frameworks for investigating the changes among various hydrological pathways that are caused by climate and human activities (Leavesley, 1994; Jiang et al., 2007; Wang et al., 2010). Distributed hydrological models, which use input parameters that directly represent land surface characteristics, have been applied to assess the impacts of LULC and climate changes on runoff in water resource management areas (Yang et al., 2008; Yang et al., 2014; Chen et al., 2015). The Soil and Water Assessment Tool (SWAT), a robust, interdisciplinary, and distributed river basin model, is commonly used to assess the effects of management practices and land disturbances on water quantity and quality (Gassman et al., 2007). The hydrological responses to LULC and climate changes are often investigated through scenario simulations using the SWAT model.

Although substantial progress has been made in assessing the impacts of LULC and climate changes on water resources (Krysanova and Arnold, 2008; Vigerstol and Aukema, 2011; Krysanova and White, 2015), most studies have focused on individual factors (i.e., either LULC or climate); thus, the combined effects of LULC and climate changes are not well understood because their contributions are difficult to separate and vary regionally (Fu et al., 2007; D'Agostino et al., 2010; Wang et al., 2014a). For example, some studies have suggested that surface runoff is affected more by climate change (increased precipitation) than by LULC changes (Guo et al., 2008; Fan and Shibata, 2015), and other studies have found that urbanization contributes more to increased runoff than precipitation (Olivera and Defee, 2007). According to Krysanova and White (2015), less than 30 papers were published between 2005 and 2014 on topics related to the combined effects of LULC and climate changes and the SWAT model, whereas 210 and 109 papers presented studies of climate and LULC changes, respectively. However, water resource management requires an in-depth understanding of the isolated and integrated effects of LULC and climate changes on runoff (Chawla and Mujumdar, 2015).

Notable evidence of drying trends exists in semi-arid and semi-humid regions (Ma and Fu, 2006; Li et al. 2007; Li et al. 2010; Li et al. 2011). These regions have experienced serious water shortages in addition to intensive human activity and climate change (Wang and Cheng, 2000; Ma and Fu, 2003). In this case, the effects of LULC and climate changes on runoff are considerably more sensitive, and a dry climate can result in serious environmental degradation and water crises (Ma et al., 2008; Jiang et al., 2011; Leng et al. 2015). The Jinghe River Basin (JRB), which is located on the central Loess Plateau, is a typical catchment located in a semi-humid and semi-arid transition zone in Northwest China. The agricultural activities in this basin play an important role in Northwest China (Zhao et al., 2014). However, the relative importance of agriculture in the basin has caused ecological problems associated with social development. For example, local water resources cannot maintain the rapid socio-economic growth in the region (Wei et al., 2012), and the river system has become unhealthy (Wu et al., 2014). Water and environmental management in the region requires improved knowledge of the hydrological impacts of LULC and climate changes. The effects of LULC and climate changes on the water cycle and water resources must be assessed in these critical regions (Zhang et al., 2008; Li et al., 2009; Qiu et al., 2011; Qiu et al., 2012; Peng et al., 2013).

Because the JRB transports the largest volume of sediment from the Loess Plateau to the Yellow River, hydrological studies of the basin have primarily assessed the impacts of soil and water conservation measures on surface runoff and sediment transport (e.g., Feng et al., 2012; He et al., 2015; Peng et al., 2015a, 2015b; Wang et al., 2016). Relatively few studies have been conducted regarding the effects of LULC and climate changes on runoff. Studies of the Weihe River Basin (Zuo et al., 2014) and

Loess Plateau (Liang et al., 2015), which included the JRB as a sub-basin, have identified the response of runoff to climate change and human activities by using a climate elasticity model based on the Budyko framework. Zuo et al. (2014) found that runoff in the JRB decreased by 17.79 mm between 1997 and 2009, with human activities and climate change accounting for 51% and 39% of this decrease, respectively. Liang et al. (2015) showed that streamflow decreased substantially from 1961 to 2009, and the contribution of climate change (65%) to streamflow reduction was much larger than that of ecological restoration measures (35%) in the JRB. Another study based on the relationship between precipitation and runoff from 1966 to 1970 showed that runoff mainly decreased due to precipitation before the 2000s and due to human activity became dominant thereafter (with a contribution greater than 76%) (Zhang et al., 2011). The different results reported by Zuo et al. (2014) and Liang et al. (2015) suggest that assessing the impacts of LULC and climate changes on runoff in relatively large basins (over 1000 km^2) is difficult (Chawla and Mujumdar, 2015; Peng et al., 2015b) due to their complex effects on streamflow (Fu et al., 2007) and the variable boundary conditions (Chen et al., 2011; Niraula et al., 2015).

Therefore, the objectives of this study were as follows: 1) to assess the surface runoff variability influenced by LULC and climate changes in recent decades in the JRB by using the SWAT model, which differs from the climate elasticity model based on the Budyko framework; 2) to quantify the combined and isolated impacts of LULC change and climate variability on surface runoff in the basin from 1971 to 2005 by using scenario simulations after calibrating and validating the SWAT model at monthly and yearly time scales; 3) to discuss how LULC and climate changes affect surface runoff; and 4) to discuss the simulation uncertainty in the context of SWAT modelling due to parameterizations and provide potential explanations for the conflicting results regarding the effects of LULC and climate changes on runoff in relatively large basins.

2 Methods and materials

2.1 Study area

The JRB, which covers an area of approximately 45421 km^2, is located at 106°14′ – 108°42′ E and 34°46′ – 37°19′ N on the central Loess Plateau in Northwest China (Fig. 1). The main stream of the Jinghe River, with a length of 450 km, originates in the Liupan Mountains in the Ningxia Autonomous Region and flows across Gansu and Shanxi Provinces before draining into the Weihe River. The outlet gauging station, Zhangjiashan, has a control area of approximately 43216 km^2. The study area is characterized by hills and syncline valleys, with the Liupan Mountains to the west and the Ziwu Mountains to the east. The elevation decreases from 2900 m to 360 m above sea level. The climate varies from sub-humid to semi-arid, with mean annual precipitation, temperature, and pan evaporation values of 390–560 mm, 8–13 °C, and 1000–1300 mm, respectively. Precipitation mainly occurs between July and September, accounting for 50–70% of the total annual rainfall.

2.2 Runoff change simulation

Under the assumption that runoff is affected only by LULC and climate changes, the effects of LULC and climate changes on surface runoff were evaluated using SWAT. Before the simulations, the SWAT model was calibrated and validated as described below.

2.2.1 SWAT model and data collection

SWAT, a semi-distributed hydrological model, was developed to assess the impacts of land management and climate on water, nutrient, and pesticide transport at the basin scale (Arnold et al., 1998; Neitsch et al., 2005). SWAT simulates hydrological processes such as surface runoff at the daily time scale based on information regarding weather, topography, soil properties, vegetation, and land management practices. In SWAT, the study basin is divided into sub-basins, and each sub-basin is further subdivided into hydrological response units (HRUs) with homogeneous characteristics (e.g., topography, soil, and land use). Hydrological components are then calculated in the HRUs based on the water balance equation.

In this study, SWAT is operated via an interface in ArcView GIS (Di Luzio et al., 2002). Therefore, the required data are either raster or vector data sets, including a digital elevation model (DEM), soil properties, vegetation, LULC, meteorological observations, and discharge observations at Zhangjiashan gauging station.

(1) DEM

The Shuttle Radar Topography Mission (SRTM) 90-m DEM (Jarvis et al., 2008) was used in this study.

(2) Soil data

Soil property information was obtained from the soil map of China at a scale of 1:1000000. The map was provided by the Chinese Natural Resources Database. Huangmiantu, which covers 75.10% of the basin area, is the major soil type in the area according to the Genetic Soil Classification of China. The other seven soil types are Heilutu (13.27%), Chongjitu (4.30%), Huihetu (3.23%), Hetu (2.41%), Hongniantu (1.10%), Cugutu (0.35%), and Shandicaodiantu (0.24%).

(3) Vegetation and LULC data

LULC data from four periods were retrieved from Landsat images by supervised classification, i.e., Multispectral Scanner (MSS) images (60 m resolution) from 1979, Thematic Mapper (TM) images (30 m resolution) from 1989, and Enhanced Thematic Mapper Plus (ETM+) images (30 m resolution) from 1999 and 2006. Each LULC dataset represents the land use patterns for one decade (e.g., LULC data obtained from 1979 represents the land use patterns in the 1970s). Land use was classified into seven categories: forest, dense grassland, sparse grassland, cropland, water, and barren areas. Then, the accuracy of the classification was verified, yielding a minimum Kappa coefficient of 0.73 (Xie et al., 2009).

(4) Meteorological data

Daily precipitation was collected from 16 rainfall stations (Fig. 1), whereas the daily minimum and maximum temperatures, wind speed, and relative humidity data required by the SWAT model were collected from 12 meteorological stations between 1970 and 2005. These data were interpolated to DEM grids using the SWAT model's built-in weather generator, which describes the weather conditions in the model simulations.

(5) Surface runoff

Daily runoff data measured at the Zhangjiashan gauging station between 1970 and

1990 were collected from the State Hydrological Statistical Yearbook. These data were compared to the modelled surface flow during model calibration and validation.

2.2.2 Model calibration and validation

The SWAT model of the basin was first calibrated for the period of 1971 to 1997 and was then validated for the period of 1981 to 1990. Based on published results (e.g., Li et al., 2009) and our previous research results (Qiu et al., 2011), the simulation was the most sensitive to the following six parameters: runoff curve number (CN_2), soil evaporation compensation factor (ESCO), the available water capacity of the soil layer (SOL_AWC), channel conductivity (CH_K_2), the baseflow alpha factor (ALPHA_BF), and the surface runoff coefficient (SURLAG). Therefore, these six parameters were calibrated in the SWAT model (Table 1) (Qiu et al., 2011). Model performance was assessed qualitatively using visual time series plots and quantitatively using the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency coefficient (*Ens*) (Eq. (1)) (Moriasi et al., 2007).

$$Ens = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs} - Q_{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs} - Q_{obs\_m}\right)^2} \qquad (1)$$

where Q_{obs} and Q_{sim} are the observed and modelled runoff, respectively; Q_{obs_m} is the mean value of observed runoff; and n is the number of data records. When *Ens* approaches 1, the model simulates the measured data more accurately, whereas a negative *Ens* indicates that the model performance is poor. In this study, a criterion proposed by Moriasi et al. (2007), the Nash-Sutcliffe coefficient, was adopted to evaluate the simulation (Table 2).

The SWAT model was calibrated and validated based on annual and monthly river discharges measured at the outlet gauging station shown in Fig. 1.

2.2.3 Simulation scenarios

In this study, the effects of LULC and climate changes on surface runoff were evaluated by comparing the SWAT outputs of ten scenarios. Each scenario represented one decade, and each simulation required an LULC map and a meteorological data set (Table 3). If the LULC map and the meteorological data were within the same decade (i.e., the 1970s, 1980s, 1990s, or 2000s), the simulation results represented "real runoff" or a "baseline" affected by the combination of LULC and climate changes. Alternatively, varying one driving factor while holding others constant simulated the effects of the variable factor on runoff (Li et al., 2009). For example, to assess the response of streamflow to combined LULC and climate changes in the 1970s and 1980s, the simulation of the 1970s (1970–1979) ($Q_{base,\,i}$), which is used as a reference period or baseline, should be based on the current LULC (year 1979) and current climate (years 1970–1979). The simulation of the 1980s (1980–1989) ($Q_{base,\,i+1}$) should be based on future LULC (year 1989) and future climate (years 1980–1989). The difference between the first and second simulations represents the combined effects of LULC and climate changes on streamflow. Regarding LULC changes, the third simulation ($Q_{sim,\,cL,\,i}$) was based on the current climate (years 1970–1979) and the LULC in the next period, or the future LULC (in this example, 1989). The difference between the first and third simulations is the effect of the LULC change on streamflow. Similarly, the difference between the first simulation and the fourth simulation ($Q_{sim,\,cc,\,i}$) based on the current LULC (year 1979) and future climate (in this example, 1980–1989) represents the impact of climate change on streamflow. The combined effects of LULC and climate changes on streamflow (ΔR_{comb}%) and the isolated effects of LULC ($\Delta R_{iso,\,cL}$%) and climate ($\Delta R_{iso,\,cc}$%) can be assessed using Eqs. (2) to (4).

$$\Delta R_{comb}\% = \left(\frac{Q_{base,i+1} - Q_{base,i}}{Q_{base,i}}\right)\times 100 \qquad (2)$$

$$\Delta R_{iso,cL}\% = \left(\frac{Q_{sim,cL,i} - Q_{base,i}}{Q_{base,i}}\right)\times 100 \qquad (3)$$

$$\Delta R_{iso,cc}\% = \left(\frac{Q_{sim,cc,i} - Q_{base,i}}{Q_{base,i}}\right)\times 100 \qquad (4)$$

3 Results

3.1 Climate change

Variations in precipitation, dryness index (E_0/P, defined as the ratio of annual potential evapotranspiration calculated using the Penman–Monteith method to annual precipitation), and air temperature were evaluated over four decades based on meteorological data from 1970 to 2009 (Fig. 2). Precipitation decreased by 3.4% from the 1970s to the 2000s. However, precipitation in the 1980s was slightly higher than that in the 1970s. The decreasing trend in precipitation was substantial from the 1980s to the 1990s, reaching 4.1%. Thereafter, the decrease in precipitation was less than that from 1980 to 1999. During the entire period (from the 1970s to the 2000s), the temperature increased by 13.6% (1.18 °C), including an abrupt increase of 0.7 °C from the 1980s to the 1990s. Although the dryness index exhibited little change (increasing by 1.8%), a large dryness index (>1.9) indicates that the climate became drier. These results indicate that the climate in the JRB changed dramatically over the last four decades, as characterized by decreased precipitation and increased temperature and dryness index values. Both warming and drying trends are evident in the JRB. These results agree with the results of other studies that reflect a broader phenomenon known as "climatic warming and drying" in northern China (Ma and Fu, 2003; Huang et al., 2012).

3.2 LULC change

Figure 3 shows the variations in LULC distributions over the last four decades. The dominant land-use types are sparse grassland (with a vegetation coverage of < 20%) and cropland, which encompass a total of > 61% of the area over the four decades. However, the percentage of sparse grassland was slightly higher than that of cropland, and the margin varied from 2.96% to 9.80%. The remaining types include dense grassland (with a vegetation coverage of ≥ 20%), forest, barren areas, urban and built-up areas, and water, with mean ratios of 17.57%, 13.71%, 6.35%, 0.31%, and 0.29%, respectively. The vegetation with low coverage that is predominant in the study basin corresponds with the regional climate, and the relatively high percentage of cropland indicates the importance of agriculture in this area.

The statistical results illustrated by the four LULC maps over the last four decades indicate that vegetation (including grassland and forest) decreased by 11% between the 1970s and the 1990s and increased by 6% thereafter. The areas of cropland and urban and built-up areas increased by 4.03% and 0.95%, respectively, over time. The area of water fluctuated slightly, increasing by 0.09%. The area of barren land increased from 3.09% to 12.35% before the 1990s but then decreased to 3.02% in the 2000s. The LULC changes potentially resulted from two major factors: social development and population growth. These factors have increased since the 1980s, leading to the expansion of urban and agricultural activities as well as unreasonable land utilization, reclamation of vulnerable land, and vegetation removal. Therefore, the areas of urban and barren land increased while the area of vegetation decreased. However, the decreasing trend in vegetation changed due to a nationwide environmental conservation programme initiated in 1999 by the Chinese government, the Grain for Green Program (GGP) (Xu et al., 2004). The main goal of the GGP was to reduce soil erosion and improve the eco-environmental status of western and northern China (Xu et al., 2004). Noticeable evidence of ecological restoration was observed on the Loess Plateau after the GGP was implemented (Chang et al., 2011; Sun et al., 2015). In addition to preventing soil erosion, the GGP improved the soil physical and chemical properties (Deng et al., 2014; Song et al., 2014) and facilitated vegetation restoration. The results indicate that vegetation increased since the late 1990s, and these results agree with the results of other studies (e.g., Liang et al., 2015; Wang et al., 2016).

3.3 Performance of the SWAT model

The SWAT model performed well in both the calibration and validation periods, accurately simulating the outlet flows according to the model performance criteria (R^2 and *Ens*) after the six sensitive parameters were optimized. During the calibration period (1971–1980), the time series plots of simulations and observations were similar at both the annual (Fig. 4 (a)) and monthly scales (Fig. 5 (a)), although overestimation was observed in the simulated streamflow. Point-by-point comparisons between the simulations and observations further showed that most of the paired streamflow values were distributed near the 1:1 line, with mean R^2 values of 0.90 (Fig. 4 (b)) and 0.84 (Fig. 5 (b)) at the annual and monthly scales, respectively (Qiu et al., 2011). In addition, the results of a statistical analysis indicated that the mean *Ens* values were 0.76 and 0.72 at the annual and monthly scales, respectively (Table 4). Similarly, although the SWAT model did not perform as well during the validation period (1981–1990) relative to the calibration period, the performance was still adequate, with *Ens* (R^2) values of 0.73 (0.83) and 0.69 (0.77) at the annual and monthly scales, respectively (Table 4, Figs. 6 and 7).

Although the *Ens* performance statistic associated with SWAT runoff modelling can be larger than 0.8 in small or humid basins (e.g., Luo et al., 2008; Qiao et al., 2015; Wu et al., 2016), *Ens* is typically less than 0.7 in relatively large river basins in arid to semi-arid regions (e.g., Xu et al., 2011; Notter et al., 2013; Zhang et al., 2015; Liu et al., 2016; Zhao et al., 2016). The *Ens* values in this study were generally good in the calibration and validation periods and were comparable to those reported in other studies in arid to semi-arid river basins. The results suggested that the SWAT model performed well and was applicable to the study basin.

3.4 Simulated surface runoff

The annual runoff simulated by SWAT under different scenarios is shown in Table 3. Generally, runoff increased minimally between the 1970s and the 2000s at a rate of 1.51 $m^3 s^{-1}$ (simulations S1 and S10) due to the combined effects of LULC and climate changes (Fig. 8). However, runoff changed differently in different decades. For example, runoff increased by 35.4% (29.75 $m^3 s^{-1}$) from the 1970s to the 1980s (simulations S1 and S4) but decreased thereafter. Notably, the simulated runoff in the 1990s was 12.59 $m^3 s^{-1}$ less than that in the 1980s (simulations S4 and S7), and runoff decreased by 15.5% (15.65 $m^3 s^{-1}$) from the 1990s to the 2000s (simulations S7 and S10) (Table 3).

4 Discussion

4.1 Impacts of LULC and climate changes on surface runoff

The hydrological effects were analysed using the simulated runoff data rather than the observed data. The combined effects of LULC and climate changes on surface runoff are presented in section 3.4. The simulated runoff increased between the 1970s and the 1980s, while precipitation increased from 521 mm to 527 mm during the same period. Thereafter, runoff decreased as precipitation decreased. However, runoff decreased by 11.1% from the 1980s to the 1990s but decreased by 15.5% from the 1990s to the 2000s. These results indicate that, although precipitation can considerably affect runoff simulation, variations in runoff and precipitation were nonlinear due to the combined effects.

The isolated impacts of LULC and climate changes on surface runoff can be analysed by comparing two sets of simulations. The differences between S1 and S2 (as well as between S4 and S5 and S7 and S8) reflect the impacts of climate change on runoff. Accordingly, the differences between S1 and S3 (as well as between S4 and S6 and S7 and S9) reflect the impacts of climate change on runoff.

4.1.1 Isolated impacts of LULC change

During the first two decades, LULC changes increased runoff by 2.30 $m^3 s^{-1}$ and accounted for 7.73% of the total change (29.75 $m^3 s^{-1}$). Thereafter, LULC change decreased runoff by 6.83 $m^3 s^{-1}$, which accounted for 54.25% of the total change in runoff (12.59 $m^3 s^{-1}$) from the 1980s to the 1990s. The impacts of LULC changes on runoff increased during the last two decades because the contribution of LULC changes to runoff increased to 70.67% from the 1990s to the 2000s (Fig. 9).

The results in section 3.2 show that the LULC changed slightly from the 1970s to the 1980s. For example, the area of cropland marginally increased by 0.76%, and the vegetative area decreased by 3.19%. This small LULC change indicates that human activities minimally influenced runoff during the first two decades because the LULC changes only accounted for 7.73% of the increase in runoff. However, the LULC changed considerably with social development and population growth beginning in the 1980s. The vegetative area decreased by 7.81% from the 1980s to the 1990s, and the percentages of cropland, barren areas, and urban and built-up areas increased by 2.39%, 5.43%, and 0.11%, respectively. LULC changes associated with increased human activities accounted for 54.25% of the increase in surface runoff. Furthermore, the GGP, which was initiated in the late 1990s, mitigated the decreasing trend in vegetation. Although cropland and urban and built-up areas still expanded by 2.40% and 0.82%, respectively, from the 1990s to the 2000s, vegetation increased by 6.00%, and barren areas decreased by 9.33%. Therefore, LULC change exhibited a relatively large influence on the surface runoff change, contributing to 70.67% of the surface runoff in the last two decades.

In addition, the spatial distributions of different land use types influence the generation of runoff. As reported in our previous publication (Qiu et al., 2011), the soil moisture content and evapotranspiration were modified by LULC changes (i.e., the GGP) after the GGP in the JRB, which led to changes in surface runoff. However, the modification was different. Fig. 10 shows that, after the GGP, the soil moisture content increased in the three selected sub-basins from the upstream to downstream regions, while the runoff and evapotranspiration decreased. When considering the upstream area as an example, barren land, with an initial percentage of 15.90%, and partial farmland, with an initial percentage of 6.56%, were converted to grassland due to the GGP, which improved water filtration and increased the soil moisture (Fig. 10 (a)). The simulation in Fig. 10 shows that the soil moisture content increased by 163.66%, 208.23%, and 262.66% in the sub-basins from the upstream to downstream, whereas the surface runoff (evapotranspiration) decreased by -37.53%, -38.55%, and -49.01% (-1.21%, -3.06%, and -25.90%), respectively. These results indicate that the impacts of LULC changes on flow regimes were larger in the downstream areas of the basin than in the upstream areas.

Although climate variables were held constant when simulating LULC changes, the isolated influences of LULC changes on runoff did not exclude the impacts of precipitation variations because the climate (including precipitation) varied in each decade (Table 3). Nonetheless, the above results indicate that LULC changes contributed considerably to decreased runoff, as reported in previous studies (e.g., Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2014b; Wang et al., 2016). Additionally, the results suggest that vegetation restoration due to the GGP reduced surface runoff, which agrees with the results of other studies (e.g., Li et al., 2009; Nunes et al., 2011).

4.1.2 Isolated impacts of climate change

Unlike the contributions of LULC changes, the influences of climate change decreased in recent decades (Fig. 9). Climate change increased runoff by 26.07 $m^3 s^{-1}$ from the 1970s to the 1980s, accounting for approximately 87.63% of the increased total runoff during that period. Since the 1980s, surface runoff decreased, and the contributions of climate change to decreased runoff were 55.92% and 42.11% from the 1980s to the 1990s and from the 1990s to the 2000s, respectively. The influence of climate change on runoff agrees with climatic warming and drying trends. Decreasing precipitation will potentially lead to less runoff, whereas increasing temperatures will result in increased evaporation.

In summary, LULC and climate changes accounted for 7.73% and 87.63% of the total runoff increase (29.75 $m^3 s^{-1}$) in the 1970s and 1980s, respectively. The isolated influences of LULC and climate changes on runoff were nearly the same from 1980 to 1999 (54.25% and 55.92%, respectively) compared to the total decrease in runoff. In the last two decades, the percentage of the total runoff decrease that was caused by LULC changes (70.67%) was greater than that caused by climate change (42.11%).

Although uncertainties exist in the simulations (see section 4.2 for details), the above results indicate that the contribution of climate variability decreased over the last four decades, while the contribution of LULC change increased. Unlike the results reported by Liang et al. (2015), the findings in this study suggested that runoff fluctuations are influenced less by climate change and more by human activities. The results also indicate that the impacts of human activities on runoff have gradually increased in the JRB, which agrees with the results of other studies (Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2016).

4.2 Uncertainty in SWAT model simulations

Uncertainty in model simulations, which is mainly caused by model structure (e.g., algorithm limitations) and model parameterizations, is a major challenge when assessing the impacts of LULC and climate changes on runoff in relatively large basins. In this study, the SWAT model performed well, with a Nash-Sutcliffe efficiency coefficient and coefficient of determination of 0.76 and 0.90, respectively, for annual runoff during the calibration period, as well as values of 0.73 and 0.83, respectively, during the validation period. However, under the assumption that runoff is affected only by LULC or climate changes, the simulated runoff associated with changes in only one driving factor was slightly different than the simulated runoff obtained when considering the combined effects of both factors due to the uncertainty in representing LULC and climate change interactions in the SWAT model. For example, 28.37 $m^3 s^{-1}$, which was the combined runoff rate in S2 and S3, was not equal to the "real or baseline runoff" of 29.75 $m^3 s^{-1}$ in S4.

Qiao et al. (2015) reported that the SWAT model performed much better in small watersheds (2–5 ha) than in a larger watershed (78 km^2) because the meteorological inputs (e.g., precipitation) do not represent the spatial variability in a given parameter over larger basins because ground-based observations are limiting. To reduce the uncertainty and improve the accuracy of the hydrological model and forecasting results for relatively large basins, the uncertainty associated with model parameterization is discussed below and potential solutions are proposed for future studies.

In this study, the basin area exceeded 45000 km^2. However, only 16 rainfall stations were available, among which six stations were outside the study basin. The station density was 0.35 stations per 1000 km^2. Xu et al. (2013) found that model simulations are influenced by rainfall station densities below 0.4 per 1000 km^2. Under such conditions, runoff simulations may contain uncertainties due to poor representation of spatial precipitation variability, which is crucial in determining the runoff hydrograph (Singh, 1997). Previous studies (e.g., Chu et al., 2011; Masih et al., 2011; Shope and Maharjan, 2015) have suggested that the density of rainfall measurement stations has a significant impact on SWAT simulations and that reducing the precipitation uncertainty can improve the accuracy of simulated streamflows. Although the SWAT model performed well in this study and the uncertainty in the simulations associated with precipitation was similar to the uncertainties observed in other studies, peak flow overestimation was observed in the simulated runoff (Figs. 4 to 7). To reduce uncertainty, precipitation from stations should be processed (e.g., via interpolation) before conducting runoff simulations, thereby improving the precision and spatial representativeness, especially in relatively large basins without reliable and precise areal rainfall data.

In addition, the coarse vegetation information provided by the LULC data in this study can lead to uncertainty in the simulations because vegetation distinction is required in SWAT modelling. Although the LULC data had a relatively high resolution of 30 m, we can only provide a general vegetation categorization, such as forest, due to the data limitations. Recent results (e.g., Pierini et al., 2014; Qiao et al., 2015) have shown that detailed biophysical parameters of vegetation species can improve the performance of distributed, physically based models such as SWAT and reduce model uncertainty. In China, detailed and reliable data related to vegetation species are uncommon. Reliable maps of vegetation species (as well as other geographic maps) at high spatial resolutions (e.g., <1000 m) are an urgently needed to provide detailed and heterogeneous information for accurate biophysical and hydrological parameterization.

5 Conclusions

In this study, the SWAT model was used to simulate the effects of LULC and climate changes on surface runoff. The satisfactory performance of the SWAT model was confirmed by the Nash-Sutcliffe coefficient and coefficient of determination values of annual runoff of 0.76 and 0.90, respectively, during the calibration period and 0.73 and 0.83, respectively, during the validation period. Simulations showed that the combined effects of LULC and climate changes increased surface runoff by 29.75 $m^3 s^{-1}$ during the 1970s and the 1980s, whereas LULC and climate changes both decreased runoff by 28.24 $m^3 s^{-1}$ during the 1980s and the 2000s. Further analysis suggested that different driving factors had different influences on surface runoff.

The isolated results indicated that the impacts of LULC changes on the hydrological cycle were gradual, and that LULC changes altered runoff to a similar or greater extent than climate change, accounting for 70.67% of the streamflow reduction since the late 1990s. This result suggests that LULC plays an important role in the transition zone between semi-humid and semi-arid regions. As an indicator that is closely related to human activities, the LULC in the study area underwent considerable changes, especially the vegetation cover rate, which decreased by 16% from the 1970s to the 1990s and increased by 6% between the 1990s and the 2000s due to the Grain for Green Program (GGP). In conclusion, the increased vegetation and land use changes inevitably altered the hydrological cycle, and large-scale LULC changes under the GGP considerably affected the hydrological cycle.

To reduce simulation uncertainty and improve the accuracy of hydrological modelling and forecasting in relatively large basins, areal input parameters (e.g., precipitation and vegetation species information) should be generated with reliable precision and high spatial resolution.

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Table 1. Calibrated values of the six parameters in SWAT

No.	Parameter name	Description	Range	Calibrated value
1	CN_2	SCS runoff curve number for moisture condition II	-8–+8	-8
2	ESCO	Soil evaporation compensation factor	0–1	0.1
3	SQL_AWC	Available water capacity of the soil layer	0–1	0.05
4	CH_K_2	Channel conductivity	0–150	0.35
5	ALPHA_BF	Baseflow alpha factor	0–1	0.01
6	SURLAG	Surface runoff coefficient	0–10	0.85

Table 2. SWAT performance of runoff simulations according to the Nash–Sutcliffe coefficient (Moriasi et al., 2007).

Simulation performance	Nash–Sutcliffe coefficient (*Ens*)
Very good	$0.75 < Ens \leq 1.00$
Good	$0.65 < Ens \leq 0.75$
Satisfactory	$0.50 < Ens \leq 0.65$
Unsatisfactory	$Ens \leq 0.50$

Table 3. Simulated annual runoff by SWAT under different scenarios considering both LULC and climate.

	Scenarios	Climate	LULC	Simulation ($m^3\ s^{-1}$)	Runoff change ($m^3\ s^{-1}$)	Runoff change (%)
S1	LULC and meteorological data from the 1970s	1970s	1970s	84.10	–	–
S2	Changing LULC while holding climate constant	1970s	1980s	86.40	+2.30	+7.73
S3	Changing climate while holding LULC constant	1980s	1970s	110.17	+26.07	+87.63
S4	LULC and meteorological data from the 1980s	1980s	1980s	113.85	+29.75	–
S5	Changing LULC while holding climate constant	1980s	1990s	107.02	-6.83	-54.25
S6	Changing climate while holding LULC constant	1990s	1980s	108.61	-7.04	-55.92
S7	LULC and meteorological data from the 1990s	1990s	1990s	101.26	-12.59	–
S8	Changing LULC while holding climate constant	1990s	2000s	90.20	-11.06	-70.67
S9	Changing climate while holding LULC constant	2000s	1990s	94.67	-6.59	-42.11
S10	LULC and meteorological data from the 2000s	2000s	2000s	85.61	-15.65	–

Table 4. Nash-Sutcliffe coefficient (*Ens*) statistics in the SWAT calibration and validation periods.

Statistic	Calibration from 1971–1980		Validation from 1981–1990	
	monthly	yearly	monthly	yearly
N	120	10	120	10
Minimum	0.58	0.53	0.54	0.58
Maximum	0.95	0.98	0.81	0.9
Mean	0.72	0.76	0.69	0.73

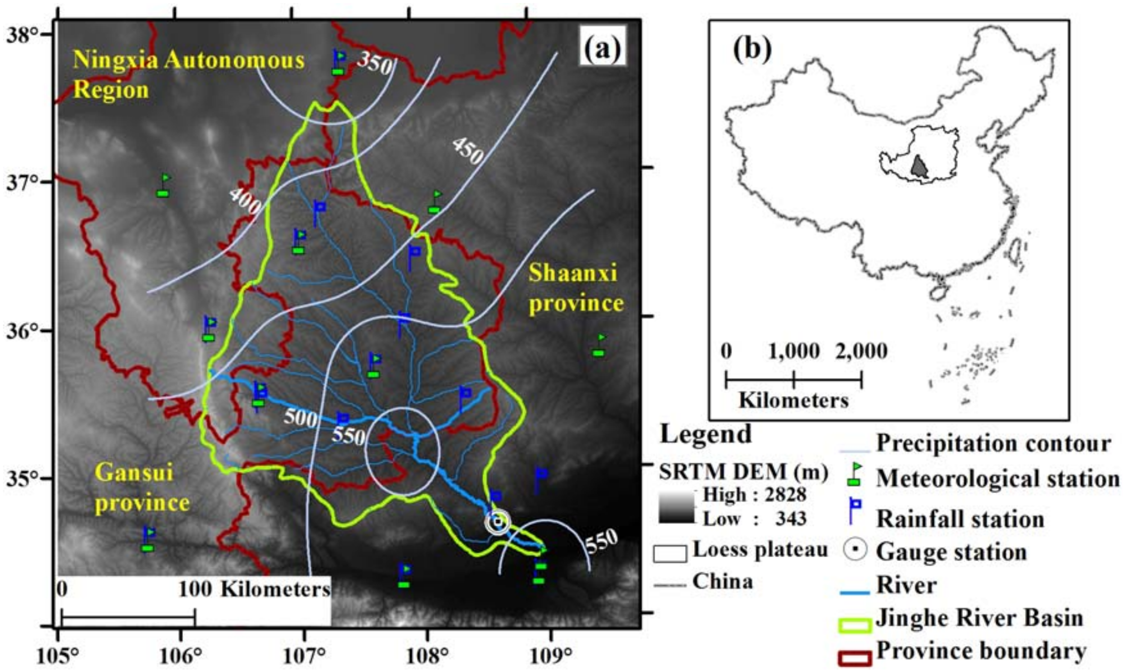


Figure 1. Geographic information regarding the study area: (a) Location and SRTM DEM of the Jinghe River Basin and (b) schematic of the selected study area in China. Precipitation (mm) is averaged and interpolated from meteorological data between 1970 and 2010.

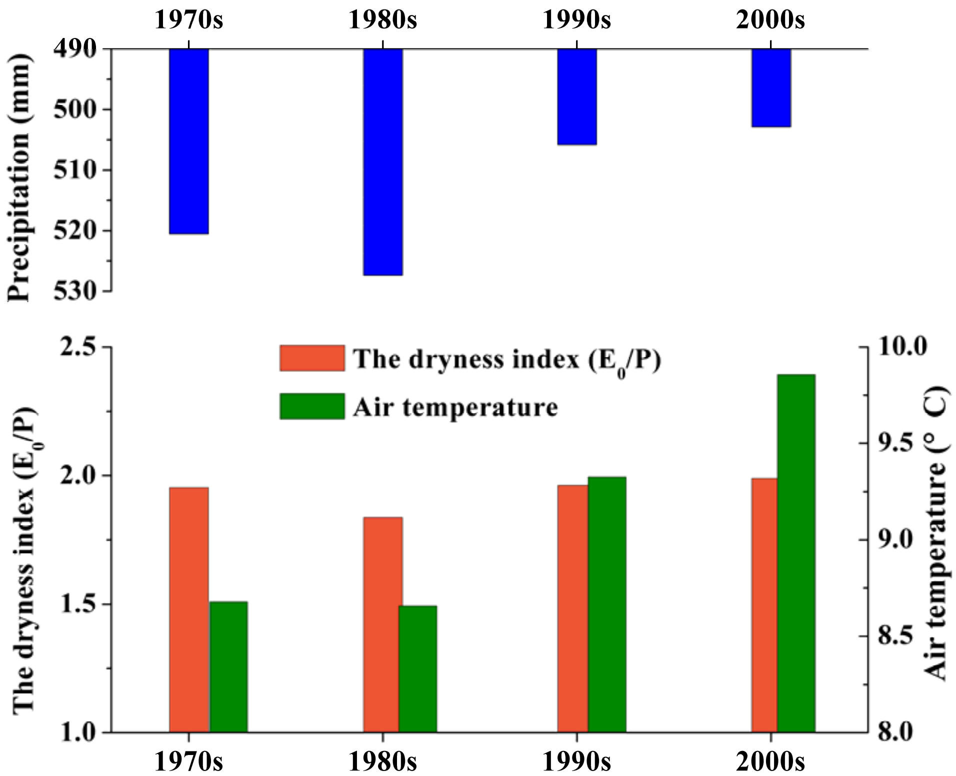


Figure 2. Variation in decadal mean precipitation (top), dryness index, and air temperature (bottom) in the Jinghe River Basin from the 1970s to the 2000s. The dryness index was defined as the ratio of annual potential evapotranspiration (E_0) to annual precipitation (P).

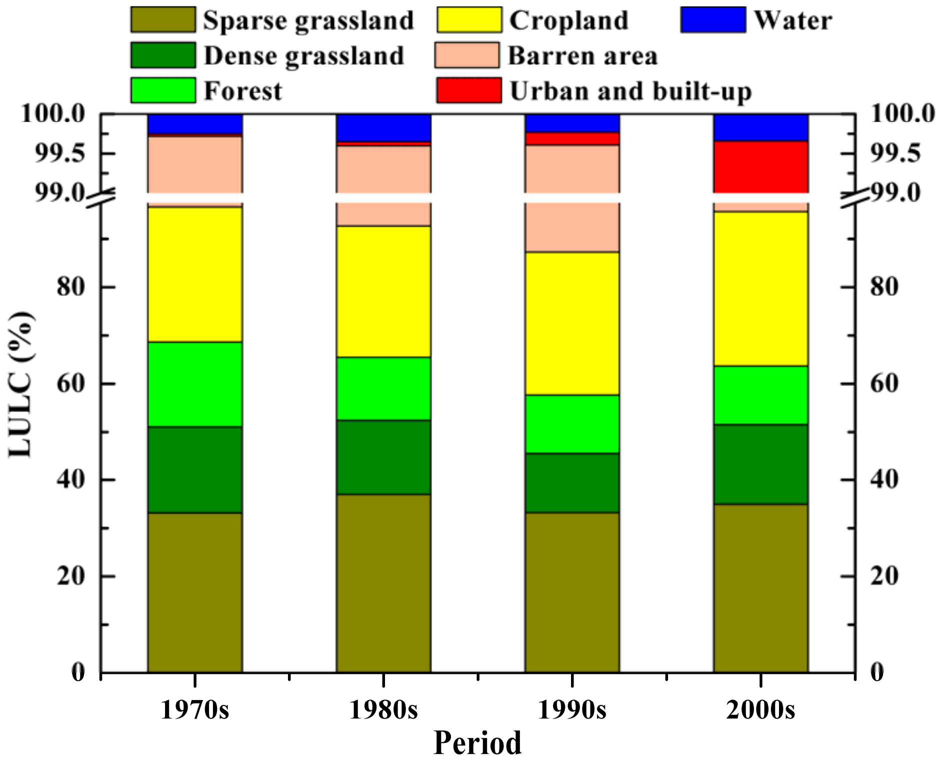


Figure 3. LULC composition and its change in the Jinghe River Basin from the 1970s to the 2000s.

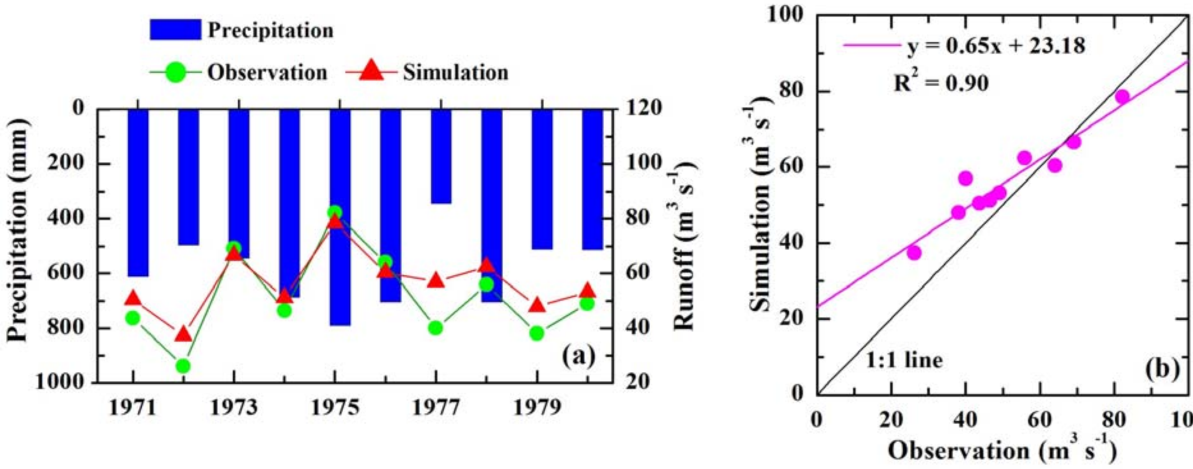


Figure 4. Comparison of observed and simulated runoff at the yearly scale in the Jinghe River Basin during the calibration period from 1971 to 1980. Fig. 4(b) is redrawn from Qiu et al. (2011).

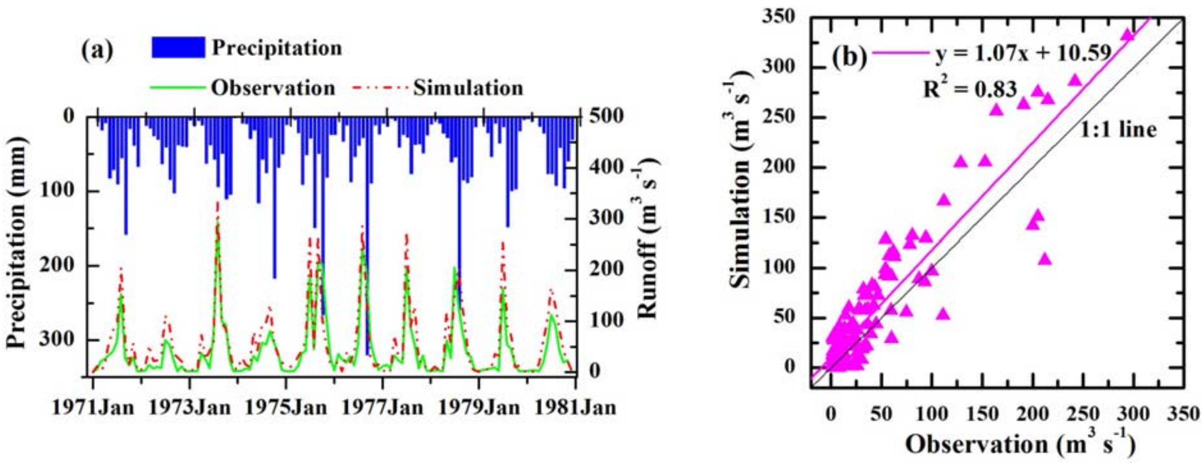


Figure 5. Comparison of observed and simulated runoff at the monthly scale in the Jinghe River Basin during the calibration period from 1971 to 1980. Fig. 5(b) is redrawn from Qiu et al. (2011).

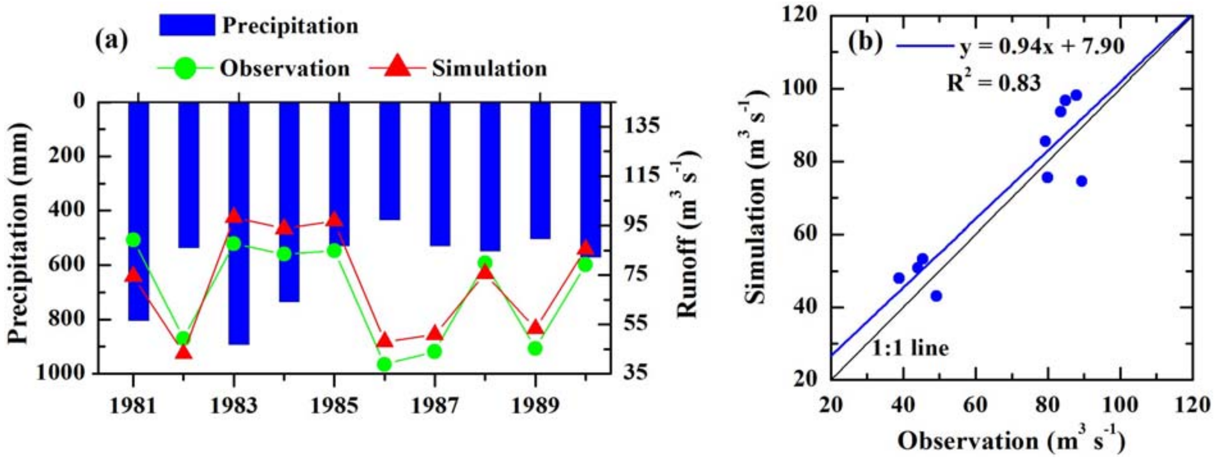


Figure 6. Comparison of observed and simulated runoff at the yearly scale in the Jinghe River Basin during the validation from 1981 to 1990. Fig. 6(b) is redrawn from Qiu et al. (2011).

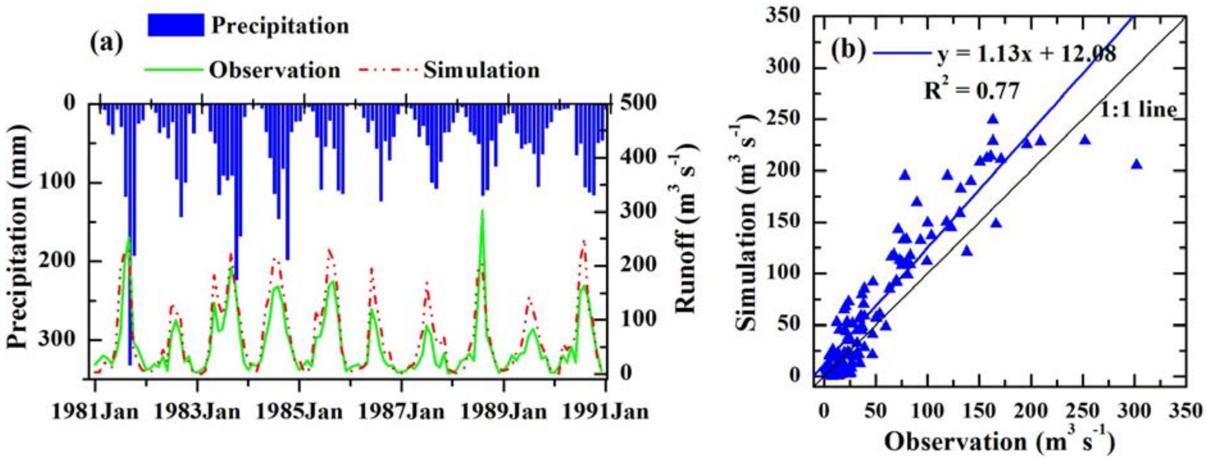


Figure 7. Comparison of observed and simulated runoff at the monthly scale in the Jinghe River Basin during the validation period from 1981 to 1990. Fig. 7(b) is redrawn from Qiu et al. (2011).

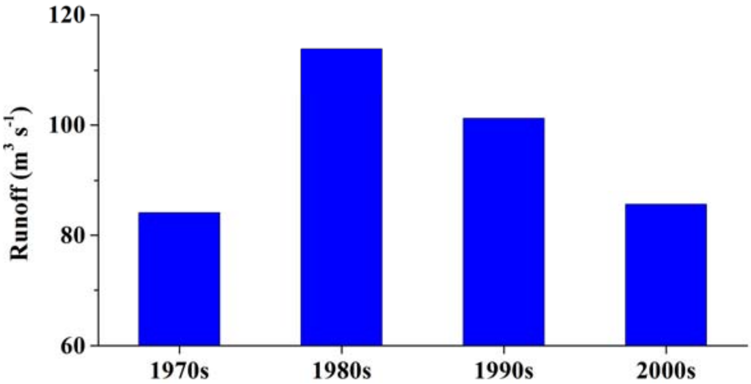


Figure 8. Variation in mean annual surface runoff at the decadal scale in the Jinghe River Basin from the 1970s to the 2000s.

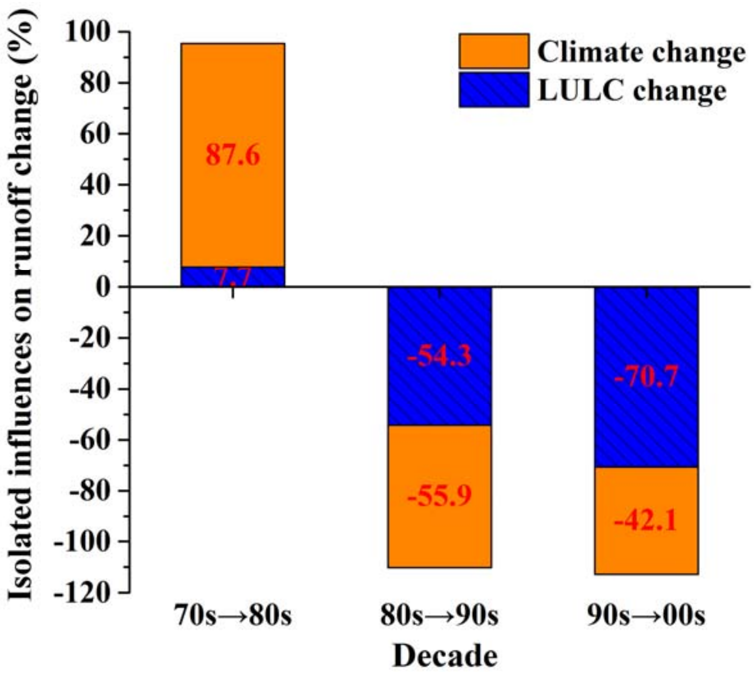
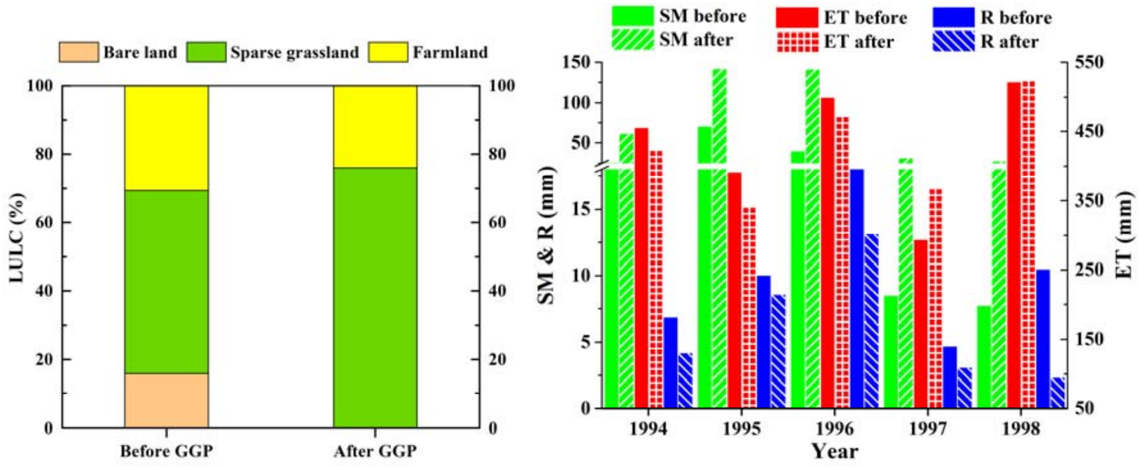
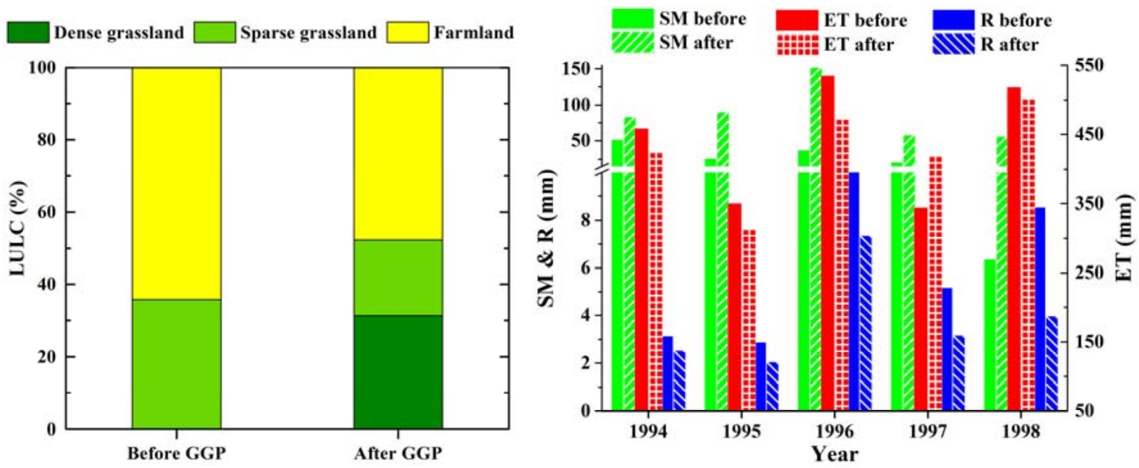


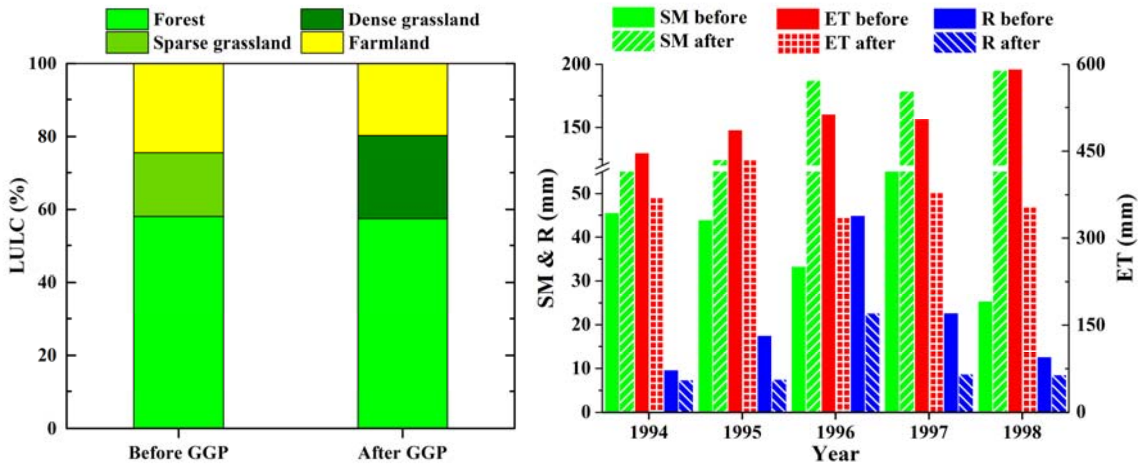
Figure 9. Isolated impacts of LULC and climate changes on surface runoff. Positive values indicate that runoff increased due to these factors, whereas negative values indicate that runoff decreased due to these factors. The summation of the isolated influences is not equal to 100% due to simulation uncertainty (see section 4.2 for details).



(a) upstream



(b) midstream



(c) downstream

Figure 10. Impact of LULC changes on surface runoff in selected sub-basins distributed in the upstream, midstream, and downstream areas of the basin. The left column shows the land use types and corresponding ratios, and the right column shows the simulated changes of the soil moisture content (SM), evapotranspiration (ET), and

surface runoff (R) before and after the Grain for Green Program (GGP) scenarios while holding climate constant.