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Effect 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 substantially affected by land use/land cover (LULC) and climate changes, are a key limiting factor for ecosystems in arid and semi-arid regions exhibiting high vulnerability. It is crucial to assess the impact of LULC and climate changes on water resources in these areas. However, conflicting results on the effect of the LULC and climate changes on runoff have been reported for relatively large basins, e.g., in the Jinghe River Basin (JRB), a typical large 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. It is hypothesized that under climatic warming and drying conditions, LULC change, which is primarily caused by intensive human activities, such as the conversion of cropland to forest and grassland program (CCFGP), will alter runoff markedly 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, i.e., runoff increased with elevated precipitation between the 1970s and the 1980s (precipitation contributed 88% to the increased runoff). Thereafter, runoff decreased and became increasingly influenced by LULC change, with a 44% contribution between the 1980s and the 1990s and a 71% contribution between the 1990s and the 2000s. Our findings revealed that large-scale LULC under the CCFGP since the late 1990s has had an important effect on the hydrological cycle and that the conflicting findings on the effect of the LULC and climate changes on runoff in relatively large basins are likely caused by uncertainty in hydrological simulations.

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., 2014). Since the 20th century, climate variability is believed to have led to changes in global patterns of precipitation (IPCC 2007), thereby changing the global water cycle and causing the redistribution of water resources in time and space (Milly et al., 2005; Murray et al., 2012). LULC change is primarily caused by human activities (Foley et al., 2005; Liu and Li, 2008) and affects the partitioning of water among various hydrologic pathways: interception, evapotranspiration, infiltration, and runoff (Sterling et al., 2012). The impact of climate and LULC changes on the hydrological processes and water resources will become further enhanced, especially in arid and semi-arid regions characterized as vulnerable (Fu, 2003; Vorosmarty et al., 2010).

The impact of LULC and climate changes on runoff can be generally identified by using hydrological models (Praskievicz and Chang, 2009). These models provide valuable frameworks within which to investigate changes among various hydrologic pathways caused by climate and human activities (Leavesley, 1994; Jiang et al., 2007). Distributed hydrological models, which use input parameters directly representing land surface characteristics, have been applied to assess the impact of LULC and climate changes on runoff in water resource management areas (Yang et al., 2008; Chen et al., 2015). The Soil and Water Assessment Tool (SWAT), a robust interdisciplinary distributed river-basin model, is one of the most widely used models for assessing water quantity and quality affected by management practices and land disturbances (Gassman et al., 2007). The hydrological response of LULC and climate changes is often achieved through scenario simulation using the SWAT model.

Although substantial progress has been made in assessing the impact of LULC and climate changes on water resources (Krysanova and Arnold, 2008; Vigerstol and Aukema, 2011; Krysanova and White, 2015), most studies focus on individual factors (i.e., either LULC or climate); thus, the combined effects of LULC and climate changes are still not well understood due to the difficulty in separating the contributions of each factor, and the contributions vary from region to region (Fu et al., 2007; D'Agostino et al., 2010; Wang et al., 2014). For example, some studies suggest that climate change (precipitation increase) is affected much more strongly by surface runoff than LULC (Guo et al., 2008; Fan and Shibata, 2015), whereas some studies find that urbanization contributes to more to an increase in runoff than precipitation (Olivera and Defee, 2007). According to statistics from Krysanova and White (2015), fewer than 30 papers published between 2005 and 2014 on topics related to the combined effects of LULC and climate changes were based on the SWAT model, whereas there were 210 and 109 papers studying climate change and LULC change, respectively. However, water resources management requires an in-depth understanding of the isolated and integrated effects of LULC and climate changes on runoff (Chawla and Mujumdar, 2015).

In Northwest China, where there is a serious water shortage and land-use is simultaneously subject to intensive human activity and climate change (Wang and Cheng, 2000; Ma and Fu, 2003), there is notable evidence of a drying trend in the semi-arid and semi-humid regions (Ma and Fu, 2006; Li et al. 2007; Li et al. 2010; Li et al. 2011). In this case, the effects of

LULC and climate changes on runoff are considerably more sensitive, and the drying climate will make the degraded environment and serious water crises even worse (Ma et al., 2008; Jiang et al., 2011; Leng et al. 2015). The Jinghe River Basin, located on the central Loess Plateau, is a typical catchment located in a semi-humid and semi-arid transition zone in Northwest China. Agriculture in this basin plays 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 are not sufficient to maintain its high socio-economic growth (Wei et al., 2012), and the river system is unhealthy (Wu et al., 2014). Water and environmental management in the region requires improved knowledge of the hydrological impacts of changes in LULC and climate. It is urgent to evaluate the impact of LULC and climate changes on the water cycle and water resources 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 Jinghe River Basin contributes the largest volume of sediment to the Yellow River from the Loess Plateau, studies of the basin related to hydrology have primarily focused on assessing the impacts of soil and water conservation measures on surface runoff and sediment (e.g., Feng et al., 2012; He et al., 2015; Peng et al., 2015a, 2015b; Wang et al., 2015). Relatively few studies on the effect of the LULC and climate changes on runoff have been conducted. Studies have identified the response of runoff to climate change and human activities using a climate elasticity model based on the Budyko framework in the Weihe River Basin (Zuo et al., 2014) and the Loess Plateau (Liang et al., 2015), including the Jinghe River Basin as a sub-basin. Zuo et al. (2014) found that between 1997 and 2009, runoff in the Jinghe River Basin decreased by 17.79 mm, with a 51% contribution from human activities and a 39% contribution from climate change. Liang et al. (2015) showed that streamflow decreased substantially during the period 1961–2009, and the contribution of climate change (65%) to streamflow reduction was much larger than that of ecological restoration measures (35%) in the Jinghe River Basin. Another study based on the precipitation-runoff relationship during the period of 1966–1970 showed that before the 2000s, the runoff decrease was caused mainly by decreased precipitation, but thereafter, human activity became the dominant factor affecting runoff decrease, with a contribution greater than 76% (Zhang et al., 2011). The different results reported by Zuo et al. (2014) and Liang et al. (2015) indicate that it is still challenging to assess the impacts of LULC and climate changes on runoff in relatively large basins (over 1000 km^2) (Chawla and Mujumdar, 2015; Peng et al., 2015b) due to the complex effect of LULC and climate changes on streamflow (Fu et al., 2007) and changed boundary conditions (Chen et al., 2011; Niraula et al., 2015).

Therefore, the objectives of this study were to 1) assess surface runoff variability influenced by LULC and climate changes in recent decades in the Jinghe River Basin using the SWAT model, which differs from the climate elasticity model based on the Budyko framework, 2) quantify both the combined and isolated impacts of LULC change and climate variability on surface runoff in the basin for the period 1971-2005 through scenario simulations after calibrating and validating the SWAT model at monthly and yearly time scales, and 3) discuss simulation uncertainty in the context of SWAT modeling due to parameterizations and provide possible explanations for the conflicting results regarding the effect of the LULC and climate changes on runoff in relatively large basins.

2 Methods and materials

2.1 Study area

The Jinghe River Basin, which has an area of approximately 45 421 km^2, is located at 106°14′ – 108°42′ E and 34°46′ – 37°19′ N on the central Loess Plateau, 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 Yellow River. The outlet gauging station, Zhangjiashan, has a control area of approximately 43 216 km^2. The study area is characterized by hills and syncline valleys, with the Liupan Mountains on the west side and the Ziwu Mountains on the east side. The elevation decreases from 2900 m to 360 m above sea level. The climate varies from sub-humid to semi-arid, with a mean annual precipitation, temperature, and pan evaporation 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 SWAT model and data collection

The Soil and Water Assessment Tool (SWAT), a semi-distributed hydrological model, was developed to assess the impact 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 a daily time scale on the basis of information that includes 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 hydrologic response units (HRUs) with homogeneous characteristics (e.g., topography, soil, and land use). Hydrological components are then calculated for the HRUs.

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

(1) DEM

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

(2) Soil data

Information regarding soil properties was obtained from the soil map of China at a scale of 1:1 000 000 provided by the Chinese Natural Resources Database. Huangmiantu, covering 75.10% of the basin area, is the major soil type 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 for four periods were retrieved from Landsat images using supervised classification, i.e., Multispectral Scanner (MSS) images (60 m resolution) for 1979, Thematic Mapper (TM) images (30 m resolution) for 1989, and Enhanced Thematic Mapper Plus (ETM+) images (30 m resolution) for 1999 and 2006. Each LULC dataset represents the land use patterns for one decade (e.g., LULC data obtained from 1979 representing the land use patterns for the 1970s) and is classified into seven categories, including forest, dense grassland, sparse grassland, cropland, water, and barren area. The classification is verified to be accurate with 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 daily minimum and maximum temperatures, wind speed, and relative humidity data required in the SWAT model were collected from 12 meteorological stations between 1970 and 2005. These data were interpolated to the DEM grids using the SWAT model's built-in weather generator to describe weather conditions in model simulations.

(5) Surface runoff

Daily runoff data measured at Zhangjiashan gauging station were collected and used for comparisons against the modelled surface flow during calibration and validation of the model.

2.3 Model calibration and validation

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

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

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-Suttclife 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.

2.4 Runoff change simulation

Under the assumption that the runoff is affected only by LULC and climate changes, the effect of LULC and climate changes on surface runoff was evaluated by comparing the SWAT outputs of ten scenarios. Each scenario represented one decade, and the simulation required an LULC map and a meteorological dataset (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 a "real runoff" or "baseline" affected by the combination of LULC and climate changes, whereas changing one driving factor at a time while holding others constant caused the simulated results to represent runoff affected by the changed factor (Li et al., 2009). For example, to assess the combined response of streamflow to LULC and climate changes between the 1970s and the 1980s, the first simulation for the 1970s (1970–1979) ($Q_{base,\,i}$), which is used as a reference period or baseline, should be based on current LULC (year 1979) and current climate (years 1970–1979). The second simulation for 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. For LULC change, the third simulation ($Q_{sim,\,cL,\,i}$) was based on the current climate (years 1970–1979) and the future LULC for the next period (here, 1989). The difference between the first and third simulations is recognized as the effect of 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 (here, 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).

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

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

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

3 Results and Discussion

3.1 Climate change

The variation in precipitation, dryness index (E_0/P, defined as a ratio of annual potential evapotranspiration calculated from the Penman–Monteith method to annual precipitation), and air temperature were evaluated for the past four decades based on the meteorological data between 1970 and 2009 (Fig. 2). Precipitation decreased from the 1970s to the 2000s and declined by 3.4%. However, precipitation in the 1980s was slightly higher than that in the 1970s. The declining trend of precipitation was substantial from the 1980s to the 1990s, with precipitation decreasing by 4.1%. Thereafter, the declining level of precipitation was less than during the period 1980–1999. 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 showed little change (increasing by 1.8%), a larger dryness index (>1.9) indicates the climate is drier. These results indicate that the climate has changed dramatically in the Jinghe River Basin during last four decades, characterized by decreased precipitation and increased temperature and dryness index. The warming and drying trends are evident in the Jinghe River Basin, which is in agreement 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 composition and variation of LULC types during the past four decades. The dominant land-use types are sparse grassland (with vegetation coverage of < 20%) and cropland, with a total area of > 61% during 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 are dense grassland (with vegetation coverage of ≥ 20%), forest, barren areas, urban and built-up areas, and water, with mean ratio values 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 well with the regional climate, and a relatively high percentage of cropland indicates the importance of agriculture.

The statistical results for the four LULC maps for the past 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 the urban and built-up areas expanded through the decades, increasing by 4.03% and 0.95%, respectively. The area of water fluctuated slightly, with an increase of 0.09%. The area of barren land exhibited an increase before the 1990s, from 3.09% to 6.92% and then to 12.35%, and decreased to 3.02% in the 2000s. The LULC changes may have been the result of two major factors. Social development and a population increase since the 1980s led to large demands of expanding urban and agricultural activity as well as unreasonable utilization, reclamation of vulnerable land, and vegetation removal. Therefore, the urban regions and barren land areas increased, whereas vegetation decreased. However, the decreasing trend of vegetation has changed due to a nationwide environmental conservation programme initiated in 1999 by the Chinese government: the conversion of cropland to forest and grassland program (CCFGP) (Xu et al., 2004). The main goal of the CCFGP was to reduce soil erosion to improve the eco-environmental status of western and northern China (Xu et al., 2004). There was noticeable evidence of ecological restoration after the implementation of the CCFGP on the Loess Plateau (Chang et al., 2011; Sun et al., 2015). In addition to preventing soil erosion, the CCFGP improved the physical and chemical properties of the soil (Deng et al., 2014; Song et al., 2014), facilitating vegetation restoration. The results of this study indicating an increase in vegetation since the late 1990s are in agreement with the results of other studies (e.g., Liang et al., 2015; Wang et al., 2015).

3.3 Performance of the SWAT model

The SWAT model performed well for both calibration and validation periods in terms of simulating outlet flow according to the model performance criteria (R^2 and *Ens*) after optimization of the six sensitive parameters. During the calibration period (1971–1980), time-series plots between simulations and observations were similar at both 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 closely along the 1:1 line, with mean R^2 values of 0.90 (Fig. 4 (b)) and 0.84 (Fig. 5 (b)), respectively, for annual and monthly scales. In addition, the results of a statistical analysis indicated that the mean *Ens* values were 0.76 and 0.72, respectively, for annual and monthly scales (Table 4). Similarly, although the performance of the SWAT model was not as good for the validation period (1981–1990) as that for calibration, the performance was still good, with *Ens* (R^2) values of 0.73 (0.83) and 0.69 (0.77), respectively, for annual and monthly scales (Table 4, Figs. 6 and 7).

Although the *Ens* performance static for 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 over the calibration and validation periods and were comparable to 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 Impacts of LULC and climate changes on surface runoff

The annual runoff simulated by the SWAT under different scenarios is shown in Table 3. The hydrological effects were analysed using the simulated runoff rather than the observed data. Generally, runoff increased minimally between the 1970s and the 2000s, with a margin of 1.51 $m^3 s^{-1}$ (simulations S1 and S10) due to the combined effects of LULC and climate changes. However, runoff changed differently in different decades. Runoff increased by 35.4% (29.75 $m^3 s^{-1}$) from the 1970s to the 1980s (simulations S1 and S4), and a decrease was observed thereafter, i.e., the simulated runoff of the 1990s was 12.59 $m^3 s^{-1}$ less than that of the 1980s (simulations S4 and S7), whereas runoff decreased by 15.5% (15.65 $m^3 s^{-1}$) from the 1990s to the 2000s (simulations S7 and S10).

Comparing the difference between two sets of simulations (i.e., S1 and S2, S4 and S5, and S7 and S8) enables the influence of LULC changes between the corresponding two adjacent decades to be analysed. Accordingly, the contrast between S1 and S3 (as well as between S4 and S6 and between S7 and S9) indicated the impact of climate change on the runoff. In the first two decades, LULC changes increased runoff by 2.3 $m^3 s^{-1}$, which accounted for 7.73% of the total change (29.75 $m^3 s^{-1}$), whereas the changed climate increased runoff by 26.07 $m^3 s^{-1}$, which accounted for approximately

87.63% of the total runoff. The isolated influences of LULC and climate changes on runoff were nearly the same from 1980 to 1999, as the percentages were 54.25% and 55.92%, respectively, compared to the total decreased runoff. For the last two decades, the decreased runoff caused by LULC changes was greater than that caused by climate change. The percentages were 70.67% and 42.11%, respectively, of the total decreased runoff. The results of this study indicate that vegetation restoration due to the CCFGP could reduce surface runoff, which is in agreement with the results of other studies (e.g., Li et al., 2009; Qiu et al., 2011; Nunes et al., 2011).

Although uncertainties exist in the simulations (see section 3.5 for detail), the above results indicated that the contribution of climate variability decreased during the past four decades, and the contribution of LULC changes increased. Unlike the results reported by Liang et al. (2015), the findings in this study suggested that the runoff fluctuation influenced by climate change is smaller than the influence from human activities and that the impact of human activities on runoff is gradually increasing in the Jinghe River Basin, which are in agreement with the results of other studies (Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2015).

3. 5 Uncertainty in model simulation

Uncertainty in model simulations, which is mainly caused by model structure (e.g., algorithm limitation) and model parameterizations, is a major challenge for 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-Suttclife model efficiency coefficient and determination coefficient of 0.76 and 0.90, respectively, for annual runoff during the calibration period, and 0.73 and 0.83, respectively, for the validation periods. However, under the assumption that runoff is affected only by LULC and climate changes, the summation of the simulated runoff caused by changes in one driving factor was slightly different from runoff simulated under the combined effect due to the uncertainty in the representation of LULC and climate change interactions in the SWAT model. For example, 28.37 $m^3 s^{-1}$, which is the combined runoff for S2 and S3, was not equal to the "real or baseline runoff ", i.e., 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 input (e.g., precipitation) does not represent the spatial variability of a given parameter over larger basins due to limited ground-based observation. To reduce the uncertainty and improve the accuracy of hydrological modelling and forecasting in relatively large basins, the following text discusses uncertainty caused by model parameterizations and proposes possible solutions, aiming to provide information 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 per 1000 km^2. Xu et al. (2013) found that model simulations are greatly influenced when the rainfall station density is below 0.4 per 1000 km^2. Under such a condition, runoff simulations may contain uncertainties due to the poor representation of precipitation spatial variability, which is key in determining the runoff hydrograph (Singh, 1997). Previous studies (e.g., Chu et al., 2011; Masih et al., 2011; Shope & Maharjan, 2015) have suggested that the density of rainfall measurement stations has a significant impact on SWAT simulations; reduced 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 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., interpolation) before conducing runoff simulations to improve the precision and spatial representation, especially in relatively large basins without reliable and precise areal rainfall data.

In addition, the vegetation and LULC data used in this study were very coarse compared to the soil data, leading to uncertainty in the simulations because vegetation speciation is required in SWAT modelling. Because even the LULC data have a relatively high resolution of 30 m, we can only provide a general vegetation catergorization, such as forest, due to the lack of data. Recent results (e.g., Pierini et al., 2014; Qiao et al., 2015) have shown that detailed biophysical parameters for vegetation species can improve the performance of distributed, physically based models, e.g., SWAT, and reduce model uncertainty. In China, detailed data related to vegetation species with reliable precision are scarce. We suggest that it is urgent to generate reliable maps of vegetation species (as well as other geographic maps) with a higher spatial resolution (e.g., <1000 m) to provide detail heterogeneity information for accurate biophysical and hydrological parameterizations.

4 Conclusions

In this study, the SWAT model was used to simulate the effects of LULC and climate changes on surface runoff. The good performance of the SWAT model was confirmed, with a Nash-Suttclife model efficiency coefficient and determination coefficients of 0.76 and 0.90, respectively, for annual runoff for the calibration period, and 0.73 and 0.83, respectively, for the validation periods. Simulation 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 the surface runoff.

The isolated results indicate that the impact of LULC on the hydrological cycle is gradual and that LULC alters runoff to a similar or greater extent than climate change, with a contribution of 70.67% to streamflow reduction since the late 1990s, suggesting that LULC plays an important role in the transition zone between semi-humid and semi-arid regions. As an indicator closely related to human activities, LULC in the study area underwent marked changes, especially the vegetation cover rate, which decreased by 16% from the 1970s to the 1990s, whereas it increased by 6% between the 1990s and the 2000s due to the CCFGP. In conclusion, the increased vegetation and the changed land use inevitably altered the hydrological cycle and large-scale LULC under the CCFGP has had an important impact on 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 products) with reliable precision and high spatial resolution should be generated.

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Table 1. Calibrated values for the six parameters for 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 simulation performance according to the Nash–Sutcliffe coefficient (Moriasi et al., 2007).

Simulation performance	Nash–Sutcliffe coefficient (*Ens*)
Very good	> 0.75
Good	0.65 – 0.75
Satisfactory	0.50 – 0.65

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 in 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 in 1980s	1980s	1980s	113.85	+29.75	–
S5	Changing LULC while holding climate constant	1990s	1980s	107.02	-6.83	-54.25
S6	Changing climate while holding LULC constant	1980s	1990s	108.61	-7.04	-55.92
S7	LULC and meteorological data in 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 in 2000s	2000s	2000s	85.61	-15.65	–

Table 4. Statistics of Nash-Suttclife coefficient (*Ens*) in SWAT calibration and validation periods.

Statistic	Calibration for 1971–1980		Validation for 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

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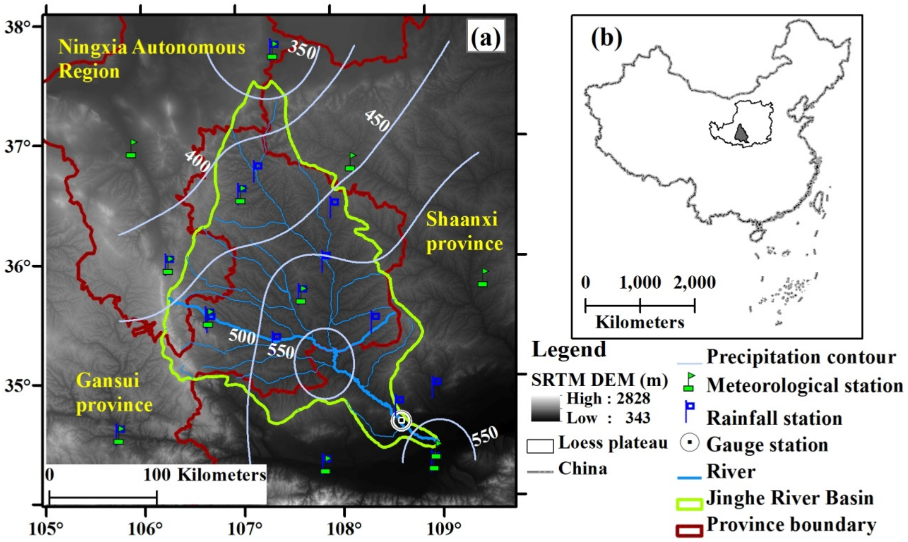

Figure 1. Geographic information of the study area: (a) Location and SRTM DEM of the Jinghe River Basin; (b) schematic of the selected study area in China. Precipitation in mm is averaged and interpolated from meteorological data between 1970 and 2010.

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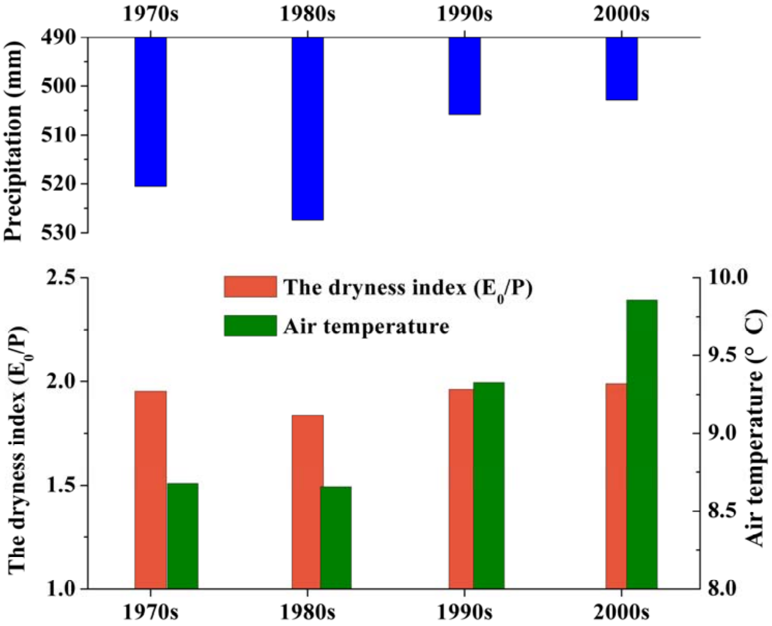

Figure 2. Variation in decade mean precipitation (top), dryness index and air temperature (bottom) in the Jinghe River Basin from the 1970s to the 2000s. The dryness index was defined as a ratio of annual potential evapotranspiration (E_0) to annual precipitation (P).

5

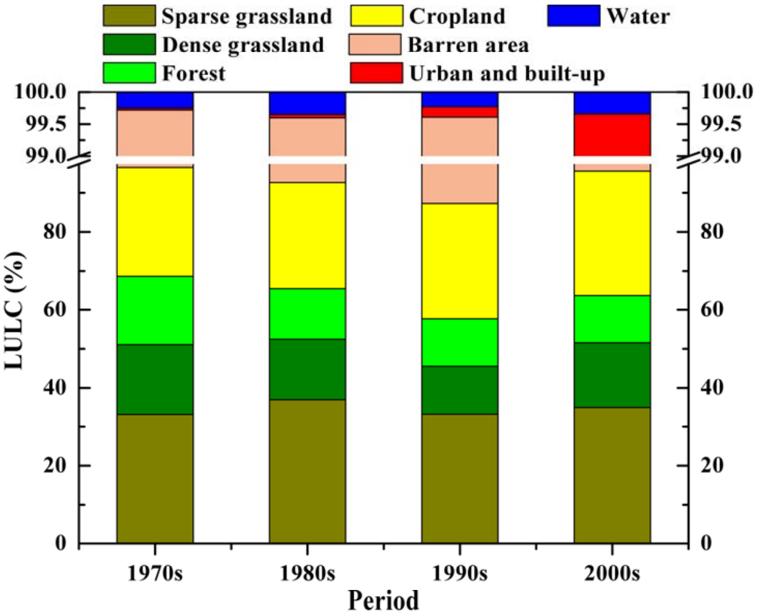

Figure 3. LULC composition and its change in the Jinghe River Basin from the 1970s to the 2000s.

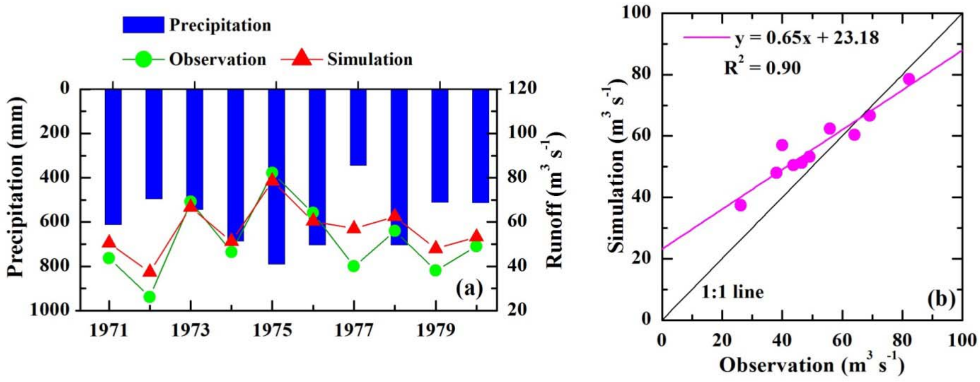

Figure 4. Comparison of the observed and simulated runoff at the yearly scale in the Jinghe River Basin for the calibration during 1971–1980.

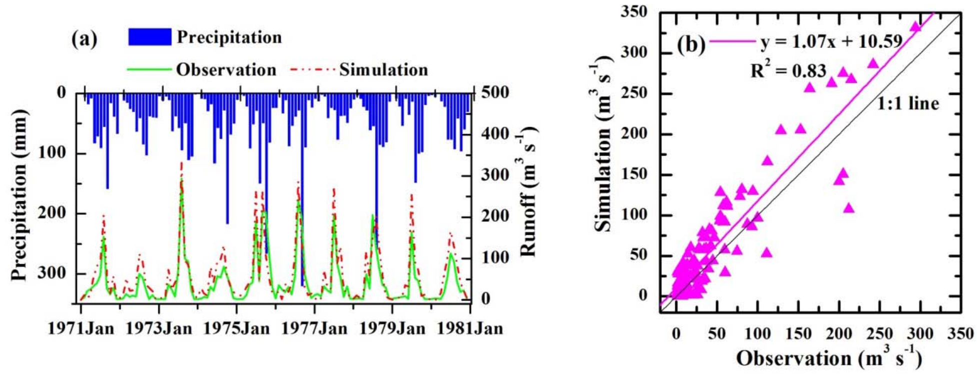

Figure 5. Comparison of the observed and simulated runoff at the monthly scale in the Jinghe River Basin for the calibration during 1971–1980.

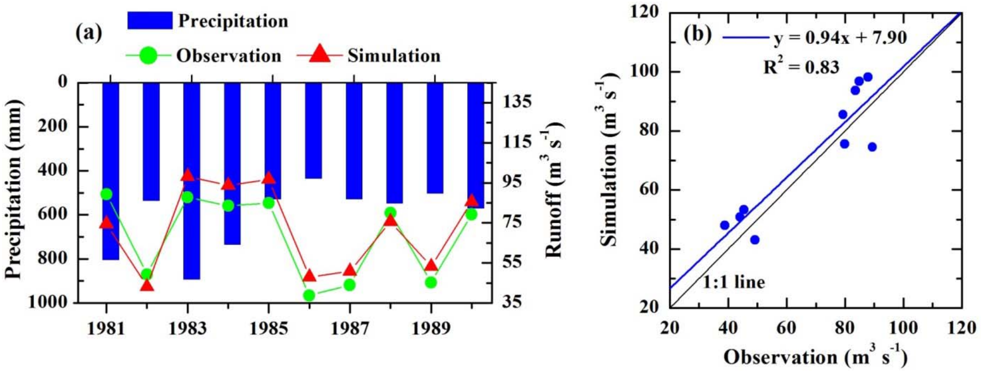

Figure 6. Comparison of the observed and simulated runoff at the yearly scale in the Jinghe River Basin for the validation during 1981–1990.

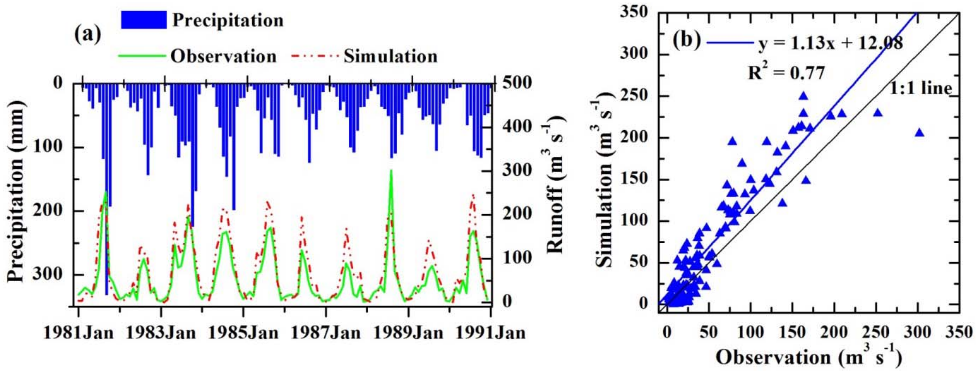

Figure 7. Comparison of the observed and simulated runoff at the monthly scale in the Jinghe River Basin for the validation during 1981–1990.