Dear Reviewer(s):

Thank you for carefully reading the manuscript and providing constructive suggestions and comments. We appreciate your time and effort in considering the manuscript for publication.

All of the questions/comments have been carefully addressed in the revised manuscript. In this revision, the newly added content is blue, and the revised content is red.

The following are the point-by-point answers to each question/comment.

Reviewer (s) Comments and our Responses

Reviewer: 1

This manuscript investigates the relationships between land use and climate changes and corresponding hydrological responses in northwest China. The paper reveals some interesting findings. The manuscript can be considered for publication, if the following comments can be addressed properly.

Major comments

1. The effects of land use change and climate change should be discussed separately.

Responses:

Thank you for the valuable comments. We reorganized section 3 ('Results and Discussion') and divided section 3.4 ('Impacts of LULC and climate changes on surface runoff') into two sections, including section 3.4 ('Combined impacts of LULC and climate changes on surface runoff') and section 3.5 ('Isolated impacts of LULC and climate changes on surface runoff'). The new sections are as follows:

3.4 Combined impacts of LULC and climate changes on surface runoff

The annual runoff simulated by 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 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. Runoff increased by 35.4% (29.75 $m^3 s^{-1}$) from the 1970s to the 1980s (simulations S1 and S4), but a decrease was observed thereafter, e.g., 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).

The simulated runoff increased between the 1970s and the 1980s, while precipitation increased from 521 mm to 527 mm in 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. The results indicate that although precipitation can considerably affect runoff simulation, variations in runoff and precipitation were nonlinear due to the combined effects.

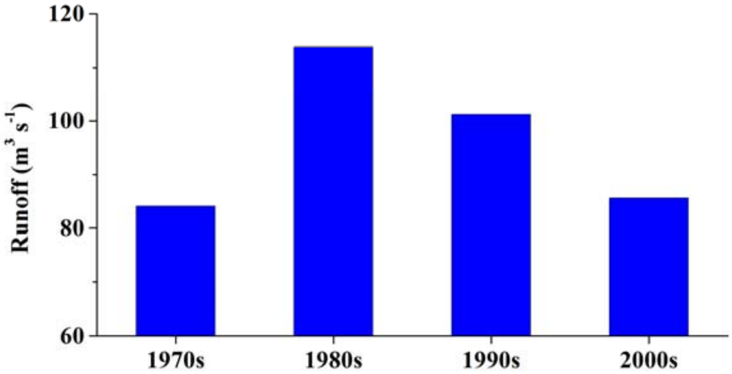


Figure 8. Variation in mean annual surface runoff at the decadal scale in the Jinghe River Basin from the 1970s to the 2000s.

3.5 Isolated impacts of LULC and climate changes on surface runoff

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

3.5.1 Impacts of LULC change

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

The results in section 3.2 showed that LULC changed slightly from the 1970s to the 1980s. For example, the area of cropland marginally increased by 0.76%, and vegetative areas decreased by 3.19%. The small LULC changes indicated that human activities minimally influenced runoff in the first two decades because LULC changes only contributed to 7.73% of the runoff increase. However, 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, whereas the percentages of cropland, barren areas, and urban and built-up areas increased by 2.39%, 5.43%, and 0.11%, respectively. LULC change associated with increased human activities contributed to 54.25% of surface runoff. Furthermore, CCFGP, 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 surface runoff in the last two decades.

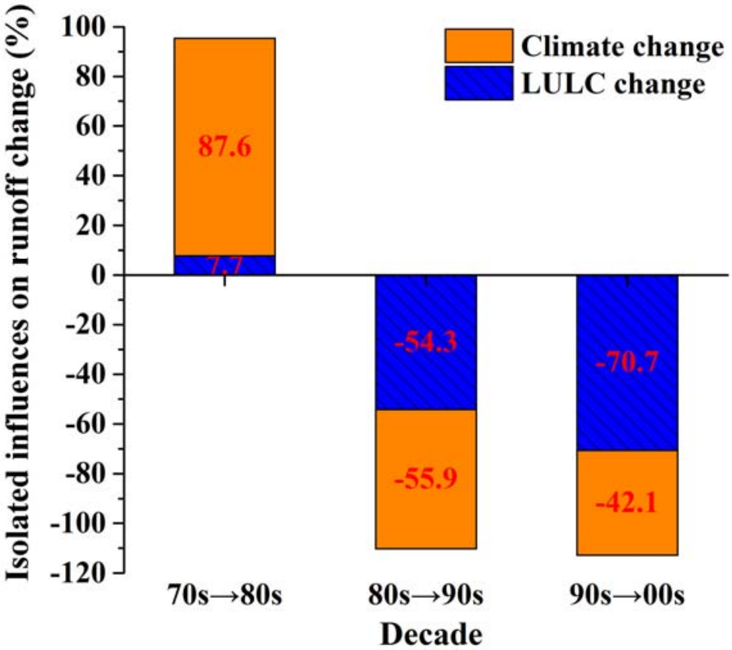


Figure 9. Isolated impacts of LULC and climate changes on surface runoff. Positive values indicate that runoff increased due to these factors, whereas negative values indicate that the runoff decreased due to these factors. The summation of the isolated influences is not equal to 100% due to simulation uncertainty (see section 3.6 for details).

Although climate variables were held constant when simulating LULC change, the isolated influence of LULC change on runoff does 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 change contributed considerably to decreased runoff, as reported in other studies (e.g., Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2014; Wang et al., 2015). Additionally, the results suggest that vegetation restoration due to the CCFGP reduced 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).

3.5.2 Impacts of climate change

Unlike the contribution of LULC change, the influence 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 total runoff in that period. Since the 1980s, surface runoff decreased, and the contributions of climate change to decreased runoff were 55.92% and 42.11% in the 1980s−1990s and 1990s−2000s, respectively. The influence of climate change on runoff is in agreement with the climatic warming and drying trends. The decreasing precipitation trend will potentially lead to less runoff, whereas the increasing temperature 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 at 54.25% and 55.92%, respectively, compared to the total runoff decrease. In the last two decades, the percent decrease in total runoff caused by LULC changes (70.67%) was greater than that caused by climate change (42.11%).

Although uncertainties exist in the simulations (see section 3.6 for details), the above results indicated 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 indicated that the impact of human activities on runoff has gradually increased in the Jinghe River Basin, which is in agreement with the results of other studies (Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2015).

New reference was also added:

Wang, G., Yang, H., Wang, L., Xu, Z., Xue, B.: Using the SWAT model to assess impacts of land use changes on runoff generation in headwaters, Hydrological Processes, 28, 1032–1042, 2014.

2. To explicitly assess the impact of land use changes on runoff generation, the impact of rainfall variation should first be excluded. Relevant discussion should be included on this topic.

Responses:

Thank you for the valuable comments. Even the isolated influence of LULC changes on runoff can be simulated by varying LULC while holding climate constant. However, climate (e.g., precipitation) varied in each decade.

According to this comment, we added the following discussion to the revised manuscript:

Although climate variables were held constant when simulating LULC change, the isolated influence of LULC change on runoff does 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 change contributed considerably to decreased runoff, as reported in other studies (e.g., Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2014; Wang et al., 2015). Additionally, the results suggest that vegetation restoration due to the CCFGP reduced 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).

3. I would encourage authors to rewrite the methodology description section. Give a clear message to the reader what you did and how you did. Some parts in the results analysis and discussion section (e.g. model calibration and validation) are more suitable to be in the methodology section.

Responses:

Thank you for this comment. In this study, we simulated runoff change using the SWAT model.

Based on your recommendation, we reorganized section 2 ('Methods and materials'), particularly from sections 2.2 to 2.4 (Table R1), and some related context was also revised.

Table R1 Changes in the structure of section 2

Structure of section 2 (Methods and materials) in the revised manuscript	**Structure of section 2 in the previous manuscript**
2 Methods and materials	2 Methods and materials
2.1 Study area	2.1 Study area
2.2 Runoff change simulation	2.2 SWAT model and data collection
2.2.1 SWAT model and data collection	2.3 Model calibration and validation
2.2.2 Model calibration and validation	2.4 Runoff change simulation
2.2.3 Simulation scenarios	

4. The values in Table 2 are not acceptable, the authors should re-check the reference (Moriasi et al., 2007).

Responses:

We re-checked the reference (Moriasi et al., 2007) and found that the values of the Nash–Sutcliffe coefficient (*Ens*) given in Table 2 in the previous manuscript may cause misleading.

Reference:

Moriasi, D. N., Arnold, J. G., van Liew, M. W., Binger, R. L. Harmel, R. D., and Veith, T.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Trans. Am. Soc. Agr. Biol. Eng., 50, 885–900, 2007.

According to this comment, we revised Table 2 as follows:

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	$Ens \leq 0.50$

5. The influences of different land use types (such as area and spatial distribution) are also important to runoff generation. How to assess these effects?

Responses:

Yes, the spatial distributions and areas of different land use types can influence runoff generation. We added some discussion regarding how the areas of different land use types affect surface runoff (see our reply to major comment 1). Additionally, previous studies have been conducted to investigate how the spatial distributions of different land use types influence runoff generation (e.g., Wang et al., 2014). Although we can obtain the spatial distributions of different land use types, assessing the influence of spatial changes in land use on runoff is difficult.

Reference:

Wang, G., Yang, H., Wang, L., Xu, Z., Xue, B.: Using the SWAT model to assess impacts of land use changes on runoff generation in headwaters, Hydrological Processes, 28, 1032–1042, 2014.

6. It seems that the authors discussed the effects of the "Conversion of Cropland to Forest and Grassland Program" on the water budget of the Jinghe River basin (Qiu et al., 2011, Journal of Environmental Quality, 40, 1–11). What's the difference between the previous publication and this study?

Responses:

In our previous publication (Qiu et al., 2011), we discussed the effects of the "Conversion of Cropland to Forest and Grassland Program" on the water budget in the Jinghe River Basin. However, for simplificity, we only chose three typical sub-basins distributed in the upstream, midstream, and downstream areas (Fig R1). In addition, we did not address climate change in the previous publication.

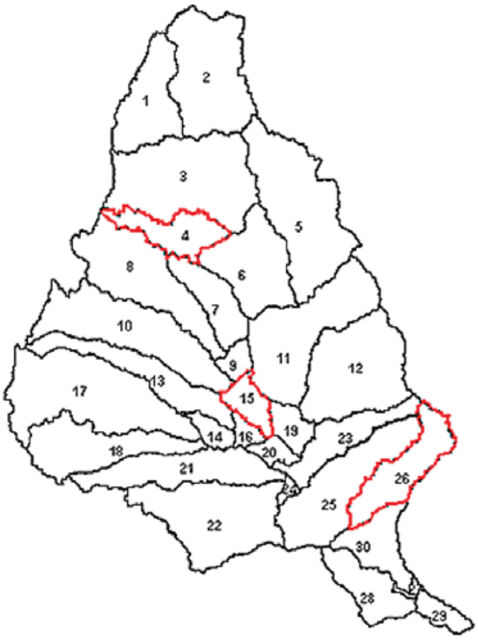
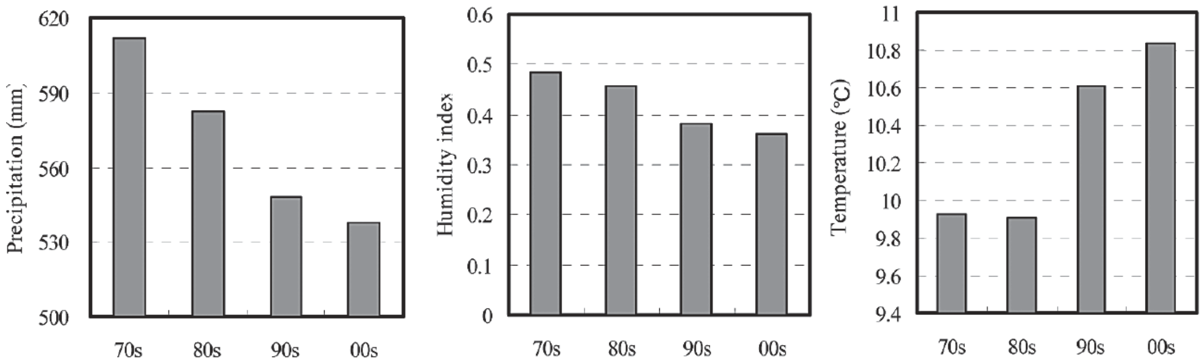


Fig. R1 The results of our previous publication (Fig. 2 in Qiu et al., 2011), which was based on three typical sub-basins: 4, 15, and 26 (shown in red).

In this study, we focused on the entire basin and discuss the effect of both land use/land cover (LULC) change (e.g., conversion of cropland to forest and grassland) and climate change on surface runoff. Furthermore, meteorological data from different stations (e.g., precipitation and air temperature: Fig. 2) were updated to 2009, and values were recalculated, whereas the data in Qiu et al. (2011) were from 1970 to 2005 (Fig. R2).



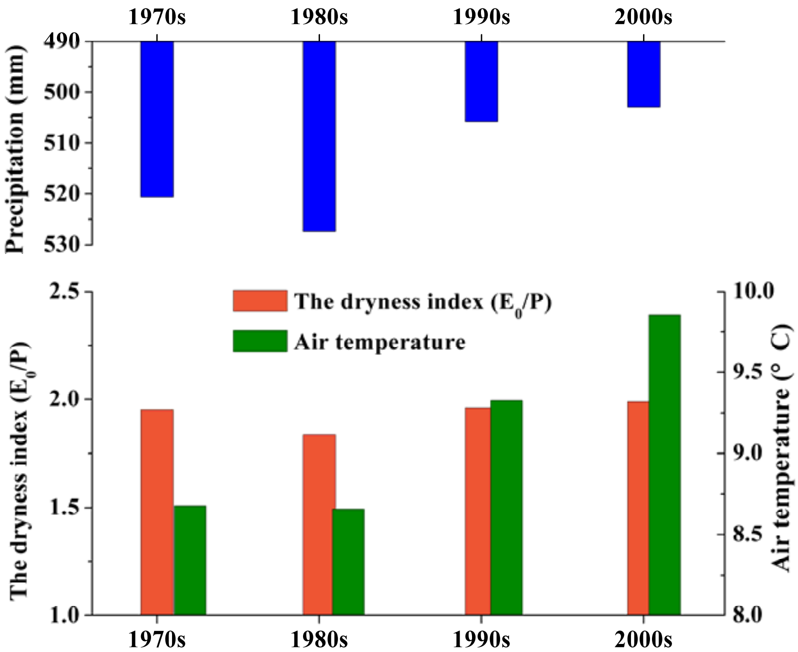


Fig. R2 Difference between weather data used in the previous study (upper figures in black and white) and this study (bottom figures in colour).

The data used for model simulation and validation were the same in both these two studies.

To avoid similarity, we reorganized some content related to model calibration and validation. Please see our revised manuscript for details.

Minor comments

1. 3-28, The objectives. I would suggest the authors to add an objective to discuss how the LULC and climate changes affect surface runoff.

Responses:

Thank you for this comment. Our revised manuscript discussed this issue (section 3.5 'Isolated impacts of LULC and climate changes on surface runoff'), and we added the objectives as suggested.

Therefore, the objectives of this study were as follows: 1) to 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) to quantify both the combined and isolated impacts of LULC change and climate variability on surface runoff in the basin from1971-2005 through scenario simulations after calibrating and validating the SWAT model at monthly and yearly time scales; 3) to discuss how the LULC and climate changes affect surface runoff; and 4) to discuss the simulation uncertainty in the context of SWAT modelling due to parameterizations, providing potential explanations for the conflicting results regarding the effects of LULC and climate changes on runoff in relatively large basins.

2. 4-6. Although finally draining into the Yellow River, the Jinghe River is a tributary of the Weihe River.

Responses:

We changed the 'Yellow River' to the 'Weihe River' in the revised manuscript.

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.

3. 5-10. How many runoff data was used and who performed the measurement?

Responses:

The runoff data were measured by the Yellow River Conservancy Commission (YRCC) of the Ministry of Water Resources, China, between 1970 and 1990. According to this comment, we added the following information:

Daily runoff data measured at 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.

4. 5-18. 'determination coefficients' should be 'determination coefficient'.

Responses:

Thank you for this valuable comment. We revised the text as suggested:

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).

5. 8-31. I suggest the authors unify the number of decimal places.

Responses:

Thank you for this valuable comment. We unified the number of decimal places used throughout the manuscript. For example, the following edit was made to the revised manuscript.

In the first two decades, LULC changes increased runoff by 2.30 $m^3\ s^{-1}$, accounting for 7.73% of the total change (29.75 $m^3\ s^{-1}$).

6. 9-32. The citation style for two authors. The authors sometimes use 'and', but sometimes '&'. I suggest the authors unify the citation style.

Responses:

Thank you for this valuable comment. We checked the manuscript and changed '&' to 'and'. For example, we made the following change:

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; …

7. The language need to be improved. There are many grammatical and spelling mistakes.

Responses:

Thank you for this valuable comment. We sent the manuscript to American Journal Experts (AJE) for English language editing prior to submission. The revised manuscript has been re-editted by AJE (Fig. R3). Please see our revised manuscript for details.

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EDITORIAL CERTIFICATE

This document certifies that the manuscript listed below was edited for proper English language, grammar, punctuation, spelling, and overall style by one or more of the highly qualified native English speaking editors at American Journal Experts.

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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

Authors:
J. Yin, G. Y. Qiu, F. He, Y. J. Xiong

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Fig. R3 Certificate for English language editing

Title Page

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

Jing Yin [1], Fan He [2], YuJiu Xiong [3, 4, *], GuoYu Qiu [5, *]

[1] Research Center for Sustainable Hydropower Development, China Institute of Water Resources and Hydropower Research, Beijing 100038, China.

[2] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China.

[3] Department of Water Resource and Environments, School of Geography and Planning, Sun Yat-Sen University, Guangzhou 510275, Guangdong, China.

[4] Key Laboratory of Water Cycle and Water Security in Southern China of Guangdong High Education Institute, Sun Yat-Sen University, Guangzhou 510275, Guangdong, China.

[5] Shenzhen Engineering Laboratory for Water Desalinization with Renewable Energy, School of Environment and Energy, Peking University, Shenzhen 518055, Guangdong, China.

First author Email address: yinjing@iwhr.com
[*] Corresponding author: YuJiu Xiong, Email address: xiongyuj@mail.sysu.edu.cn. Tel./Fax: +86 20 84114575.
Co-corresponding author: GuoYu Qiu, Email address: qiugy@pkusz.edu.cn. Tel./Fax: +86 755 26033309.

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), 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. We 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 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 became increasingly influenced by LULC change, which contributed to 44% of the runoff change between the 1980s and the 1990s and 71% of the runoff change between the 1990s and the 2000s. Our findings revealed that large-scale LULC under the CCFGP 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., 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 it affects 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 be generally identified using hydrological models (Praskievicz and Chang, 2009). These models provide valuable frameworks within which to investigate changes among various hydrological 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 impacts of LULC and climate changes on runoff in areas of water resource management (Yang et al., 2008; Chen et al., 2015). The Soil and Water Assessment Tool (SWAT), a robust, interdisciplinary, 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 simulation 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 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 have suggested that surface runoff is affected more by climate change (increased precipitation) than by LULC (Guo et al., 2008; Fan and Shibata, 2015), whereas some studies have found that urbanization contributes more to increased runoff than does precipitation (Olivera and Defee, 2007). According to 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 210 and 109 papers studied climate change and LULC change, 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).

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). These regions have experienced serious water shortages, and land use has been simultaneously affected by 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 the 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, 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 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 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 Jinghe River Basin contributes 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., 2015). Relatively few studies have been conducted regarding the effects of LULC and climate changes on runoff. Studies in the Weihe River Basin (Zuo et al., 2014) and on the Loess Plateau (Liang et al., 2015), which have included the Jinghe

River Basin as a sub-basin, have identified the response of runoff to climate change and human activities using a climate elasticity model based on the Budyko framework. 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 from 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 from 1966–1970 showed the runoff decrease was caused mainly by decreased precipitation before the 2000s, but human activity became the dominant factor affecting decreased runoff 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 the complex effects of LULC and climate changes on streamflow (Fu et al., 2007), as well as variable boundary conditions (Chen et al., 2011; Niraula et al., 2015).

Therefore, the objectives of this study were as follows: 1) to 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) to quantify both the combined and isolated impacts of LULC change and climate variability on surface runoff in the basin from1971-2005 through scenario simulations after calibrating and validating the SWAT model at monthly and yearly time scales; 3) to discuss how the LULC and climate changes affect surface runoff; and 4) to discuss the simulation uncertainty in the context of SWAT modelling due to parameterizations, providing 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 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 Weihe 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 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 simulations, the SWAT model should be calibrated and validated, as described in the following context.

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 a 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 1:1

000 000. The map was provided by the Chinese Natural Resources Database. Huangmiantu, which covers 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 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 area. 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 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 the DEM grids using the SWAT model's built-in weather generator, which describes the weather conditions in model simulations.

(5) Surface runoff

Daily runoff data measured at 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 (Qiu et al., 2011), 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), 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 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 "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 change, the third simulation ($Q_{sim,\,cL,\,i}$) was based on the current climate (years 1970–1979) and the LULC in the next period, or future LULC (in this example, 1989). The difference between the first and third simulations is 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 (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 and Discussion

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 and 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 1980–1999. 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 larger dryness index (>1.9) indicates that the climate became drier. These results indicate that the climate in the Jinghe River Basin changed dramatically over the last four decades, as characterized by decreased precipitation and increased temperature and dryness index values. The warming and drying trends are evident in the Jinghe River Basin. 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, encompassing a total area of > 61% 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 well with the regional climate, and a relatively high percentage of cropland indicates the importance of agriculture.

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 expanded over time, increasing by 4.03% and 0.95%, respectively. 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 may have been the result of 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, urban and barren land areas increased, whereas vegetation decreased. However, the decreasing trend in 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 and improve the eco-environmental status in western and northern China (Xu et al., 2004). Noticeable evidence of ecological restoration was observed on the Loess Plateau after the implementation of the CCFGP (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 indicate an increase in vegetation since the late 1990s, agreeing 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 in both the calibration and validation periods based on accurately 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 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 the majority 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) as it did during 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 Combined impacts of LULC and climate changes on surface runoff

The annual runoff simulated by 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 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. Runoff increased by 35.4% (29.75 $m^3 s^{-1}$) from the 1970s to the 1980s (simulations S1 and S4), but a decrease was observed thereafter, e.g., 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).

The simulated runoff increased between the 1970s and the 1980s, while precipitation increased from 521 mm to 527 mm in 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. The results indicate that although precipitation can considerably affect runoff simulation, variations in runoff and precipitation were nonlinear due to the combined effects.

3.5 Isolated impacts of LULC and climate changes on surface runoff

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

3.5.1 Impacts of LULC change

In the first two decades, LULC changes increased runoff by 2.30 $m^3 s^{-1}$, accounting for 7.73% of the total change (29.75 $m^3 s^{-1}$). Thereafter, LULC change decreased runoff by

6.83 $m^3 s^{-1}$, accounting for 54.25% of the total change (12.59 $m^3 s^{-1}$) from the 1980s to the 1990s. The impact of LULC change on runoff increased in the last two decades, because the contribution of LULC change to runoff increased to 70.67% from the 1990s to the 2000s (Fig. 9).

The results in section 3.2 showed that LULC changed slightly from the 1970s to the 1980s. For example, the area of cropland marginally increased by 0.76%, and vegetative areas decreased by 3.19%. The small LULC changes indicated that human activities minimally influenced runoff in the first two decades because LULC changes only contributed to 7.73% of the runoff increase. However, 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, whereas the percentages of cropland, barren areas, and urban and built-up areas increased by 2.39%, 5.43%, and 0.11%, respectively. LULC change associated with increased human activities contributed to 54.25% of surface runoff. Furthermore, CCFGP, 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 surface runoff in the last two decades.

Although climate variables were held constant when simulating LULC change, the isolated influence of LULC change on runoff does 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 change contributed considerably to decreased runoff, as reported in other studies (e.g., Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2014; Wang et al., 2015). Additionally, the results suggest that vegetation restoration due to the CCFGP reduced 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).

3.5.2 Impacts of climate change

Unlike the contribution of LULC change, the influence 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 total runoff in that period. Since the 1980s, surface runoff decreased, and the contributions of climate change to decreased runoff were 55.92% and 42.11% in the 1980s−1990s and 1990s−2000s, respectively. The influence of climate change on runoff is in agreement with the climatic warming and drying trends. The decreasing precipitation trend will potentially lead to less runoff, whereas the increasing temperature 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 at 54.25% and 55.92%, respectively, compared to the total runoff decrease. In the last two decades, the percent decrease in total runoff caused by LULC changes (70.67%) was greater than that caused by climate change (42.11%).

Although uncertainties exist in the simulations (see section 3.6 for details), the above results indicated 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 indicated that the impact of human activities on runoff has gradually increased in the Jinghe River Basin, which is in agreement with the results of other studies (Zhang et al., 2011; Zuo et al., 2014; Wang et al., 2015).

3.6 Uncertainty in 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 change or climate change, the simulated runoff associated with changes in only one driving factor was slightly different than the runoff simulated under 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" (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 due to limited ground-based observations. To reduce the uncertainty and improve the accuracy of hydrological modelling and forecasting in relatively large basins, the following portion of the manuscript discusses the uncertainty associated with model parameterization and proposes potential solutions 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 a condition, runoff simulations may contain uncertainties due to the 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 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 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 vegetation and LULC data used in this study were very coarse compared to the soil data resolution, leading 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 limitation. 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. Generating reliable maps of vegetation species (as well as other geographic maps) at high spatial resolutions (e.g., <1000 m) is an urgent need that can provide detailed and heterogeneous 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 satisfactory performance of the SWAT model was confirmed by a Nash-Sutcliffe coefficient and coefficient of determination values for annual runoff of 0.76 and 0.90, respectively, in the calibration period and 0.73 and 0.83, respectively, in 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 impact of LULC on the hydrological cycle was gradual, and LULC altered runoff to a similar or greater extent than did climate change, with a contribution of 70.67% to streamflow reduction since the late 1990s. This result suggested 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 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 CCFGP. In conclusion, the increased vegetation and land use changes inevitably altered the hydrological cycle, and large-scale LULC under the CCFGP 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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References

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R.: Large area hydrologic modeling and assessment-Part 1: Model development, J. American Water Resour. Assoc., 34, 73–89, 1998.

Chang, R. Y., Fu, B. J., Liu, G. H., and Liu, S.G.: Soil carbon sequestration potential for Grain for Green Project in Loess Plateau, China, Environ. Manage., 48, 1158–1172, 2011.

Chawla, I., and Mujumdar, P. P.: Isolating the impacts of land use and climate change on streamflow, Hydrology and Earth System Sciences, 19, 3633–3651, 2015.

Chen,Y., Li, J., and Xu, H. J.: Improving flood forecasting capability of physically based distributed hydrological model by parameter optimization, Hydrology and Earth System Sciences, 20, 375–392, 2016.

Chen,Y., Ren, Q. W., Huang, F. H., Xu, H. J., and Cluckie, I.: Liuxihe Model and its modeling to river basin flood, Journal of Hydrologic Engineering, 16, 33–50, 2011.

Chu, J., Zhang, C., Wang, Y., Zhou, H., and Shoemaker, C. A.: A watershed rainfall data recovery approach with application to distributed hydrological models, Hydrol. Process., 26, 1937–1948, 2012.

D'Agostino D. R., Trisorio, L. G., Lamaddalena, N., and Ragab, R.: Assessing the results of scenarios of climate and land use changes on the hydrology of an Italian catchment: modelling study, Hydrological Processes, 24, 2693–2704, 2010.

Deng, L., Liu, G. B., and Shangguan, Z. P.: Land use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program': a synthesis, Global Change

Biol., 20, 3544–3556, 2014.

Di Luzio, M., Srinivasan, R., Arnold, J. G., and Neitsch, S. L.: ArcView Interface for SWAT2000, User's Guide. Temple, Tex.: Texas A&M Agricultural Experiment Station, Blackland Research and Extension Center, 2002.

Fan, M., and Shibata, H.: Simulation of watershed hydrology and stream water quality under land use and climate change scenarios in Teshio River watershed, northern Japan, Ecol. Indic. 50, 79–89, 2015.

Feng, X. M., Sun, G., Fu, B. J., Su, C. H., Liu, Y., and Lamparski, H.: Regional effects of vegetation restoration on water yield across the Loess Plateau, China, Hydrology and Earth System Sciences, 16, 2617–2628, doi:10.5194/hess-16-2617-2012, 2012.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., and Gibbs, H. K.: Global consequences of land use, Science, 309, 570–574, 2005.

Fu, C. B.: Potential impacts of human-induced land cover change on East Asia monsoon, Global and Planetary Change, 37, 219–229, 2003.

Fu, G. B., Charles, S. P., and Chiew, F. H. S.: A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow, Water Resour. Res., 43, W11419, 2007.

Fu, G., Charles, S. P., and Chiew, F. H. S.: A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow, Water Resources Research, 43, W11419, 2007.

Gassman, P., Reyes, M. R., Green, C. H., and Arnold, J.G.: The soil and water assessment tool: Historical development, applications, and future research directions, Trans. ASABE, 50, 1211–1250, 2007.

Guo, H., Qi, H., and Jiang, T.: Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, J. Hydrol., 355, 106–122, 2008.

He, Y., Wang, F., Mu, X. M., Yan, H. T., and Zhao, G. J.: An Assessment of Human versus Climatic Impacts on Jing River Basin, Loess Plateau, China, Advances in Meteorology, 2015, 478739, 2015.

Huang, J., Guan, X., and Ji, F.: Enhanced cold-season warming in semi-arid regions, Atmos. Chem. Phys., 12, 5391–5398, 2012.

IPCC: Climate change 2007: the physical science basis, in: Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK, 2007.

Jarvis, A., Reuter, H. I., Nelson, A., Guevara, E.: Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database at: http://srtm.csi.cgiar.org , 2008 (last access: 24 October 2015).

Jiang, S., Ren, L., Yong, B., Singh, V. P., Yang, X., and Yuan, F.: Quantifying the effects of climate variability and human activities on runoff from the Laohahe basin in northern China using three different methods, Hydrol. Process., 25, 2492–2505, 2011.

Jiang, T., Chen, Y. Q., Xu, C. Y., Chen, X. H., Chen, X., and Singh, V. P.: Comparison of hydrological impacts of climate change simulated by six hydrological models in the

Dongjiang Basin, South China, J. Hydrol., 336, 316–333, 2007.

Krysanova, V, and Arnold, J. G.: Advances in ecohydrological modelling with SWAT. A review, Hydrological Sciences Journal, 53, 939–947, 2008.

Krysanova, V, and Arnold, J. G.: Advances in water resources assessment with SWAT—an overview, Hydrological Sciences Journal, 60, 771–783, 2015.

Leavesley, G. H.: Modeling the effects of climate change on water resources: A review, Climate Change, 28, 159–177, 1994.

Leng, G., Tang, Q., Huang, S., Zhang, X., and Cao, J.: Assessments of joint hydrological extreme risks in a warming climate in China, International Journal of Climatology, 36: 1632–1642, 2016.

Li, J., Chen, F., Cook, E. R., Gou, X., and Zhang, Y.: Drought reconstruction for North Central China from tree rings: the value of the Palmer drought severity index, Int. J. Climatol., 27, 903–909, 2007.

Li, M. X., Ma, Z. G., and Niu, G. Y.: Modeling spatial and temporal variations in soil moisture in China, Chin. Sci. Bull., 56, 1809–1820, 2011.

Li, Z., Liu, W. Z., Zhang, X. C., and Zheng, F. L.: Impacts of land use change and climate variability on hydrology in an agricultural catchment on the loess plateau of China, J. Hydrol., 377, 35–42, 2009.

Li, Z., Zheng, F. L., Liu, W. Z., and Flanagan, D. C.: Spatial distribution and temporal trends of extreme temperature and precipitation events on the Loess Plateau of China during 1961–2007, Quaternary International, 226, 92–100, 2010.

Liang, W., Bai, D., Wang, F., Fu, B., Yan, J., Wang, S., Yang, Y., Long, D., and Feng M.:

Quantifying the impacts of climate change and ecological restoration on streamflow changes based on a Budyko hydrological model in China's Loess Plateau, Water Resources Research, 51, 6500–6519, doi:10.1002/2014WR016589, 2015.

Liu, J., Liu, T., Bao, A. M., De Maeyer, P., Feng, X. W., Miller, S. N., and Chen, X.: Assessment of Different Modelling Studies on the Spatial Hydrological Processes in an Arid Alpine Catchment, Water Resources Management, 30, 1757–1770, 2016.

Liu, X. P., Li X.: Simulating complex urban development using kernel-based non-linear cellular automata, Ecological Modelling, 211 (1–2), 169–181, 2008.

Luo, Y., Zhang, X., Liu, X., Ficklin, D., and Zhang, M.: Dynamic modeling of organophosphate pesticide load in surface water in the northern San Joaquin Valley watershed of California, Environmental Pollution, 156, 1171–1181, 2008.

Ma, Z. G., and Fu, C. B.: Interannual characteristics of the surface hydrological variables over the arid and semi-arid areas of northern China, Global and Planetary Change, 37, 189–200, 2003.

Ma, Z., and Fu, C.: Some evidence of drying trend over northern China from 1951 to 2004, Chinese Sci. Bull., 51, 2913–2925, 2006.

Ma, Z., Kang, S., Zhang, L., Tong, L., and Su, X.: Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China, J. Hydrol., 352, 239–249, 2008.

Masih, I., Maskey, S., Uhlenbrook, S., and Smakhtin, V.: Assessing the Impact of Areal Precipitation Input on Streamflow Simulations Using the SWAT Model, J. American Water Resour. Assoc., 47, 179–195, 2011.

Milly, P. C. D., Dunne, K. A., and Vecchia, A. V.: Global pattern of trends in streamflow and water availability in a changing climate, Nature, 438, 347–350, 2005.

Moriasi, D. N., Arnold, J. G., van Liew, M. W., Binger, R. L. Harmel, R. D., and Veith, T.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Trans. Am. Soc. Agr. Biol. Eng., 50, 885–900, 2007.

Murray, S. J., Foster, P. N., and Prentice, I. C.: Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model, Journal of Hydrology, 448–449, 14–29, 2012.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R.: Soil and Water Assessment Tool Theoretical Documentation. Ver. 2005. Temple, Tex.: USDA - ARS Grassland Soil and Water. Research Laboratory, and Texas A&M University, Blackland Research and Extension Center, 2005.

Niraula, R., Meixner, T., and Norman, L. M.: Determining the importance of model calibration for forecasting absolute/relative changes in streamflow from LULC and climate changes, Journal of Hydrology, 522, 439–451, 2015.

Notter, B., Hans, H., Wiesmann, U., and Ngana, J. O.: Evaluating watershed service availability under future management and climate change scenarios in the Pangani Basin, Phys. Chem. Earth, 61–62, 1–11, 2013.

Nunes, A. N., de Almeida, A. C., and Coelho C. O. A.: Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal, Appl. Geogr., 31, 687–699, 2011.

Oki, T., and Kanae, S.: Global hydrological cycles and world water resources, Science, 313, 1068–1072, 2006.

Olivera, F., and DeFee, B. B.: Urbanization and its effect on runoff in the Whiteoak Bayou watershed, Texas, J. American Water Resour. Assoc., 43, 170–182, 2007.

Peng, H., Jia, Y. W., Qiu, Y. Q., and Niu, C. W.: Assessing climate change impacts on the ecohydrology of the Jinghe River basin in the Loess Plateau, China, Hydrological Sciences Journal, 58 (3), 651–670, 2013.

Peng, H., Jia, Y., Niu, C. W., Gong, J. G., Hao, C. F., Gou, S.: Eco-hydrological simulation of soil and water conservation in the Jinghe River Basin in the Loess Plateau, China, Journal of Hydro-environment Research, 9 (3), 452–464, 2015b.

Peng, H., Jia, Y., Tague, C., and Slaughter, P.: An Eco-Hydrological Model-Based Assessment of the Impacts of Soil and Water Conservation Management in the Jinghe River Basin, China, Water, 7, 6301–6320, 2015a.

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudré, N., Labat, D., and Zaehle, S.: Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends, PNAS, 104, 15242–15247, 2007.

Pierini, N., Vivoni, E., Robles-Morua, A., Scott, R., and Nearing, M.: Using observations and a distributed hydrologic model to explore runoff thresholds linked with mesquite encroachment in the Sonoran Desert, Water Resour. Res., 50, 8191–8215, 2014.

Praskievicz, S., and Chang, H.: A review of hydrological modeling of basin-scale climate change and urban development impacts, Progress in Physical Geography, 33, 650–671, 2009.

Qiao, L., Zou, C., Will, R., and Stebler, E.: Calibration of SWAT model for woody plant encroachment using paired experimental watershed data, Journal of Hydrology, 523, 231–239, 2015.

Qiu, G. Y., Yin, J., Geng, S.: Impact of climate and land-use changes on water security for agriculture in Northern China, J. Integr. Agr., 11, 144–150, 2012.

Qiu, G. Y., Yin, J., Tian, F., and Geng, S.: Effects of the "Conversion of Cropland to Forest and Grassland Program" on the water budget of the Jinghe River Catchment in China, Journal of Environmental Quality, 40, 1–11, 2011.

Sherwood, S., and Fu, Q.: A drier future, Science, 343, 737–739, 2014.

Shope, C. L., and Maharjan, G. R.: Modeling Spatiotemporal Precipitation: Effects of Density, Interpolation, and Land Use Distribution, Advances in Meteorology, 2015, 174196, 2015.

Singh, V. P.: Effect of spatial and temporal variability in rainfall and watershed characteristics on stream flow hydrograph, Hydrol. Process., 11, 1649–1669, 1997.

Song, X., Peng, C., Zhou, G., Jiang, H., and Wang, W.: Chinese Grain for Green Program led to highly increased soil organic carbon level: A meta-analysis, Sci Rep., 4, 4460, 2014.

Sterling, S. M., Ducharne, A., and Polcher, J.: The impact of global land-cover change on the terrestrial water cycle, Nature Climate Change, 3, 385–390, 2012.

Sun, W., Song, X., Mu, X., Gao, P., Wang, F., and Zhao, G.: Spatiotemporal vegetation cover variations associated with climate change and ecological restoration in the Loess Plateau, Agric. For. Meteorol., 209–210, 87–99, 2015.

Vigerstol, K., and Aukema, J. E.: A comparison of tools for modeling freshwater ecosystem services, J. Environ. Manag., 92, 2403–2409, 2011.

Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Reidy Liermann, C., and Davies, P. M.: Global threats to human water security and river biodiversity, Nature, 467, 555–561, 2010.

Wang, G., and Cheng, G.: The characteristics of water resources and the changes of the hydrological process and environment in the arid zone of northwest China, Environmental Geology, 39, 783–790, 2000.

Wang, G., Yang, H., Wang, L., Xu, Z., Xue, B.: Using the SWAT model to assess impacts of land use changes on runoff generation in headwaters, Hydrological Processes, 28, 1032–1042, 2014.

Wang, R., Kalin, L., Kuang, W., and Tian, H.: Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama, Hydrol. Process., 28, 5530–5546, 2014.

Wang, S., Fu, B. J., Piao, S. L., Lu, Y. H., Ciais, P., Feng, X. M., and Wang, Y. F.: Reduced sediment transport in the Yellow River due to anthropogenic changes, Nature Geoscience, 9, 38–41, 2016.

Wei, S., Yang, H., Song, J., Abbaspour, K. C., Xu, Z.: System dynamics simulation model for assessing socio-economic impacts of different levels of environmental flow allocation in the Weihe River Basin, China, European Journal of Operational Research, 221, 248–262, 2012.

Wu, W., Xu, Z. X., Yin, X., W., and Zuo, D. P.: Assessment of ecosystem health based on fish assemblages in the Wei River basin, China, Environmental Monitoring and Assessment, 186 (6), 3701–3716, 2014.

Wu, Y. P., Liu, S. G., Yan, W. D., Xia, J. Z., Xiang, W. H., Wang, K. L., Luo, Q., Fu, W., and Yuan, W. P.: Climate change and consequences on the water cycle in the humid Xiangjiang River Basin, China, Stochastic Environmental Research and Risk Assessment, 30, 225–235, 2016.

Xie, F., Qiu, G. Y., Yin, J., Xiong, Y. J., and Wang, P.: Comparison of land use/land cover change in three sections of the Jinghe River basin between the 1970s and 2006, Journal of Natural Resources, 24 (8), 1354–1365, 2009. (in Chinese with English abstract)

Xu, H., Taylor, R. G., and Xu, Y.: Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River Basins, China, Hydrol. Earth Syst. Sci., 15, 333–344, 2011.

Xu, H., Xu, C. Y., Chen, H., Zhang, Z., and Li, L.: Assessing the influence of rain gauge density and distribution on hydrological model performance in a humid region of China, J. Hydrol., 505, 1–12, 2013.

Xu, Z., Bennett, M. T., Tao, R., and Xu, J.: China's Sloping Land Conversion Programme four years on: current situation, pending issues, International Forestry Review, 6 (3–4), 317–326, 2004.

Yang, J., Reichert, P., Abbaspour, K. C., Xia, J., and Yang, H.: Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China, J. Hydrol., 358, 1–23, 2008.

Zhang, S. L., Wang, Y. H., Yu, P. T., Zhang, H. J., and Tu, X. W.: Impact of human activities on the spatial and temporal variation of runoff of Jinghe Basin, Northwest China, Journal of Arid Land Resource and Environment, 25 (6), 66–72, 2011. (in Chinese with English abstract)

Zhang, X. P., Zhang, L., Zhao, J., Rustomji, P., and Hairsine, P.: Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China, Water Resources Research, 44, W00A07.1–W00A07.12, 2008.

Zhang, Y., Fu, G., Sun, B., Zhang, S., and Men B.: Simulation and classification of the impacts of projected climate change on flow regimes in the arid Hexi Corridor of Northwest China, Journal of Geophysical Research: Atmospheres, 120, 7429–7453, 2015.

Zhao, A. Z., Zhu, X. F., Liu, X. F., Pan, Y. Z., and Zuo, D. P.: Impacts of land use change and climate variability on green and blue water resources in the Weihe River Basin of northwest China, CATENA, 137, 318–327, 2016.

Zhao, L., Lyu, A. F., Wu, J. J., Hayes, M., Tang, Z. H., He, B., Liu J. H., and Liu, M.: Impact of meteorological drought on streamflow drought in Jinghe River Basin of China, Chinese Geographical Science, 24 (6), 694–705. doi: 10.1007/s11769-014-0726-x, 2014.

Zuo, D. P., Xu, Z. X., Wu, W., Zhao, J., and Zhao, F. F.: Identification of Streamflow Response to Climate Change and Human Activities in the Wei River Basin, China, Water Resources Management, 28 (3), 833–851, 2014.

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 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 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	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 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-Sutcliffe 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

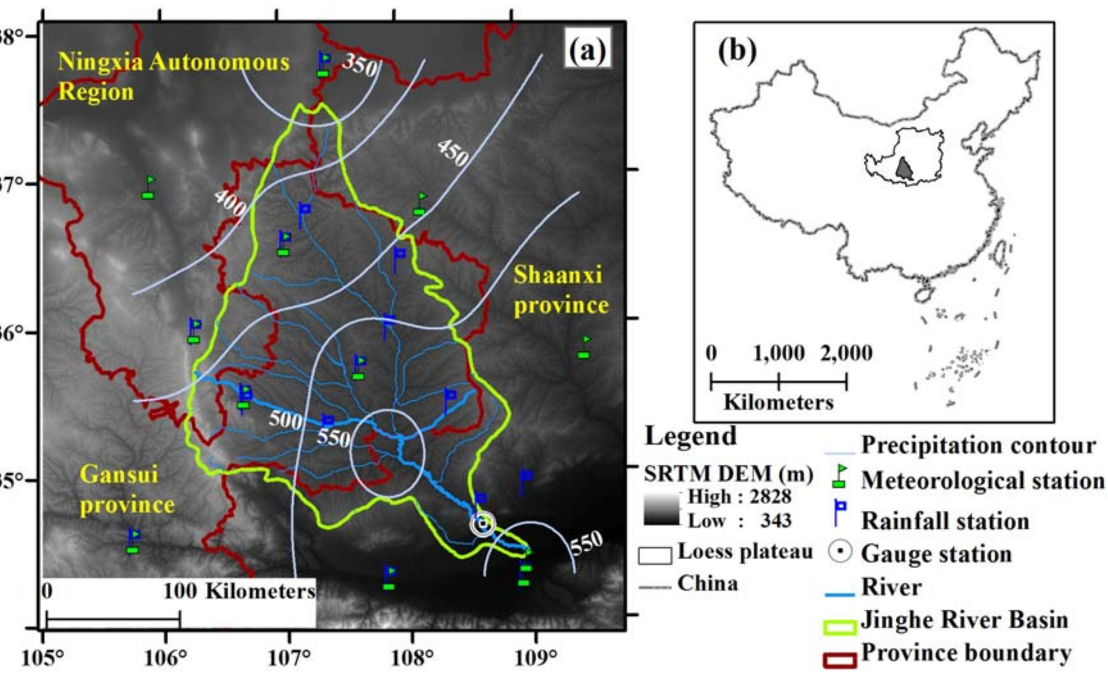

Figure 1. Geographic information of the study area: (a) Location and SRTM DEM of the Jinghe River Basin; (b) schematic of the selected study area in China. Precipitation in mm is averaged and interpolated from meteorological data between 1970 and 2010.

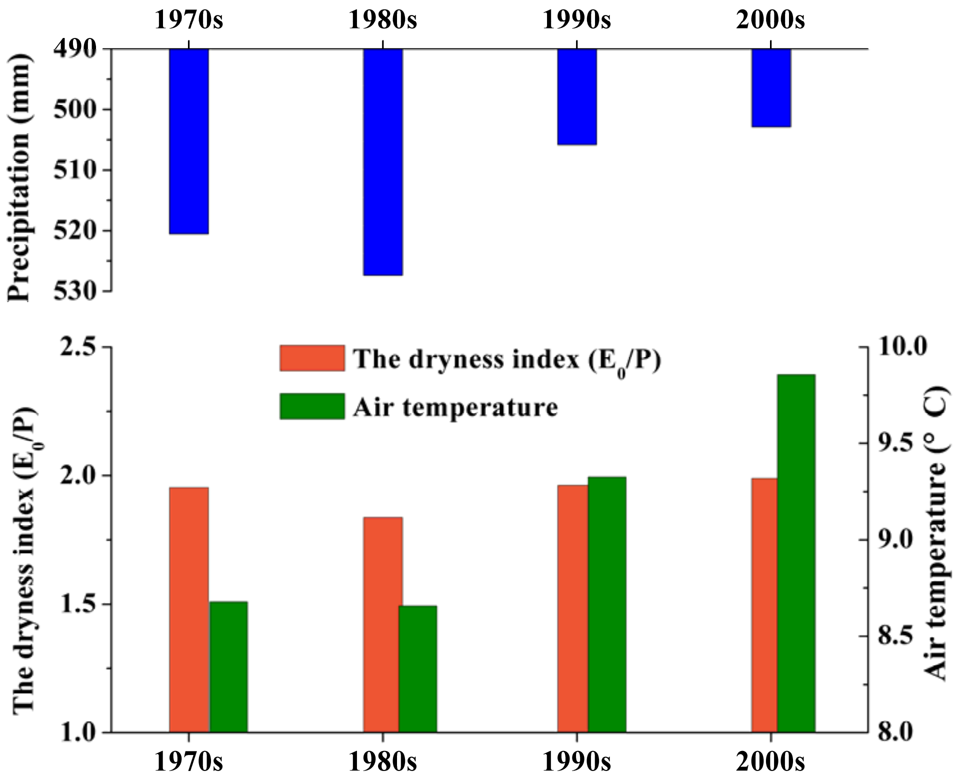

Figure 2. Variation in decade mean precipitation (top), dryness index and air temperature (bottom) in the Jinghe River Basin from the 1970s to the 2000s. The dryness index was defined as a ratio of annual potential evapotranspiration (E_0) to annual precipitation (P).

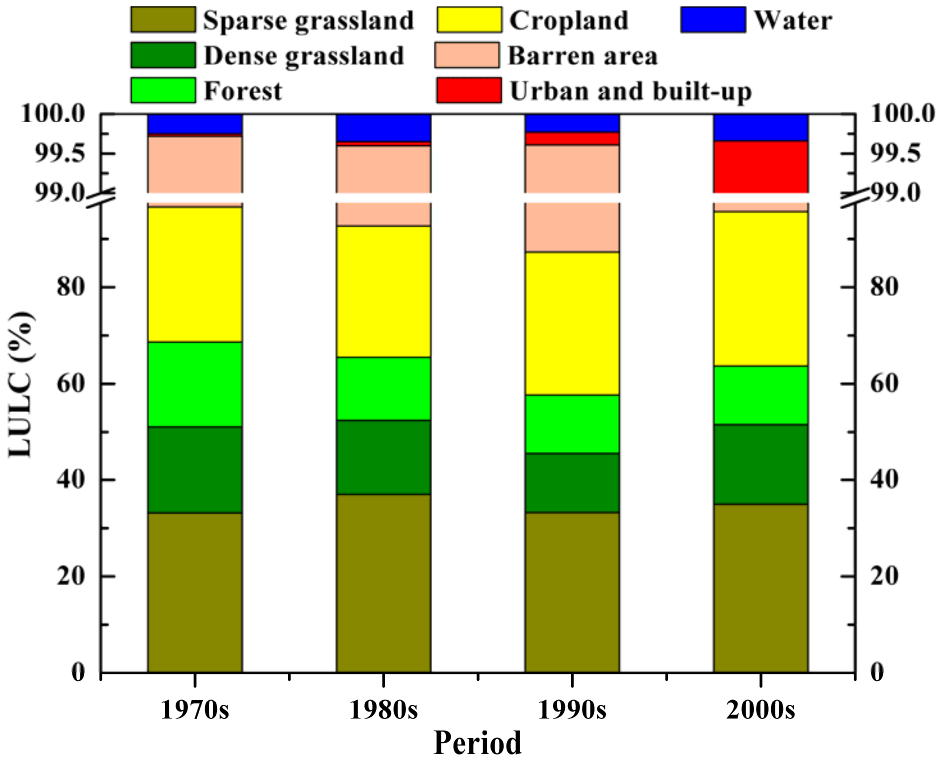

Figure 3. LULC composition and its change in the Jinghe River Basin from the 1970s to the 2000s.

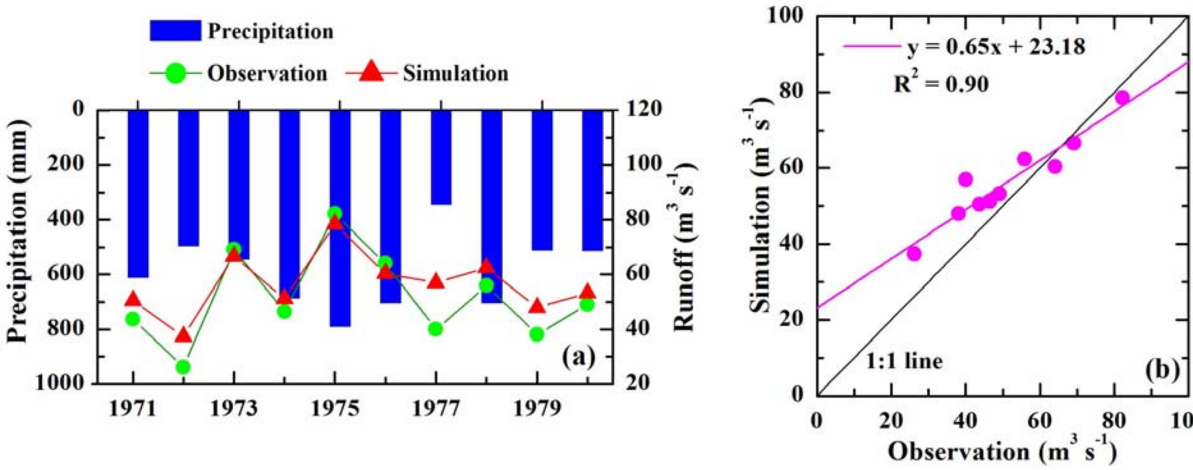

Figure 4. Comparison of observed and simulated runoffs at the yearly scale in the Jinghe River Basin during the calibration period from 1971–1980. Fig. 4 (b) is redrawn from Qiu et al. (2011).

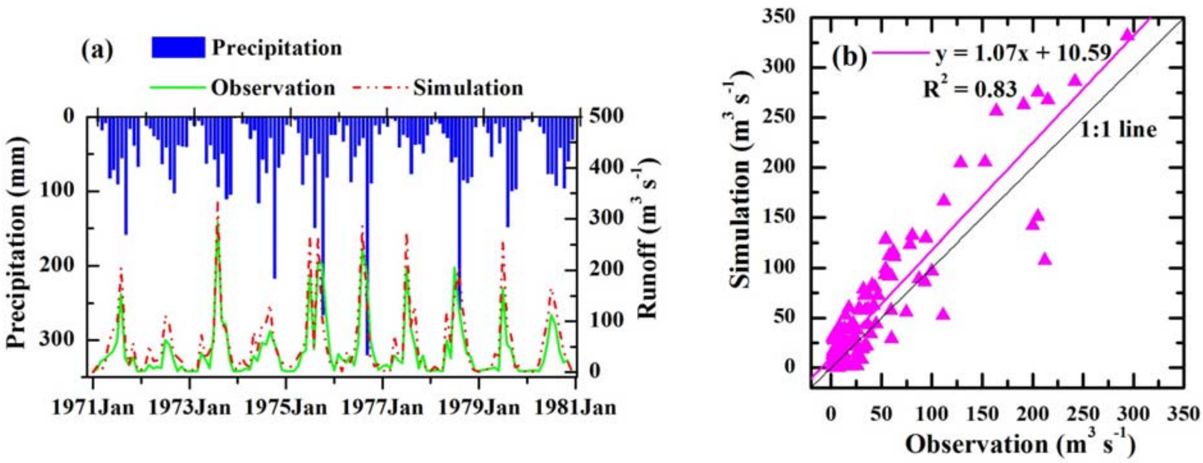

Figure 5. Comparison of observed and simulated runoffs at the monthly scale in the Jinghe River Basin during the calibration period from 1971–1980. Fig. 5 (b) is redrawn from Qiu et al. (2011).

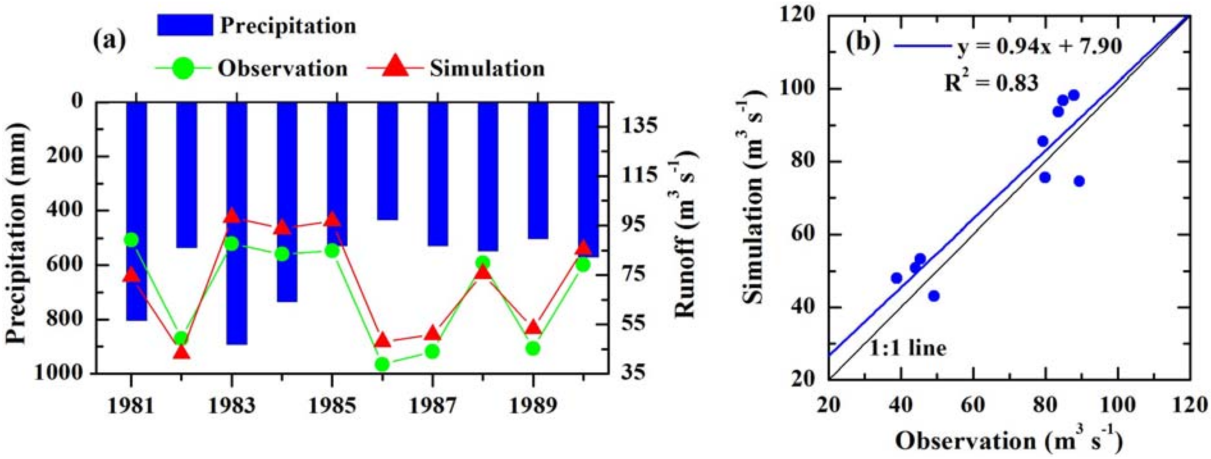

Figure 6. Comparison of observed and simulated runoffs at the yearly scale in the Jinghe River Basin during the validation from 1981–1990. Fig. 6 (b) is redrawn from Qiu et al. (2011).

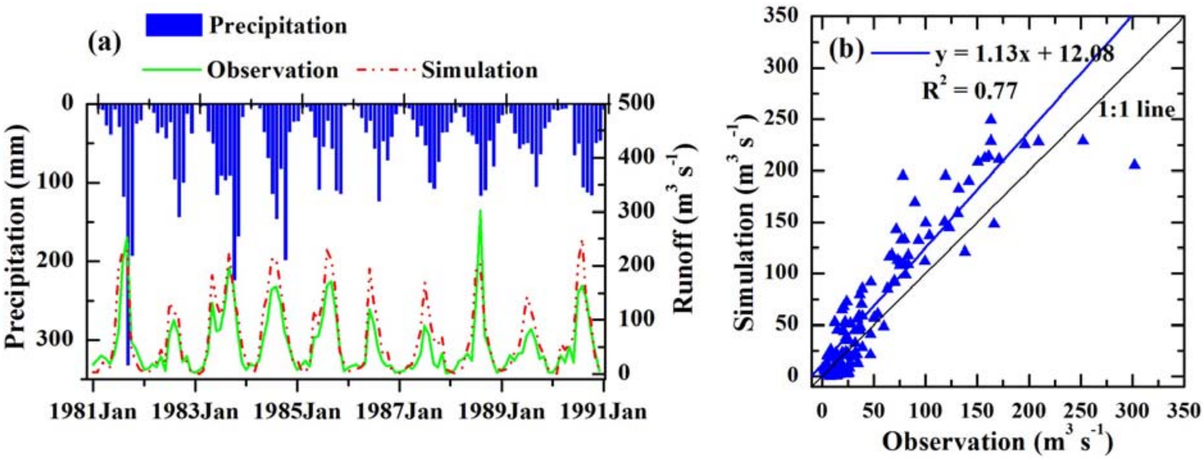

Figure 7. Comparison of observed and simulated runoffs at the monthly scale in the Jinghe River Basin during the validation period form 1981–1990. Fig. 7 (b) is redrawn from Qiu et al. (2011).

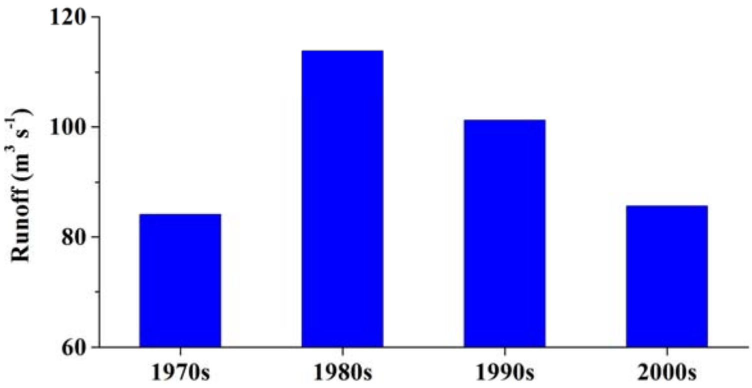

Figure 8. Variation in mean annual surface runoff at the decadal scale in the Jinghe River Basin from the 1970s to the 2000s.

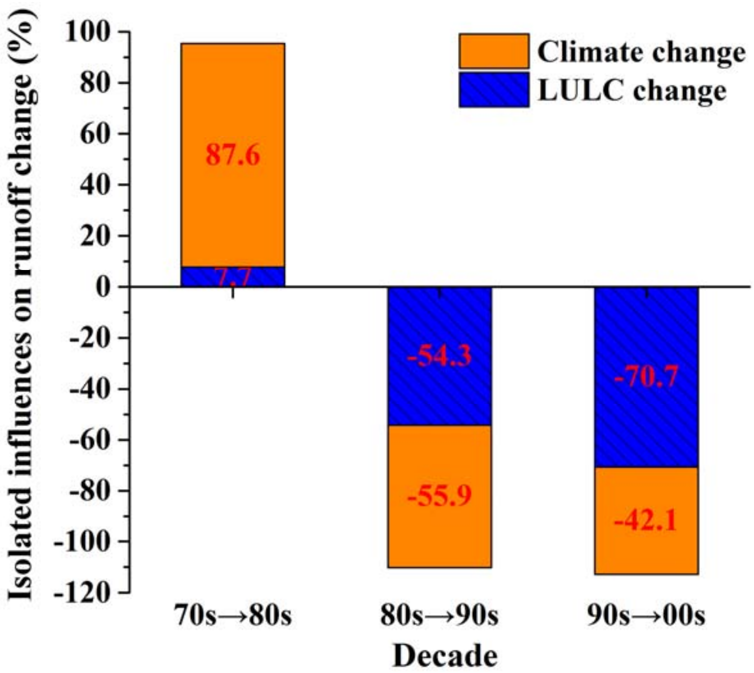

Figure 9. Isolated impacts of LULC and climate changes on surface runoff. Positive values indicate that runoff increased due to these factors, whereas negative values indicate that the runoff decreased due to these factors. The summation of the isolated influences is not equal to 100% due to simulation uncertainty (see section 3.6 for details).