Responses to reviewers

We thank two reviewers very much for their insightful comments and suggestions. All comments are valuable and helpful for improving the quality of the manuscript and have been carefully checked and addressed. Please see our point-to-point responses below. A kindly note: reviewers' comments are in blue color and our responses are in black color; page and line numbers cited in our responses refer to the revised manuscript with track changes for easy evaluation. A track-changed version of the revised manuscript can be found after the response to reviewers.

Reviewer #1:

Qiu et al.- Spatiotemporal response of the water cycle to land use conversions in a typical hilly-gully basin on the Loess Plateau, China- studies the hydrological response of land cover and land use change in a hilly-gully basin of the Loess Plateau in China. This region is very lack of water resources and land use and management play very important role in increasing its resilience and sustainability. This study based on modeling approach adds new and important information for effective water resource conservation and management. Meanwhile it would serve as a useful reference with broad impact for similar arid region worldwide. However, the present form is lack of some details on model construction and validation, especially for the dry period simulation. I would also suggest the author check and improve the input data accuracy. English word selection and expression accuracy need improvement too. There are too many usage of "exhibit" in the text. The following specific comments provide more suggestion for author to consider in their manuscript revision.

Response: We thank for the positive evaluation and instructive comments and suggestions.

(1) According to the reviewer's suggestion, we add more details on model construction, and this procedure is as follows: a geographic information system (GIS) interface, ArcSWAT (Version 2012.10_2.18), was used to set up the model. The DEM was used to delineate the watershed, and this process produced 88 subbasins. The 30 m land use map of 1990 and soil map were from the Chinese Academy of Sciences, and the digitalized soil data were from the Data Center of West China (http://westdc.westgis.ac.cn/). We used the multiple Hydrological Response Unit (HRU) option in ArcSWAT to represent each unique field (combination of land cover, soil, and slope) as a separate unit, leading to a total of 1,136 HRUs using a threshold value of 10% for the three categories. To meet the needs of the model, the SWAT codes for main land use types in the study area were defined as cropland (AGRR), woodland (FRST), grassland (RNGE), residential land (URBN), barren land (BARR) in the attribute data (*Please see P6 L19 ~ P7 L4*).

(2) In terms of model verification, we firstly calibrated the SWAT model with 10-year (1983–1992) monthly streamflow data of Ganguyi hydrological station using SWAT-CUP (SUFI2 algorithm). Then the model was validated using data from the subsequent eight years (1993–2000). To evaluate the model performance numerically, we used three statistical measures, including percent bias (PBIAS), Nash-Sutcliffe efficiency (NSE), and the coefficient of determination (squared correlation coefficient, r^2). Typically, a model simulation is considered satisfactory with NSE>0.5, -25%≤PBIAS≤25%, and r^2>0.5 (Wu and Chen, 2013; Neupane and Kumar, 2015) (*Please see P7 L4 ~ P7 L14*). In the calibration and validation periods, the statistics of NSE, PBIAS and r^2 ranged from 0.51~0.70, 15.7%~16.9% and 0.71~0.82, respectively, indicating a satisfactory performance. However, PBIAS value showed that SWAT

underestimated the streamflow in both calibration and validation periods. Visual inspection as shown in Fig. 3 indicated that the underestimation mainly occurred in the dry period, and the potential reasons are measurement quality and model behavior for dry areas. Measurement quality refers to the missing precipitation data or streamflow measuring error. The study area belongs to the hilly-gullied loess region, and complex and rugged terrain results in highly variable precipitation and difficulties in spatially estimating the precipitation (Cao et al., 2006). Additionally, this region has limited meteorological and hydrological stations. In this study, there are five meteorological stations, whereas only three stations are located inside the basin and the remaining two are located outside the basin (Fig. 1). It has been reported that the accuracy of the streamflow prediction mainly depends upon the precipitation gage numbers and their locations (Cao et al., 2006; Mul et al., 2009). Thus, the insufficient precipitation records and relatively distant geographical position of meteorological stations resulted in poor streamflow simulation. “Model deficiency” refers to the model limitations such as inadequate representation of physical mechanism of hydrological processes. For example, SWAT uses total daily precipitation and does not consider rainfall intensity within a day, thus it can result in underestimation of streamflow for some precipitation events (Qiu et al., 2012). Another example is the use of runoff curve number to simulate the surface runoff behavior, and this does not account for saturation excess runoff or contributions from variable source areas (Garen and Moore, 2005; Easton et al., 2008). Although the simulation results in our research met the calibration criteria, the model performance can be improved further if precipitation from additional gages available in the basin. Above information was added in the paragraph one of the discussion section (*Please see P12 L9 ~ P13 L3*).

(3) We thank the reviewer for pointing out our language problems (e.g., too many use of a word). Now we have checked the manuscript carefully and revised it further to improve its quality and accuracy.

Line 22-23, pp1: “These results suggest that the expansive revegetation of sloping land could reduce runoff generation, particularly in woodland areas, but these effects could reduce the soil water volume in the region.” What are the percentages of runoff and soil water volume reductions?

Response: Following the reviewer’s suggestion, we calculated the decrease percentage. When the cropland with slope ≥15° was converted to woodland in S4, the surface runoff and soil water decreased by 17.1% and 6.4%, respectively, compared to the land use condition of 2010. We added this information in the abstract (*please see P1 L22 ~ P1 L23*).

Line 6, pp2: change to “considered as?”

Response: Done (*please see P2 L17*).

Line 23, pp2: “between runoff and increased LULC” what kind of land cover and land use is that?

Response: “LULC” should be changed to “land cover”, and thanks for pointing out this writing error. In the literature, it was reported that mean runoff in 2005–2010 declined significantly compared with the time period of 1997–2005, and this can be attributed mainly to changes in land use/land cover, i.e., increases in forests, shrubs, and grasses, and decreases in sloping farmlands. Thus, we rephrased the sentence to make the description more accurate (*please see P3 L11 ~ P3 L13*).

Line 27-29, pp3: need valid data sources for the climate information.

Response: The climate information of study area was based on the collected observation data, and the data was provided by the Meteorological Institute of Shaanxi Province, China. We added the data source in the manuscript accordingly (*please see P5 L1*).

Line 4, p4: figure 2 shows that the streamflow is about 80% of precipitation. This is against common sense. Pls check your data again.

Response: The units of the streamflow (10^6 m^3) and precipitation (mm) are different, and the calculated ratio of streamflow to precipitation is around 6.6%.

Line 10-20, pp5: lulc of 2010 was used as baseline. How about the lulc of 1990 and 2000? Did you use these two maps as model calibration and validation? It seems only 2010 map was used for the slope related scenario creation. It is a little bit confusing here. You may need to clarify more on the model and scenario configurations.

Response: We have added more details on model set up and scenario configurations based on the reviewer's comments. We firstly calibrated the SWAT model using land use data of 1990. Then we test different land use data of 1990, 2000 and 2010 under the same climate data from 1986-2015 to separate the unique effect of land use change. Finally, the hydrological effects of hypothetical land use conversion were assessed using same procedures with evaluating historic land use change effects (*please see P6 L18 ~ P7 L24*).

Line 29-30, pp5: do you mean the precipitation input miss the streamflow simulations? If so, you may need to prove/show that in a new figure.

Response: Indeed, here we tried to explain the reason for the discrepancy between measured precipitation and streamflow during the dry period. We deleted this sentence and gave the explanations in the section of Discussion (*please see P12 L9 ~ P13 L3*).

Table 3: change "Ratio" to "Percentage" for consistence.

Response: Done (*please see P25 Table 3*)**.**

Line 23, pp6: it should be "in the same period" and "resulting the small net change"

Response: Done (*please see P9 L13*).

Line 28, pp8: change "classes" to "types"

Response: Done (*please see P13 L5*).

Line 11, pp9: what the difference between surface runoff and streamflow?

Response: In SWAT, surface runoff is flow that occurs along the sloping surface (i.e., quick-response overland flow), which contributed to streamflow. It occurs whenever the net rainfall exceeds the rate of infiltration or the it was saturated.

Streamflow is the water flowing downhill through creeks, streams, and rivers toward the outlet of the basin, and it includes surface runoff, lateral flow within soil profile, and base flow.

Line 23, pp9: why cropland has the highest soil water storage?

Response: The reason can be explained as follows: Firstly, in the Yanhe basin, the cropland was mainly distributed in the bottom region of the valley or the sloping land with gentle slope. The valley bottom generally receives more water flow from hillslope and have lower temperature, resulting in more soil moisture (Wang et al., 2012). Additionally, gentle sloping area had higher soil water retention ability compared with steep sloping area (Famiglietti et al., 1998). Secondly, our results showed that the cropland had lower evapotranspiration per unit area compared with other land use types. Thus, these interrelated above two reasons led to the highest soil water storage. This explanation has been added to the revised manuscript (*please see P13 L8 ~ P13 L15*).

Line 4, pp10: sloped cropland or sloping cropland? Pls make this term consistent throughout the manuscript.

Response: Thanks for the suggestion, and we used “sloping cropland” in the whole manuscript (*please see P15 L3*).

Line 13, pp10: “transition analysis”? Pretty new and never heard. Pls consider changing it. Otherwise more definition should be given.

Response: “Land us transition analysis” summarizes the amount of certain land that changes from each category at the initial time to each category at the subsequent time, and it has been widely used in landscape ecology and GIS studies of land use to quantitatively estimate the rate of change. To avoid confusion, we took “land use change analysis” in the revision (*please see P8 L24 ~ P9 L1*).

Line 24, pp10: change planting wood to afforestation?

Response: Done (*please see P15 L23*).

The study (Qiao et al., 2017, Woody plant encroachment reduce annual runoff and shifts runoff mechanisms in the tallgrass prairie, USA. Water Resource Research) provides some evidence of water budget difference between woodland and grassland and would be a useful reference for this study.

Response: Thanks for recommending a valuable reference to our study, and we have cited this article in our revision (*please see P13 L20*).

Reviewer #2:

General Comment: This manuscript investigated the response of main hydrological components to land use change and basin management policy in the loess region of China. It is interesting to see the spatial distribution of hydrological responses at the unit (HRU) level and the quantitative assessment of the roles of different land use types in basin hydrology. In particular, it is attractive to interpret the mechanism of the streamflow decrease associated with vegetation restoration on the Loess Plateau and thus may have a broad readership. Overall, the article was well organized, well written, and easy to follow. All figures and tables are of high quality and informative. What I would suggest is give more discussion on the reason why the different land use types show different hydrological characteristics (e.g., soil water and ET) in this region. That would help reader better understand the findings from the article.

Response: We thank the reviewer for his/her positive remarks and constructive comments. We considered the comments of reviewer and added more discussion on hydrological characteristics. For soil water, explanations for differences among different land use types need to combine the topography and land cover on the land surface. In our study, woodland had lowest surface runoff and water yield, because woodland areas capture more rainfall and uptake more water than other land use types (e.g., cropland and grassland) (Wang et al., 2012; Jian et al., 2015), resulting in a lower infiltration, runoff, and water discharge (Wang et al., 2013; Duan et al., 2016). Less soil water on woodland is because forests in the Yanhe basin generally grew on landform with high slopes, and steeper slopes generally retain less soil water due to low infiltration (Famiglietti et al., 1998). Moreover, woodland may lose more water through ET than other land use types. Cropland had highest soil water in our study, and this can be partly attributed to the topography of croplands. The primary croplands are situated in the bottom region of the valley or the sloping land with gentle slope, and valley bottom generally receives more water flow from hillslope and have lower temperature, resulting in more soil water (Wang et al., 2012). Moreover, gentle sloping area had higher soil water retention ability compared with steep sloping area (Panagopoulos et al., 2011). Besides, the cropland had lower evapotranspiration per unit area compared with other land use types. In contrast, grassland had lower soil water, and this can be because grassland had higher soil water loss through evapotranspiration. Wang et al. (2012) reported that grass cover types cannot protect the soil surface from solar radiation, leading to greater water loss via direct evaporation. As for ET on the Loess Plateau region, it has been widely demonstrated that the woodland had highest ET, followed by grassland, and cropland (Xiao et al., 2013; Wang et al., 2012). (*please see P13 L8 ~ P14 L4*)

Specific comments:

P2 L6: Use “sloping cropland” here to guarantee the consistence, because you use “sloping land” in the whole manuscript.

Response: Corrected (*please see P15 L3-4*).

P7 L26 Add “of” between “trend” and “surface runoff”.

Response: Done (*please see P10 L3*).

P7 L29 Replace “because of the decreased area of cropland” by “because of its decreased area”.

Response: Corrected (*please see P11 L2*).

P8 L1 Replace “deceasing” by “decrease”.

Response: Corrected (*please see P11 L5*).

P9 L1-12 the response of soil water in woodland are well discussed, how about in cropland and grassland and try to explain more.

Response: As responded to the reviewer #1, highest soil water in cropland may be due to two related reasons: Firstly, in the Yanhe basin, the primary croplands were situated in the bottom region of the valley or the sloping land with gentle slope, and valley bottom generally receives more water flow from hillslope and have lower temperature, resulting in more soil moisture (Wang et al., 2012); gentle sloping area had higher soil water retention ability compared with steep sloping area (Panagopoulos et al., 2011). Secondly, our results showed that the cropland had lower evapotranspiration per unit area compared with other land use types. Thus, these interrelated two main reasons led to the highest soil water storage in cropland. In contrast, grassland had lower soil water, and this can be because grassland had higher soil water loss through evapotranspiration. Wang et al. (2012) reported that grass cover types cannot protect the soil surface from solar radiation, leading to greater water loss via direct evaporation (*please see P13 L8-19*).

P9 L14 Rephrase the sentence and clearly state what are the main forms of land use change in the Yanhe basin.

Response: It was rephrased, and the revised sentence is “After the implementation of the GFGP, the area of cropland decreased continuously because it was transformed into grassland and woodland from 1990 to 2010, and the conversions among cropland, grassland and woodland were the main forms of land use change in the Yanhe basin” (*please see P14 L5-6*).

P9 L20 Where are the locations of 26 watersheds?

Response: This study reported in the literature was conducted globally. The researchers selected 26 catchments around the world and evaluated the effect of afforestation on water yield. To avoid confusion, we added “globally” in this sentence (*please see P14 L12*).

P18: “Ratio” should be changed to “Percentage” in Table 3.

Response: Corrected (*please see P25 Table3*).

References

Cao, W. Z., Bowden, W. B., Davie, T., and Fenemor, A.: Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability, Hydrological Processes, 20, 1057-1073, 10.1002/hyp.5933, 2006.

Duan, L., Huang, M., and Zhang, L.: Differences in hydrological responses for different vegetation types on a steep slope on the Loess Plateau, China, Journal of Hydrology, 537, 356-366, 10.1016/j.jhydrol.2016.03.057, 2016.

Easton, Z. M., Fuka, D. R., Walter, M. T., Cowan, D. M., Schneiderman, E. M., and Steenhuis, T. S.: Re-conceptualizing the soil and water assessment tool (SWAT) model to predict runoff from variable source areas, Journal of Hydrology, 348, 279-291, 10.1016/j.jhydrol.2007.10.008, 2008.

Famiglietti, J. S., Rudnicki, J. W., and Rodell, M.: Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas, Journal of Hydrology, 210, 259-281, http://doi.org/10.1016/S0022-1694(98)00187-5, 1998.

Garen, D. C., and Moore, D. S.: Curve number hydrology in water quality modeling: Uses, abuses, and future directions, Journal of the American Water Resources Association, 41, 377-388, 10.1111/j.1752-1688.2005.tb03742.x, 2005.

Jian, S. Q., Zhao, C. Y., Fang, S. M., and Yu, K.: Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau, Agricultural and Forest Meteorology, 206, 85-96, 10.1016/j.agrformet.2015.03.009, 2015.

Mul, M. L., Savenije, H. H. G., and Uhlenbrook, S.: Spatial rainfall variability and runoff response during an extreme event in a semi-arid catchment in the South Pare Mountains, Tanzania, Hydrology and Earth System Sciences, 13, 1659-1670, 2009.

Neupane, R. P., and Kumar, S.: Estimating the effects of potential climate and land use changes on hydrologic processes of a large agriculture dominated watershed, Journal of Hydrology, 529, 418-429, 10.1016/j.jhydrol.2015.07.050, 2015.

Panagopoulos, Y., Makropoulos, C., Baltas, E., and Mimikou, M.: SWAT parameterization for the identification of critical diffuse pollution source areas under data limitations, Ecological Modelling, 222, 3500-3512, http://dx.doi.org/10.1016/j.ecolmodel.2011.08.008, 2011.

Qiao, L., Zou, C. B., Stebler, E., and Will, R. E.: Woody plant encroachment reduces annual runoff and shifts runoff mechanisms in the tallgrass prairie, USA, Water Resources Research, 53, 4838-4849, 10.1002/2016WR019951, 2017.

Qiu, L.-j., Zheng, F.-l., and Yin, R.-s.: SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges, Int. J. Sediment Res., 27, 226-234, 2012.

Wang, S., Fu, B. J., Gao, G. Y., Yao, X. L., and Zhou, J.: Soil moisture and evapotranspiration of different land cover types in the Loess Plateau, China, Hydrology and Earth System Sciences, 16, 2883-2892, 10.5194/hess-16-2883-2012, 2012.

Wang, S., Fu, B., Gao, G., Liu, Y., and Zhou, J.: Responses of soil moisture in different land cover types to rainfall events in a re-vegetation catchment area of the Loess Plateau, China, Catena, 101, 122-128, http://doi.org/10.1016/j.catena.2012.10.006, 2013.

Wu, Y., and Chen, J.: Analyzing the water budget and hydrological characteristics and responses to land use in a monsoonal climate river basin in south China, Environmental Management, 51, 1174-1186, 10.1007/s00267-013-0045-5, 2013.

Xiao, J., Sun, G., Chen, J., Chen, H., Chen, S., Dong, G., Gao, S., Guo, H., Guo, J., Han, S., Kato, T., Li, Y., Lin, G., Lu, W., Ma, M., McNulty, S., Shao, C., Wang, X., Xie, X., Zhang, X., Zhang, Z., Zhao, B., Zhou, G., and Zhou, J.: Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China, Agricultural and Forest Meteorology, 182, 76-90, http://dx.doi.org/10.1016/j.agrformet.2013.08.007, 2013.

Spatiotemporal response of the water cycle to land use conversions in a typical hilly-gully basin on the Loess Plateau, China

Linjing Qiu[1], Yiping Wu[1], Lijing Wang[1], Xiaohui Lei[2], Weihong Liao[2], Ying Hui[3], Xianyong Meng[4]

[1]Department of Earth and Environmental Science, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

[2]State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China

[3]Meteorological Institute of Shaanxi Province, Xi'an, China

[4]Institute of Water Resources and Hydropower Research, Beijing, 100038, China

Correspondence to: Yiping Wu (yipingwu@xjtu.edu.cn)

Abstract. The hydrological effects of the 'Grain for Green' project (GFGP) on the Loess Plateau have been largely debated due to the complexity of the water system and its multiple driving factors. The aim of this study was to investigate the response of the hydrological cycle to the GFGP measures based on a case study of the Yanhe basin, a typical hilly-gully area on the Loess Plateau of China. First, we analyzed the land use and land cover (LULC) changes from 1990 to 2010. Then, we evaluated the effects of LULC changes and sloping land conversion on the main hydrological components in the basin ~~considering the land surface characteristics and climate impacts. The~~using Soil and Water Assessment Tool (SWAT)~~ was used for this analysis~~. The results indicated that ~~farmland~~ cropland exhibited a decreasing trend declining from 40.2% of the basin area in 1990 to 17.6% in 2010, and the woodland and grassland areas correspondingly increased~~ due to the implementation of the GFGP in the basin~~. ~~Due to~~With the land use changes from 1990 to 2010, ~~surface runoff and~~ the water yield ~~exhibited~~ showed a decreasing trend~~s~~ which was mainly caused by surface runoff decrease, whereas evapotranspiration (ET) had an ~~increased~~increasing trend, resulting in a persistent decrease in soil water. ~~Additionally, c~~Converting sloping cropland ~~areas with slopes ≥15° or >25°~~ to grassland ~~and~~or woodland ~~had~~exerted negative effects on ~~surface runoff, the~~ water yield and soil water~~ and a positive effect on ET~~. Particularly when cropland with slope ≥15° was converted to woodland, reduction effects were most evident, and the surface runoff and soil water decreased by 17.1% and 6.4% compared with land use condition of 2010, respectively. ~~.converting cropland areas with slopes ≥15° or >25° to grassland and woodland had negative effects on surface runoff, the water yield and~~

~~soil water and a positive effect on ET.~~ ~~The magnitudes of the hydrological effects generated by sloping cropland to woodland conversion were greater than those for sloping cropland to grassland conversion.~~ These results suggest that the expansive ~~revegetation~~ reforestation ~~of~~ on sloping land in the loess hilly-gully region could ~~reduce~~ decrease the ~~runoff generation~~water yield and increase the ET, and consequently~~, particularly in woodland areas, but these effects could reduce~~ caused ~~the~~ soil water reduction ~~volume in the region~~. Overall, this study can be used to improve sustainable land use planning and water resource management on the Loess Plateau in China.

1 Introduction

Land surface change is one of the most important drivers of eco-hydrological changes (Li et al., 2009; Bloeschl et al., 2007). The impacts of land use and land cover (LULC) changes on water resources and hydrological processes in a river basin are mainly reflected in the overland surface runoff, streamflow, evapotranspiration (ET), soil moisture, etc. (Bari and Smettem, 2004; Chawla and Mujumdar, 2015; Liu et al., 2008b; Zucco et al., 2014). Many studies have investigated the interactive mechanisms between land use patterns and basin hydrology, and they found that the characteristics of basin hydrology vary among different land use patterns, due not only to different land use types (Wang et al., 2012; Jian et al., 2015; Duan et al., 2016), but also to the spatial heterogeneity of LULC (Chu et al., 2010; Liu et al., 2013). However, debate exists among ecohydrologists regarding the effects of past and ongoing land use changes because of the spatial and temporal complexity of hydrological processes (Lørup et al., 1998; Lopez-Moreno et al., 2011; Alkama et al., 2013; Liu et al., 2016).

Land use planning in China is considered as a crucial strategy for the sustainable management of a river basin system and has been widely adopted for ecological restoration and water resource protection, especially in the Loess Plateau region, which is famous for its fragile ecology (Liu et al., 2008a; Zhang et al., 2009; Zhen et al., 2014). The river basins on the Loess Plateau are important because of the dense population, intensive cultivation, and the high demand for water in the area. Unfortunately, this region is characterized by insufficient water resources and severe soil erosion, and it has historically experienced vegetation degradation and desertification (Zhao et al., 2013; Guo et al., 2002). Thus, land use change and basin hydrology have attracted a considerable deal of attention, and soil and water conservation practices have been implemented in the area to overcome the ever-increasing environmental problems since the 1970s. In 1999, the ‘Grain for Green’ project (GFGP) was launched by the Chinese government in the Loess Plateau region, and the primary goal was to retire and convert steep cropland~~s~~ (slope ≥ 15°) to green lands (Zhou et al., 2012; Liu et al., 2008a). It was reported that the vegetation coverage on the Loess Plateau increased from 6.5% in the 1970s to 51% in 2010 (Wang et al., 2012), and approximately 16,000 km^2 of rain-fed cropland was converted to planted vegetation during the past decade (Feng et al., 2016). Consequently, the hydrological processes on the sloping land and in the river systems have changed, but the extent of these changes and the ties to LULC change remain topics of scientific research.

In the past decades, the hydrological effects of land use change have been widely explored across different spatiotemporal scales on the Loess Plateau. Huang et al. (2003) investigated the runoff response to afforestation using a paired watershed analysis and revealed that forest revegetation reduced annual runoff and the reduction increased with the age of trees. McVicar et al. (2007, 2010) developed a decision support tool for China’ s re-vegetation program and simulated the annual streamflow based on the revegetation planning. Wei et al. (2015) ~~observed~~ found a strong inverse relationship between runoff and increased forests, shrubs, and grasses during the period of 2005-2010 in a typical watershed on the Loess Plateau ~~strong inverse relationship between runoff and increased LULC~~ using statistical analysis. ~~from 1997 through 2000.~~ Feng et al. (2016) reported that revegetation increased ET and resulted in a significant ($P<0.001$) decrease in the ratio of streamflow to precipitation on the Chinese Loess Plateau. Zuo et al. (2016) combined statistical tests and hydrological modeling to assess the effects of land use on runoff and found that the water resources in the upstream region decreased more than those in the downstream region. Liang et al. (2015) used an elasticity and decomposition model based on the Budyko framework to simulate and forecast the hydrological effects of ecological restoration and demonstrated that ecological restoration played a dominant role in the reduction of streamflow in 14 main subbasins on the Chinese Loess Plateau. Another study showed that the GFGP can potentially increase the soil water content and water yield and decrease the runoff and ET (Tian et al., 2016). Moreover, some researchers stated that woody species consume more water by evapotranspiration than do other vegetation types (Wang et al., 2012; Yang et al., 2014), and some studies have documented that large-scale reforestation has greatly~~-~~ decreased the water yield and exacerbated water scarcity (Sun et al., 2006), gradually leading to soil desiccation (Chen et al., 2008; Chen et al., 2007; Wang et al., 2008). In general, these studies indicated that the GFGP on the Loess Plateau has had an evident influence on basin hydrology; however, because these studies were performed from different perspectives or concentrated on single hydrological elements, the effects of ecosystem restoration on the water balance have not been clarified. In addition, most of the studies have been based on statistical methods with short time scales. Although numerical models are useful tools for quantitatively assessing the hydrological responses to environmental changes, the existing modeling studies mainly focused on the water discharge in a river channel, and few have analyzed the spatial features of hydrological responses. Spatially studying such responses could improve watershed management and the development of strategies for water resource optimization. Therefore, a comprehensive understanding of how LULC change and its spatial heterogeneity affect the water balance is essential for long-term land use planning and water resource management.

In this study, the Soil and Water Assessment tool (SWAT) was applied to investigate the hydrological impacts of land use changes, including the sloping land conversion (SLC) program on the Loess Plateau. The Yanhe basin, a main tributary of the middle reach of the Yellow River that has undergone large-scale revegetation and SLC, was selected to analyze the hydrological response mechanism using the modeling technique. The specific objectives were as follows: 1) to investigate the spatiotemporal variations in key water balance components as a result of LULC change, 2) to evaluate the potential effects of land conversion on water availability under the SLC program, and 3) to examine the changes in soil water storage under different land use condition. The results provide a useful reference for sustainable land use planning and water resources management on the Loess Plateau in China.

2 Materials and methods

2.1 Study area

The Yanhe basin, which is located in northern Shaanxi Province, China (36°21′–37°19′ N and 108°38′–110°29′ E), is a typical hilly loess area on the Loess Plateau. The drainage area of the basin is 7591 km^2, and its elevation rangs from 560 m to 1760 m (Fig. 1). The slope of the basin varies from 0° to 85.3°, with a mean value of 17.7°. The main channel of the Yanhe River is 284.3 km long and originates in Jingbian County. It flows from northwest to southeast through Zhidan County, Ansai County, Yanan City, and Yanchang County before entering the Yellow River. The soil in the basin developed from loess deposits, and the dominant soil type is loessial soil which is classified as Calcaric cambisols (FAO 2014). The Yanhe basin characterized by a semi-arid continental climate with warm and concentrated precipitation in summer and cold, dry winters with occasional snowfall. According to the collected meteorological data from the Meteorological Institute of Shaanxi Province, China, t~~T~~he precipitation from 1952–2015 ranged from 300 mm to 803 mm, with a mean annual value of 495 mm. Additionally, the mean annual maximum and the minimum air temperatures were 17.4 ℃ and 4.2 ℃, respectively. Grassland, ~~farmland~~cropland, and woodland (mainly artificial woods) are the dominant land use types in this region. Most crops are cultivated on sloping lands, and woodlands are generally located on the steeper parts of the landform. The mean annual streamflow at the most downstream station of Ganguyi was 205×10^6 m^3 from 1952 through 2008, and the streamflow from June to September accounted for 64.1% of the total annual discharge at this station. The GFGP was implemented in the basin in 1999, and the observed streamflow ~~exhibited~~ showed a decreasing trend during the 2010s (Fig. 2).

2.2 Data

The SWAT model setup requires data inputs including topography, soil, land use, climate and streamflow discharge. A digital elevation model (DEM) of the basin with a 30-m resolution was obtained from the National Geomatics Center of China (http://www.ngcc.cn/). The soil survey ~~data~~map~~, including~~ with a 20-m resolution ~~a raster map with soil property database at a 20-m resolution,~~ were obtained from the Institute of Soil and Water Conservation (ISWC), Chinese Academy of Sciences (CAS), and we developed a user's soil database required for model that linked to the digital soil map using ArcGIS (version 10.2). LULC data from 1990, 2000 and 2010 with a 30-m resolution were supplied by the Institute of Remote Sensing and Digital Earth, CAS, and ~~. T~~the land use~~d area~~ was ~~divided into~~classified as six ~~main land use~~ types~~, including~~: grassland, woodland, cropland, water, residential land and barren land, according to the ecosystem classification system of China. Required ~~.~~ ~~daily~~ meteorological data for SWAT model consist of daily precipitation, maximum and minimum temperature, relative humidity, wind speed and solar radiation~~,~~, which were available ~~which were collected~~ from 1980 to 2015 in five county level meteorological stations including Jingbian, Zhidan, Aansai, Yan'an and Yanchang stations, and they were provided by~~from~~ the Meteorological Institute of Shaanxi Province, China. ~~The datasets consist of daily precipitation, maximum and minimum temperature, relative humidity, wind speed and solar radiation, for five county level meteorological stations including Jingbian, Zhidan, Aansai, Yan'an and Yanchang stations.~~ Observed monthly streamflow data at the Ganguyi hydrological station were obtained from the Yellow River Conservancy Commission (YRCC) from 1980-2010. The data were used for model calibration and validation, although some data gaps (missing values) were present. Ganguyi station is the most downstream station on the Yanhe River and controls an area of 5891 km^2. ~~A digital elevation model (DEM) of the basin with a 30-m resolution was obtained from the National Geomatics Center of China (http://www.ngcc.cn/). The soil data, including a raster map with soil property database at a 20-m resolution, were obtained from the Institute of Soil and Water Conservation (ISWC), Chinese Academy of Sciences (CAS). LULC data from 1990, 2000 and 2010 with a 30-m resolution were supplied by the Institute of Remote Sensing and Digital Earth, CAS. The land area was divided into six main land use types, including grassland, woodland, cropland, water, residential land and barren land, according to the ecosystem classification system of China.~~

2.3 Model description

The SWAT model (version 2012), which was developed by the U.S. Department of Agriculture (USDA)—Agricultural Research Services (ARS), is a physically based, temporally continuous, and distributed watershed-scale hydrological model (Neitsch et al., 2011; Douglas-Mankin et al., 2010). The SWAT-modeled hydrological cycle is based on the water balance, as documented by Arnold et al. (1998). SWAT has been widely tested and successfully used to explore the effects of climate and land use/management changes on watershed hydrology and water quality (Nyeko, 2015; Panagopoulos et al., 2011; Gassman et al., 2014; Douglas-Mankin et al., 2010; Zhang et al., 2013; Bosch et al., 2010; Wu and Chen, 2013; Xu et al., 2012; Zhang et al., 2011; Zhang et al., 2008; Qiu et al., 2012). Detailed descriptions of the mechanisms and structure of the SWAT model can be found in several literatures (Neitsch et al., 2011; Arnold et al., 2012).

2.4 Model setup and calibration/validation

A geographic information system (GIS) interface, ArcSWAT (Version 2012.10_2.18), was used to set up the model. ~~A~~ The ~~30-m~~ DEM was used to delineate the watershed, and this process produced 88 subbasins with the threshold area of subbasins set to 50 km^2. Then the land use map of 1990 and soil map were imported and overlaid to create the hydrological response units (HRUs). HRUs are portions of a subbasin that represents unique combinations of land use, soil and slope. To accurately reflect the spatial variability in the basin, multiple ~~hydrological response units (~~HRUs~~)~~ were selected~~.~~, and 1136 HRUs were further defined using a minimum threshold value of 5% for each land use, soil and slope categories. To meet the needs of the model~~was~~

~~used to delineate the basin. With the threshold area of subbasins set to 50 km^2, this process produced 88 subbasins. The land use map of 1990 and soil map were used to parameterize the SWAT model.~~ , the SWAT codes for main land use types in the study area were defined as cropland (AGRR), woodland (FRST), grassland (RNGE), residential land (URBN), barren land (BARR) in the attribute data. The SWAT model was calibrated using monthly streamflow data of Ganguyi hydrological station, and we~~To accurately reflect the spatial variability in the basin, multiple hydrological response units (HRUs) were selected.~~ ~~A single HRU represents a unique combination of land cover, soil type and slope, and 1136 HRUs were established in the basin. We~~ ~~us~~adopted the SWAT-CUP (SUFI-2) ~~module~~ to perform ~~a~~ the sensitivity analysis ~~of~~ for model parameters~~, and the SUFI-2 algorithm was used for optimization~~. The ~~SWAT was calibrated~~calibration was conducted using the first ten-year (1983–1992) record of ~~of monthly~~ streamflow, then the ~~and~~ model was validated using data from the subsequent ~~eight~~ eight-year~~s~~ (1993–2000). Additionally, a three-year warm-up period (1980-1982) was used to minimize the effects of uncertain initial conditions (e.g., soil water storage) in the model simulation. To evaluate the model performance numerically, we used ~~six~~ three statistical measures, including percent bias (PBIAS), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), and the coefficient of determination (squared correlation coefficient, r^2). Typically, a model simulation is considered satisfactory with NSE>0.5, $-25\% \leqslant \text{PBIAS} \leqslant 25\%$, and $r^2>0.5$ (Neupane and Kumar, 2015; Wu and Chen, 2013).

2.5 Modeling scenarios

In this study, we used three land use conditions (land use maps in 1990, 2000 and 2010, corresponding to LU1990, LU2000 and LU2010, respectively) to evaluate the hydrological impacts of past land use changes from 1986 through 2015. To assess the long-term effects of SLC on the hydrological cycle in the Yanhe basin, the land use condition of 2010 was set as the baseline scenario (BS), and four land conversion scenarios were reestablished based on the land use of 2010 and the SLC policy of the GFGP. During the baseline period, the model was driven by the 30 years (1986-2015) of climate data. Then, we established four hypothetical SLC scenarios. Scenario 1 (S1) and scenario 2 (S2) refer to the conversion of ~~farmland~~cropland on slopes steeper than 25° to grassland and woodland, respectively, and scenario 3 (S3) and scenario 4 (S4) assumes that ~~farmland~~cropland on slopes greater than or equal to 15° is converted to grassland and woodland, respectively. The above four scenarios were implemented using the same climate forcing data to isolate the effects of SLC change.

3 Results

3.1 Model performance evaluation

We performed a global sensitivity analysis to examine 18 parameters that are potentially related to streamflow and identified the most sensitive 8 parameters for subsequent model calibration (Table 1). The selected 8 parameters represent key hydrological components such as surface runoff, soil water capacity and conductivity, ET, and groundwater recharge in this region. Although the calibrated model slightly underestimated streamflow, the model performance was satisfactory in the calibration period (1983-1992), with NSE, r^2 and PBIAS values of 0.51, 0.71 and 15.7%, respectively (Fig. 3a). In the 8-year (1993-2000) validation period, the streamflow characteristics were well captured by the calibrated model~~ exhibited good performance~~, with an NSE value of 0.82, although PBIAS still indicated a 16.9% underestimation (Fig. 3b). In both the calibration and validation periods, the underestimation mainly occurred in spring and winter, when little discharge occurs in the watershed. Thus, the model performed poorly during the dry period. ~~Furthermore, a discrepancy can be observed between measured precipitation and streamflow during the dry period because some small peaks in observed streamflow could not have been caused by the observed precipitation amount.~~ ~~The potential reasons for this issue include missing precipitation events due to a limited number of stations or errors in streamflow measurements.~~ Nonetheless, both visual comparison and numerical evaluation indicated that the overall model performance was acceptable for simulating the hydrological processes in the Yanhe basin.

3.2 Land use changes in Yanhe basin from 1990 to 2010

~~Farmland~~Cropland, woodland and grassland were the primary land use types in the Yanhe basin, and rapid land use change occurred from 1990 to 2010 (Table 2). A downward trend was found in ~~Farmland~~cropland~~ exhibited a decreasing trend~~, declining from 40.2% of the basin area in 1990 to 17.6% in 2010~~.~~, while the upward trends were occurred in ~~B~~both grassland and woodland~~ exhibited increasing trends~~, although these trends differed. Grassland increased slowly from 44.7% to 45.3% between 1990 and 2000, followed by a rapid increase from 45.3% to 55.1% between 2000 and 2010. Woodland exhibited an increase of 73.9% from 1990 to 2000 followed by a smaller increase of 7.8% from 2000 to 2010. To identify the details of the land use conversion patterns, we explored the mutual ~~transition~~ conversion between three major land use types—

~~farmland~~cropland, grassland, and woodland (Table 3). The conversion ~~transition~~ of ~~farmland~~cropland to other land use types was observed in the periods of 1990-2000 and 2000-2010, while the conversions of grassland and woodland to other land use types were only evident from 1990-2000. The ~~farmland~~cropland area decreased dramatically from 1990 to 2010 because it was largely converted to woodland and grassland, with conversion percentages of 16.7% and 39.5% from 1990 to 2000 and 6.4% and 33.2% from 2000 to 2010, respectively. Spatially, Fig. 4 shows that the conversions mostly occurred in the central and northwestern parts of the basin from 1990–2000 and were scattered from 2000 to 2010. We also examined the land use conversions over the 20-year periods (1990 to 2010) and found that 19.6% and 54.5% of ~~farmland~~cropland was transformed to woodland and grassland, respectively, indicating evident LULC change due to the implementation of the GFGP policy in the basin (Table 3). Although the percentages of grassland and woodland increased, 20.1% of grassland and 19.5% of woodland were converted into ~~farmland~~cropland from 1990 to 2000. Additionally, mutual conversions were observed between grassland and other land use types, but the total area of grassland changed only slightly from 1990 to 2000. For example, 1204.6 km^2 of ~~farmland~~cropland and 281.5 km^2 woodland were converted into grassland, whereas 762.3 km^2 and 683.2 km^2 of grassland were transformed to woodlands and ~~farmland~~cropland, respectively, in the same period, resulting ~~in a~~the small net change ~~in the net area~~ (Table 3). Additionally, despite the increase in woodland from 1990 to 2010, 12.6% and 31.1% of the woodland from 1990 were converted into ~~farmland~~cropland and grassland, respectively, particular in the southern part of the basin.

3.3 Water balance components under different land use types

To further analyze the quantitative impacts of LULC changes on the hydrological cycle, the main hydrological components of individual land use types were assessed via model simulation. The analysis results indicated that the water balance varied among different land use types in the basin (Fig. 5). The overland surface runoff per unit area from residential land was the highest, with an average value of 58.9 mm, followed by those of cropland and grassland, at 19.2 mm and 9.3 mm, respectively. Woodland ~~exhibited~~ had the lowest surface runoff of 3.7 mm, which was approximately about 80.7% lower than that of cropland and 62.2% lower than that of grassland (Fig. 5a). The water yield from individual land use types ~~exhibited~~ had a trend similar to that of surface runoff. These results implied that the conversions of cropland and grassland to woodland could reduce runoff and streamflow at the regional scale. By contrast, the ET of woodland areas was the highest, followed by those of grassland, cropland, and residential land. With the exception of residential land, the soil water from other land use types exhibited an inverse trend compared with that of ET (cropland > grassland > woodland); thus, woodland areas used more soil water for ET and generated less runoff and streamflow. Fig. 5b shows the total water volumes on the different land use types in the basin. The highest volumes of surface runoff and water yield were associated with cropland because of its large water volume per unit area and large total area in the basin. Grassland had the largest soil water storage and highest ET in the basin. The surface runoff, water yield, soil water, and ET of woodland were the lowest among different land use types, with the exception of residential land, due to the small total area of woodland in 1990.

3.4 Hydrological impacts of historical land use changes

The impacts of land use changes were simulated through applying the model to three land use scenarios (LU1990, LU2000, and LU2010) with the same climate forcing data (from 1986 to 2015). The ~~results showed that~~simulated streamflow at the outlet of the Yanhe basin exhibited a ~~negative responses to land use~~downward trend with land use change~~s~~ from~~between~~ 1990 ~~and~~to 2010, and the magnitude of the ~~decrease~~ reduction under LU2010 was larger than that under LU2000 (Fig. 6a). Further analysis showed that relatively large responses mainly occurred from May to September (Fig. 6b). Table 4 presents the simulated average annual components of the water balance in the Yanhe basin. A decreasing trend was shown in ~~S~~surface runoff ~~generated~~ at the basin scale ~~exhibited a decreasing trend~~ as land use changes occurred from 1990 to 2010, and it decreased by 16.6% in LU2000 and 29% in LU2010. Land use changes had minor effects on subsurface flow, with a slight increase of 1.8% in LU2000 and 2.7% in LU2010 compared with that in LU1990. Similar to the subsurface flow, ET displayed a weak increasing trend in the basin due to land use changes. The water yield in the basin under LU2000 and LU2010 changed in a similar manner as surface runoff, with decreases of 5.6% and 9.9%, respectively, compared with that of LU1990. The soil water decreased by 11% from 1990 to 2010, with a rapid decrease from 1990-2000 and a slow decrease afterward.

The spatial distributions of the main hydrological components at the HRU scale are shown in Fig. 7. The central part of the basin ~~exhibited~~ produced high surface runoff, while most western portion and southern edge of the basin ~~exhibited~~ had little runoff (Fig. 7a and 7e). Additionally, the decreasing trend of surface runoff mainly locat~~occurr~~ed on the middle part of the basin from 1990 to 2010. To further understand the hydrological changes associated with land use change, we analyzed the long-term (30-year) average total water volumes of the main hydrological components (Fig. 8). The results showed that decreases in total surface runoff mainly occurred in cropland areas because of ~~the~~ its decreased area ~~of cropland~~. The associated decreased percentages were 26.8% under LU2000 and 57.3% under LU2010 compared to that of LU1990 (Fig. 8a). Although the total surface runoff generated in grassland and woodland areas increased from LU1990 to LU2010, the total magnitude of these increases could not compensate for the ~~decreasing~~ decrease associated with cropland. Thus, the total surface runoff of the basin decreased. The water yield ~~exhibited~~ displayed a trend similar to that of surface runoff from LU1990 to LU2010 (Fig. 7b and f)—the total water yield decreased by 60.9% in cropland areas and increased by 18.8% and 136.4% on grassland and woodland, respectively. These changes were due to the dramatic conversion of cropland to grassland and woodland between LU1990 and LU2010 (Fig. 8b). Similar to the spatiotemporal trends in the water yield, ET increased under LU2010 compared with that of LU1990 (Fig. 7c and g), whereas it decreased by 58.7% in cropland and increased by 21.4% and 124.0% for grassland and woodland from LU1990 to LU2010, respectively (Fig. 8c). In terms of the spatial distribution of soil water, an evident decrease occurred under LU2010, and the highest decrease occurred in the north-central part of the region (Fig. 7d and h). Although ~~t~~the total soil water increased in woodland ~~exhibited an increasing trend~~ with historic land use change, it was the lowest when compared with the soil water in cropland and grassland areas under the three land use conditions (Fig. 8d).

3.5 Potential impacts of hypothetical SLC

The potential hydrological effects of SLC were projected through inputting four land conversion scenarios that were reconstructed based on the LU2010 baseline (Table 5). The changes in land use in S1 led to the conversion of 131.6 km^2 cropland with slope >25° to grassland, which resulted in slight decreases in surface runoff, water yield and soil water, while a minor increase was found in subsurface flow and ET ~~exhibited minor increase~~. With the same acreage of cropland to woodland conversion in S2, the induced hydrological effects were similar to those in S1, whereas the differences between S2 and the baseline were larger in magnitude than those between S1 and the baseline. When the land conversion was extended to cropland with slope ≥15°, the trends of hydrological change were further strengthened. For example, in S3, grassland increased by 23.9% and 15.3% on land surfaces with slopes of 15°-25° and >25°, resulting in 12.4% and 2.7% decreases in surface runoff and the water yield compared to the baseline. Conversely, the subsurface flow and ET minimally increased by 2.2% and 0.2%, respectively. Although soil water consistently exhibited a negative response, the decrement was small. When the same area of cropland with slope ≥15° was converted to woodland in S4, the surface runoff and water yield decreased by 17.1% and 6.4% compared to the baseline, while subsurface flow and ET ~~exhibited~~ increased by 3.9% and 0.3% ~~increases~~, respectively. Soil water notably changed in S4, decreasing by 6.4% compared with the baseline soil water. Fig. 9 illustrates the spatial response of soil water to land use conversion scenarios compared with the baseline of 2010. Soil water decreases in S4 mainly occurred along the southern edge of the basin and north-central part of the basin, which have a high elevation and slope gradient (Fig. 9d).

4 Discussion

In this study, the SWAT model performance was evaluated on monthly step using streamflow data of the Ganguyi hydrological station. Although the calibrated model slightly underestimated the streamflow in the dry period in both calibration and validation periods, the three statistical indexes (NSE, PBIAS, r^2) indicated that the modelling accuracy was acceptable. The potential reasons for underestimation may be categorized as "measurement quality" and "model behavior". "Measurement quality" refers to the missing precipitation data or streamflow measuring error. The study area belongs to the hilly-gullied loess region, and complex and rugged terrain results in highly variable precipitation and difficulties in spatially estimating the precipitation (Cao et al., 2006). Additionally, this region has limited meteorological and hydrological stations. In this study, there are five meteorological stations, whereas only three stations are located inside the basin and the remaining two are located outside the basin (Fig. 1). It has been reported that the accuracy of the streamflow prediction mainly depends upon the precipitation gage numbers and their locations (Cao et al., 2006; Mul et al., 2009). Thus, the insufficient precipitation records and relatively distant geographical position of meteorological stations resulted in poor streamflow simulation. "Model behavior" refers to the model limitations such as inadequate representation of physical mechanism of hydrological processes. For example, SWAT uses total daily precipitation and does not consider rainfall intensity within a day, thus it can result in underestimation of streamflow for some precipitation events (Qiu et al., 2012). Another example is the use of runoff curve number to simulate the surface runoff behavior, and this does not account for saturation excess runoff or contributions from variable source areas (Garen and Moore, 2005;

Easton et al., 2008).~~The potential reasons for this issue include missing precipitation events due to a limited number of stations or errors in streamflow measurements.~~ Although the simulation results in our research met the calibration criteria, the model performance can be improved further if precipitation from additional gages available in the basin.

~~Farmland~~Cropland, grassland and woodland were the primary land use ~~classes~~ types in the Yanhe basin, and the sum of their area accounted for more than 95% of the total area during our study period. To investigate the effects of land use change and management practices on the water balance, three land use scenarios were assessed using the SWAT model. The contributions of individual land use types to basin hydrology differed. Cropland had highest soil water in our study, and this can be partly attributed to the topography of cropland. The cropland was mainly distributed in the bottom region of the valley or the sloping land with gentle slope. The valley bottom generally receives more water flow from hillslope and have lower temperature, resulting in more soil water (Wang et al., 2012), and gentle sloping area had higher soil water retention ability compared with steep sloping area (Panagopoulos et al., 2011). Besides, the cropland had lower evapotranspiration per unit area compared with other land use types. In contrast, grassland had lower soil water, and this can be because grassland had higher soil water loss through evapotranspiration. Wang et al. (2012) reported that grass cover types cannot protect the soil surface from solar radiation, leading to greater water loss via direct evaporation. ~~Compared to cropland, g~~Grassland and woodland areas were generally associated with ~~reduced~~ lower surface runoff and~~ decreases in the~~ water yield of the basin, particularly woodland. This result is consistent with those of previous studies, which showed that woodland areas capture~~s~~ more rainfall and uptake more water than do other land use types (e.g., cropland and grassland) (Jian et al., 2015; Wang et al., 2012), resulting in a ~~reduced~~lower runoff ~~,~~and water discharge (Wang et al., 2013; Duan et al., 2016). ~~Additionally,~~ Qiao et al. (2017) reported that woody plant reduces runoff compared with grassland is associated with shift in runoff generation mechanisms, thus the shift from saturation excess overland flow to infiltration excess overland flow might be the another reason. Additionally, ~~w~~woodland areas might ~~lost~~lose more water through ET compared to other vegetation types. This trend was demonstrated by the change in soil water, exhibiting less soil water on the woodland at same precipitation compared to the trends in other areas. Less ~~In addition, another possible explanation for the low~~ soil water ~~volumes in~~on woodland ~~areas~~ was ~~that~~ because forests in the Yanhe basin generally grew on landform with high slopes~~. O~~, and our analysis indicated that more than 62% of woodland was located on slopes ≥15° (Table 5). Steeper slopes generally retain less soil water due to low infiltration ~~rates~~ and rapid surface drainage (Famiglietti et al., 1998). Thus, a large amount of precipitation was associated with forest growth and ET rather than discharge out of the basin as surface runoff and streamflow. Such water patterns prevent water loss but at the expense of reduced soil water in the region.

After the implementation of the GFGP, the area of cropland decreased continuously because it was transformed into grassland and woodland from 1990 to 2010, and the conversions among land use types were the main forms of land use change in the Yanhe basin. These results are consistent with previous findings regarding trends in land use change on the Loess Plateau (Li et al., 2016). We compared monthly and annual average streamflow under three land use scenarios, and the results showed that the decreased average monthly streamflow in the rainy season is the primary mechanism for the decrease in annual average streamflow in the basin. In addition, we found that the decrease in surface runoff was the main reason for the streamflow decrease in the basin, and our quantitative evaluation suggested that surface runoff decreased by 29.1% due to land use change from 1990 to 2010. A similar conclusion was drawn by Farley et al. (2005), who studied 26 watersheds globally to assess the hydrological effect of afforestation and found that annual runoff was reduced by 31-44% on average. Notably, the average annual volume of soil water ~~exhibited~~ presented an evident decrease under the 2010 land use scenario. This trend may be due to two interrelated reasons. First, the area of cropland decreased dramatically in 2010, while cropland ~~exhibited~~ was characterized by the highest soil water volume per unit area relative to other land use types (Fig. 5a), leading to the large decrease in soil water. Second, a certain proportion of cropland was converted to grassland and woodland, which had the lowest soil water per unit area; thus, the soil water decreased due to the cropland area reduction, and this decrease could not be offset by increases in total soil water in grassland and woodland areas (Fig. 8). Although the area of woodland peaked in 2010, the total soil water in woodland areas only slightly increased. Th~~is trend could have occurred~~e main reason for this phenomenon might be that ~~because~~ more water was consumed by woodland than cropland and grassland. Additionally, cropland areas with high slopes were converted to woodland after the GFGP was implemented (Zhou et al., 2012), whereas areas with steep slopes have lower soil moisture retention potentials than areas with gentle slopes (Pachepsky et al., 2001). Thus, topographical factors also played important roles in the spatial heterogeneity of the water balance (Qiu et al., 2001; Bi et al., 2008).

Four future SLC scenarios were proposed to demonstrate the hydrological effects of land use changes. Increase in grassland

and woodland cover due to the land conversion of cropland with slopes ≥15° or >25° had negative effects on surface runoff, the water yield and soil water, whereas subsurface flow and ET increased. We found that the magnitudes of the hydrological effects of the conversion of ~~sloped~~sloping cropland to woodland were greater than those associated with the conversion of ~~sloped~~sloping cropland to grassland. This result suggests that the expansion of woodland could reduce runoff generation and drainage because of overland flow retention and intensification of ET in this region. However, the revegetated sloping land was prone to reduced soil moisture due to its steep slope. Some studies have reported that revegetation can cause soil water shortages in both the near-surface soil and deep soil layers (Farley et al., 2005; Jian et al., 2015), likely resulting in soil desiccation (Wang et al., 2011; Fu et al., 2012). Therefore, watershed management should consider all water balance components (Duan et al., 2016), and vegetative structure and management measures should be optimized to improve the ecohydrological functions and promote the watershed sustainability.

5 Conclusions

In this study, we ~~investigated the land use changes from 1990 to 2010 based on a transition analysis. C~~found that cropland, grassland and woodland were the dominant land use types in the Yanhe basin, and land use conversion occurred among these types since 1990 due to the implementation of the GFGP. The decrease in cropland led to increase in grassland and woodland. The impacts of LULC changes on the water balance components were assessed quantitatively using the SWAT model and three periods of land use maps and four hypothetical SLC scenarios based on the GFGP policy on the Loess Plateau. Our analysis showed that cropland was associated with the highest surface runoff and water discharge per unit area, followed by grassland and woodland. These differences can partly explain the relationships between hydrological characteristics and land use change at the basin scale. Surface runoff and water yield ~~exhibited~~ decreas~~ing trends~~ed due to land use changes from 1990 to 2010, while subsurface flow and ET increased. Consequently, soil water decreased between 2000 and 2010. By adopting four cropland land conversion scenarios, we found that the function of reducing surface runoff was more effective when cropland~~s~~ with slopes ≥15° were converted into grassland or woodland compared to converting areas with slopes >25°. Furthermore, ~~planting wood~~afforestation on sloping land had greater hydrological effects than did planting grass. Notably, surface runoff and soil water decreased and ET increased. Overall, this study provides useful information for land use planning and soil and water conservation on the Loess Plateau, and further studies are required to investigate the optimization of the vegetative structure and the avoidance of undesired hydrological effects.

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References

Alkama, R., Marchand, L., Ribes, A., and Decharme, B.: Detection of global runoff changes: results from observations and CMIP5 experiments, Hydrology and Earth System Sciences, 17, 2967-2979, 10.5194/hess-17-2967-2013, 2013.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R.: Large area hydrologic modeling and assessment - Part 1: Model development, Journal of the American Water Resources Association, 34, 73-89, 10.1111/j.1752-1688.1998.tb05961.x, 1998.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., van Griensven, A., Van Liew, M. W., Kannan, N., and Jha, M. K.: SWAT: Model use, calibration, and validation, Transactions of the ASABE, 55, 1491-1508, 2012.

Bari, M., and Smettem, K. R. J.: Modelling monthly runoff generation processes following land use changes: groundwater-surface runoff interactions, Hydrology and Earth System Sciences, 8, 903-922, 2004.

Bi, H., Zhang, J., Zhu, J., Lin, L., Guo, C., Ren, Y., Yun, L., and Ma, N.: Spatial dynamics of soil moisture in a complex terrain in the semi-arid Loess Plateau region, China, Journal of the American Water Resources Association, 44, 1121-1131, 10.1111/j.1752-1688.2008.00236.x, 2008.

Bloeschl, G., Ardoin-Bardin, S., Bonell, M., Dorninger, M., Goodrich, D., Gutknecht, D., Matamoros, D., Merz, B., Shand, P., and Szolgay, J.: At what scales do climate variability and land cover change impact on flooding and low flows?, Hydrological Processes, 21, 1241-1247, 10.1002/hyp.6669, 2007.

Bosch, D. D., Arnold, J. G., Volk, M., and Allen, P. M.: Simulation of a low-gradient coastal plain watershed using the SWAT landscape model, Transactions of the ASABE, 53, 1445-1456, 2010.

Cao, W. Z., Bowden, W. B., Davie, T., and Fenemor, A.: Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability, Hydrological Processes, 20, 1057-1073, 10.1002/hyp.5933, 2006.

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, 10.5194/hess-19-3633-2015, 2015.

Chen, H., Shao, M., and Li, Y.: Soil desiccation in the Loess Plateau of China, Geoderma, 143, 91-100, http://dx.doi.org/10.1016/j.geoderma.2007.10.013, 2008.

Chen, L., Huang, Z., Gong, J., Fu, B., and Huang, Y.: The effect of land cover/vegetation on soil water dynamic in the hilly area of the loess plateau, China, Catena, 70, 200-208, 10.1016/j.catena.2006.08.007, 2007.

Chu, H.-J., Lin, Y.-P., Huang, C.-W., Hsu, C.-Y., and Chen, H.-Y.: Modelling the hydrologic effects of dynamic land-use change using a distributed hydrologic model and a spatial land-use allocation model, Hydrological Processes, 24, 2538-2554, 10.1002/hyp.7667, 2010.

Douglas-Mankin, K. R., Srinivasan, R., and Arnold, J. G.: Soil and water assessment tool (SWAT) model: current developments and applications, Transactions of the ASABE, 53, 1423-1431, 2010.

Duan, L. X., Huang, M. B., and Zhang, L. D.: Differences in hydrological responses for different vegetation types on a steep slope on the Loess Plateau, China, Journal of Hydrology, 537, 356-366, 10.1016/j.jhydrol.2016.03.057, 2016.

Easton, Z. M., Fuka, D. R., Walter, M. T., Cowan, D. M., Schneiderman, E. M., and Steenhuis, T. S.: Re-conceptualizing the soil and water assessment tool (SWAT) model to predict runoff from variable source areas, Journal of Hydrology, 348, 279-291, 10.1016/j.jhydrol.2007.10.008, 2008.

Famiglietti, J. S., Rudnicki, J. W., and Rodell, M.: Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas, Journal of Hydrology, 210, 259-281, http://doi.org/10.1016/S0022-1694(98)00187-5, 1998.

Farley, K. A., Jobbagy, E. G., and Jackson, R. B.: Effects of afforestation on water yield: a global synthesis with implications for policy, Glob. Change Biol., 11, 1565-1576, 10.1111/j.1365-2486.2005.01011.x, 2005.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lu, Y., Zeng, Y., Li, Y., Jiang, X., and Wu, B.: Revegetation in China's Loess Plateau is approaching sustainable water resource limits, Nature Climate Change, 6, 1019-+, 10.1038/nclimate3092, 2016.

Fu, W., Huang, M., Gallichand, J., and Shao, M.: Optimization of plant coverage in relation to water balance in the Loess Plateau of China, Geoderma, 173–174, 134-144, http://doi.org/10.1016/j.geoderma.2011.12.016, 2012.

Garen, D. C., and Moore, D. S.: Curve number hydrology in water quality modeling: Uses, abuses, and future directions, Journal of the American Water Resources Association, 41, 377-388, 10.1111/j.1752-1688.2005.tb03742.x, 2005.

Gassman, P. W., Sadeghi, A. M., and Srinivasan, R.: Applications of the SWAT Model Special Section: Overview and Insights, Journal of Environmental Quality, 43, 1-8, 10.2134/jeq2013.11.0466, 2014.

Guo, Z. T., Ruddiman, W. F., Hao, Q. Z., Wu, H. B., Qiao, Y. S., Zhu, R. X., Peng, S. Z., Wei, J. J., Yuan, B. Y., and Liu, T. S.: Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China, Nature, 416, 159-163, 10.1038/416159a, 2002.

Huang, M. B., Zhang, L., and Gallichand, J.: Runoff responses to afforestation in a watershed of the Loess Plateau, China, Hydrological Processes, 17, 2599-2609, 10.1002/hyp.1281, 2003.

Jian, S. Q., Zhao, C. Y., Fang, S. M., and Yu, K.: Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau, Agricultural and Forest Meteorology, 206, 85-96, 10.1016/j.agrformet.2015.03.009, 2015.

Lørup, J. K., Refsgaard, J. C., and Mazvimavi, D.: Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe, Journal of Hydrology, 205, 147-163, http://dx.doi.org/10.1016/S0168-1176(97)00311-9, 1998.

Li, J. J., Li, Z., and Lu, Z. M.: Analysis of spatiotemporal variations in land use on the Loess Plateau of China during 1986-2010, Environmental Earth Sciences, 75, 10.1007/s12665-016-5807-y, 2016.

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, Journal of Hydrology, 377, 35-42, 10.1016/j.jhydrol.2009.08.007, 2009.

Liang, W., Bai, D., Wang, F. Y., Fu, B. J., Yan, J. P., Wang, S., Yang, Y. T., Long, D., and Feng, M. Q.: 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, 10.1002/2014wr016589, 2015.

Liu, J., Li, S., Ouyang, Z., Tam, C., and Chen, X.: Ecological and socioeconomic effects of China's policies for ecosystem services, Proceedings of the National Academy of Sciences of the United States of America, 105, 9477-9482, 10.1073/pnas.0706436105, 2008a.

Liu, M., Tian, H., Chen, G., Ren, W., Zhang, C., and Liu, J.: Effects of land-use and land-cover change on evapotranspiration and water yield in China during 1900-2000, Journal of the American Water Resources Association, 44, 1193-1207, 10.1111/j.1752-1688.2008.00243.x, 2008b.

Liu, M., Tian, H., Yang, Q., Yang, J., Song, X., Lohrenz, S. E., and Cai, W.-J.: Long-term trends in evapotranspiration and runoff over the drainage basins of the Gulf of Mexico during 19012008, Water Resources Research, 49, 1988-2012, 10.1002/wrcr.20180, 2013.

Liu, Y., Xiao, J., Ju, W., Xu, K., Zhou, Y., and Zhao, Y.: Recent trends in vegetation greenness in China significantly altered annual evapotranspiration and water yield, Environmental Research Letters, 11, 10.1088/1748-9326/11/9/094010, 2016.

Lopez-Moreno, J. I., Vicente-Serrano, S. M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., and Garcia-Ruiz, J. M.: Impact of climate evolution and land use changes on water yield in the ebro basin, Hydrology and Earth System Sciences, 15, 311-322, 10.5194/hess-15-311-2011, 2011.

McVicar, T. R., Li, L., Van Niel, T. G., Zhang, L., Li, R., Yang, Q., Zhang, X., Mu, X., Wen, Z., Liu, W., Zhao, Y. A., Liu, Z., and Gao, P.: Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau, Forest Ecology and Management, 251, 65-81, http://dx.doi.org/10.1016/j.foreco.2007.06.025, 2007.

McVicar, T. R., Van Niel, T. G., Li, L., Wen, Z., Yang, Q., Li, R., and Jiao, F.: Parsimoniously modelling perennial vegetation suitability and identifying priority areas to support China's re-vegetation program in the Loess Plateau: Matching model complexity to data availability, Forest Ecology and Management, 259, 1277-1290, http://dx.doi.org/10.1016/j.foreco.2009.05.002, 2010.

Mul, M. L., Savenije, H. H. G., and Uhlenbrook, S.: Spatial rainfall variability and runoff response during an extreme event in a semi-arid catchment in the South Pare Mountains, Tanzania, Hydrology and Earth System Sciences, 13, 1659-1670, 2009.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R.: Soil and water assessment tool theoretical documentation version 2009, Texas Water Resources Institute, 2011.

Nyeko, M.: Hydrologic modelling of data scarce basin with SWAT model: capabilities andl imitations, Water Resources Management, 29, 81-94, 10.1007/s11269-014-0828-3, 2015.

Pachepsky, Y. A., Timlin, D. J., and Rawls, W. J.: Soil water retention as related to topographic variables, Soil Science Society of America Journal, 65, 1787-1795, 10.2136/sssaj2001.1787, 2001.

Panagopoulos, Y., Makropoulos, C., Baltas, E., and Mimikou, M.: SWAT parameterization for the identification of critical diffuse pollution source areas under data limitations, Ecological Modelling, 222, 3500-3512, http://dx.doi.org/10.1016/j.ecolmodel.2011.08.008, 2011.

Qiao, L., Zou, C. B., Stebler, E., and Will, R. E.: Woody plant encroachment reduces annual runoff and shifts runoff mechanisms in the tallgrass prairie, USA, Water Resources Research, 53, 4838-4849, 10.1002/2016WR019951, 2017.

Qiu, L. J., Zheng, F. L., and Yin, R. S.: SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges, International Journal of Sediment Research, 27, 226-234, 2012.

Qiu, Y., Fu, B. J., Wang, J., and Chen, L. D.: Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China, Journal of Hydrology, 240, 243-263, 10.1016/s0022-1694(00)00362-0, 2001.

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S. G., and Vose, J. M.: Potential water yield reduction due to forestation across China, Journal of Hydrology, 328, 548-558, 10.1016/j.jhydrol.2005.12.013, 2006.

Tian, F., Lu, Y., Fu, B., Yang, Y., Qiu, G., Zang, C., and Zhang, L.: Effects of ecological engineering on water balance under two different vegetation scenarios in the Qilian Mountain, northwestern China, Journal of Hydrology: Regional Studies, 5, 324-335, 10.1016/j.ejrh.2015.11.015, 2016.

Wang, L., Wang, Q., Wei, S., Shao, M. a., and Li, Y.: Soil desiccation for Loess soils on natural and regrown areas, Forest

Ecology and Management, 255, 2467-2477, http://dx.doi.org/10.1016/j.foreco.2008.01.006, 2008.

Wang, S., Fu, B. J., Gao, G. Y., Yao, X. L., and Zhou, J.: Soil moisture and evapotranspiration of different land cover types in the Loess Plateau, China, Hydrology and Earth System Sciences, 16, 2883-2892, 10.5194/hess-16-2883-2012, 2012.

Wang, S., Fu, B., Gao, G., Liu, Y., and Zhou, J.: Responses of soil moisture in different land cover types to rainfall events in a re-vegetation catchment area of the Loess Plateau, China, Catena, 101, 122-128, http://doi.org/10.1016/j.catena.2012.10.006, 2013.

Wang, Y., Shao, M. a., Zhu, Y., and Liu, Z.: Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China, Agricultural and Forest Meteorology, 151, 437-448, http://doi.org/10.1016/j.agrformet.2010.11.016, 2011.

Wei, W., Chen, L. D., Zhang, H. D., and Chen, J.: Effect of rainfall variation and landscape change on runoff and sediment yield from a loess hilly catchment in China, Environmental Earth Sciences, 73, 1005-1016, 10.1007/s12665-014-3451-y, 2015.

Wu, Y., and Chen, J.: Analyzing the water budget and hydrological characteristics and responses to land use in a monsoonal climate river basin in south China, Environmental Management, 51, 1174-1186, 10.1007/s00267-013-0045-5, 2013.

Xu, Y. D., Fu, B. J., He, C. S., and Gao, G. Y.: Watershed discretization based on multiple factors and its application in the Chinese Loess Plateau, Hydrology and Earth System Sciences, 16, 59-68, 10.5194/hess-16-59-2012, 2012.

Yang, L., Wei, W., Chen, L., Chen, W., and Wang, J.: Response of temporal variation of soil moisture to vegetation restoration in semi-arid Loess Plateau, China, Catena, 115, 123-133, http://dx.doi.org/10.1016/j.catena.2013.12.005, 2014.

Zhang, G.-h., Tang, M.-k., and Zhang, X. C.: Temporal variation in soil detachment under different land uses in the Loess Plateau of China, Earth Surface Processes and Landforms, 34, 1302-1309, 10.1002/esp.1827, 2009.

Zhang, X., Srinivasan, R., Debele, B., and Hao, F.: Runoff simulation of the headwaters of the Yellow River using the SWAT model with three snowmelt algorithms, Journal of the American Water Resources Association, 44, 48-61, 10.1111/j.1752-1688.2007.00137.x, 2008.

Zhang, X., Srinivasan, R., Arnold, J., Izaurralde, R. C., and Bosch, D.: Simultaneous calibration of surface flow and baseflow simulations: a revisit of the SWAT model calibration framework, Hydrological Processes, 25, 2313-2320, 10.1002/hyp.8058, 2011.

Zhang, X., Izaurralde, R. C., Arnold, J. G., Williams, J. R., and Srinivasan, R.: Modifying the Soil and Water Assessment Tool to simulate cropland carbon flux: Model development and initial evaluation, Science of the Total Environment, 463–464, 810-822, https://doi.org/10.1016/j.scitotenv.2013.06.056, 2013.

Zhao, G., Mu, X., Wen, Z., Wang, F., and Gao, P.: Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China, Land Degradation & Development, 24, 499-510, 10.1002/ldr.2246, 2013.

Zhen, N., Fu, B., Lü, Y., and Zheng, Z.: Changes of livelihood due to land use shifts: A case study of Yanchang County in the Loess Plateau of China, Land Use Policy, 40, 28-35, http://dx.doi.org/10.1016/j.landusepol.2013.05.004, 2014.

Zhou, D., Zhao, S., and Zhu, C.: The Grain for Green Project induced land cover change in the Loess Plateau: A case study with Ansai County, Shanxi Province, China, Ecological Indicators, 23, 88-94, 10.1016/j.ecolind.2012.03.021, 2012.

Zucco, G., Brocca, L., Moramarco, T., and Morbidelli, R.: Influence of land use on soil moisture spatial-temporal variability and monitoring, Journal of Hydrology, 516, 193-199, 10.1016/j.jhydrol.2014.01.043, 2014.

Zuo, D., Xu, Z., Yao, W., Jin, S., Xiao, P., and Ran, D.: Assessing the effects of changes in land use and climate on runoff and sediment yields from a watershed in the Loess Plateau of China, Science of the Total Environment, 544, 238-250, 10.1016/j.scitotenv.2015.11.060, 2016.

Table 1 Sensitive parameters for streamflow simulation and calibrated values

Parameters	Description	Range	Optimized value/ Percent change
CN2	Soil conservation service (SCS) runoff curve number	-20%~20%	-4.03%^{r}
SOL_AWC	Soil available water capacity	-20%~20%	10.71%^{r}
SOL_K	Soil saturated hydraulic conductivity (mm/h)	-20%~20%	7.36%^{r}
ESCO	Soil evaporation compensation factor	0~1	0.51^{v}
EPCO	Plant uptake compensation factor	0~1	0.65^{v}
ALPHA_BF	Baseflow alpha factor (day)	0~0.5	0.36^{v}
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	100~1200	906.20^{v}
SURLAG	Surface runoff lag coefficient	0.05~6	2.93^{v}
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	100~1200	499.40^{v}

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

Table 2 The land use changes in the Yanhe basin from 1990 to 2010

	~~Farmland~~Cropland		Grassland		Woodland		Residential land		Water		Barren land	
	Area (km^2)	~~Ratio~~Pct. (%)	Area (km^2)	~~Ratio~~Pct. (%)	Area (km^2)	~~Ratio~~Pct. (%)	Area (km^2)	~~Ratio~~Pct. (%)	Area (km^2)	~~Ratio~~Pct. (%)	Area (km^2)	~~Ratio~~Pct. (%)
1990	3051.2	40.2	3390.4	44.7	1059.6	13.9	21.4	0.28	65.4	0.86	3.1	0.040
2000	2246.4	29.6	3436.3	45.3	1842.4	24.3	43.9	0.58	17.2	0.23	0.7	0.009
2010	1338.3	17.6	4178.7	55.1	1986.3	26.2	66.4	0.87	16.6	0.22	0.5	0.006

Table 3 The primary patterns of land use ~~transition~~ change in the Yanhe basin from 1990 to 2010

	1990-2000		2000-2010		1990-2010	
	Area (km^2)	~~Ratio~~Pct. (%)	Area (km^2)	~~Ratio~~Pct. (%)	Area (km^2)	~~Ratio~~Pct. (%)
~~Farmland~~Cropland to woodland	509.2	16.7	143.6	6.4	598.5	19.6
~~Farmland~~Cropland to grassland	1204.6	39.5	745.4	33.2	1661.8	54.5
~~Farmland~~Cropland to residential land	15.9	0.5	20.7	0.9	28.5	0.9
~~Farmland~~Cropland to barren land	0.3	0.0	0.0	0.0	0.1	0.0
Grassland to woodland	762.3	22.5	0.6	0.0	796.7	23.5
Grassland to ~~farmland~~cropland	683.1	20.1	1.5	0.0	410.4	12.1
Grassland to residential land	7.1	0.2	0.6	0.0	10.4	0.3
Grassland to barren land	0.4	0.0	0.0	0.0	0.3	0.0
Woodland to ~~farmland~~cropland	206.5	19.5	0.0	0.0	133.8	12.6
Woodland to grassland	281.5	26.6	0.0	0.0	330.1	31.1
Woodland to residential land	5.2	0.5	0.5	0.0	9.4	0.9
Woodland to barren land	0.0	0.0	0.0	0.0	0.0	0.0
Barren land to woodland	0.2	7.4	0.0	0.0	0.2	7.4
Barren land to grassland	0.8	25.9	0.0	0	1.0	31.7
Barren land to ~~farmland~~cropland	2. 0	65.1	0.0	0.0	1.7	54.6
Barren land to residential land	0.0	0.0	0.0	0.0	0.2	6.4

Table 4 Simulated average annual values of hydrological components in the Yanhe basin under different land use conditions

	Surface runoff (mm)	Subsurface flow (mm)	ET (mm)	Water yield (mm)	Soil water (mm)
LU1990	15.1	22.2	461.8	37.3	123.0
LU2000	12.6	22.6	464.5	35.2	113.1
LU2010	10.7	22.8	466.5	33.6	109.5

Table 5 Slope characteristics of each land use type in 2010 and slope land conversion scenarios (unit: km^2)

		~~Farmland~~Cropland	Woodland	Grassland	Residential land	Barren land
LU2010	<15°	814.3	761.2	1677.7	52.5	0.3
	15°~25°	392.7	808.4	1640.8	10.8	0.1
	>25°	131.6	417.3	860.9	3.2	0.0
S1	<15°	—	—	—	—	—
	15°~25°	—	—	—	—	—
	>25°	0	417.3	992.5	3.2	0.0
S2	<15°	—	—	—	—	—
	15°~25°	—	—	—	—	—
	>25°	0	548.9	860.9	3.2	0.0
S3	<15°	—	—	—	—	—
	15°~25°	0	808.4	2033.5	10.8	0.1
	>25°	0	417.3	992.5	3.2	0.0
S4	<15°	—	—	—	—	—
	15°~25°	0	1201.0	1640.8	10.8	0.1
	>25°	0	548.9	860.9	3.2	0.0

Note: '—' represents the same value as that of LU2010.

Table 6 Simulated average annual values of hydrological components under different scenarios of slope land conversion

	Surface runoff (mm)	Subsurface flow (mm)	ET (mm)	Water yield (mm)	Soil water (mm)
S1	10.4	22.9	466.8	33.3	109.0
S2	10.3	23.0	466.9	33.2	107.7
S3	9.37	23.3	467.6	32.7	107.5
S4	8.87	23.7	467.8	32.6	102.5

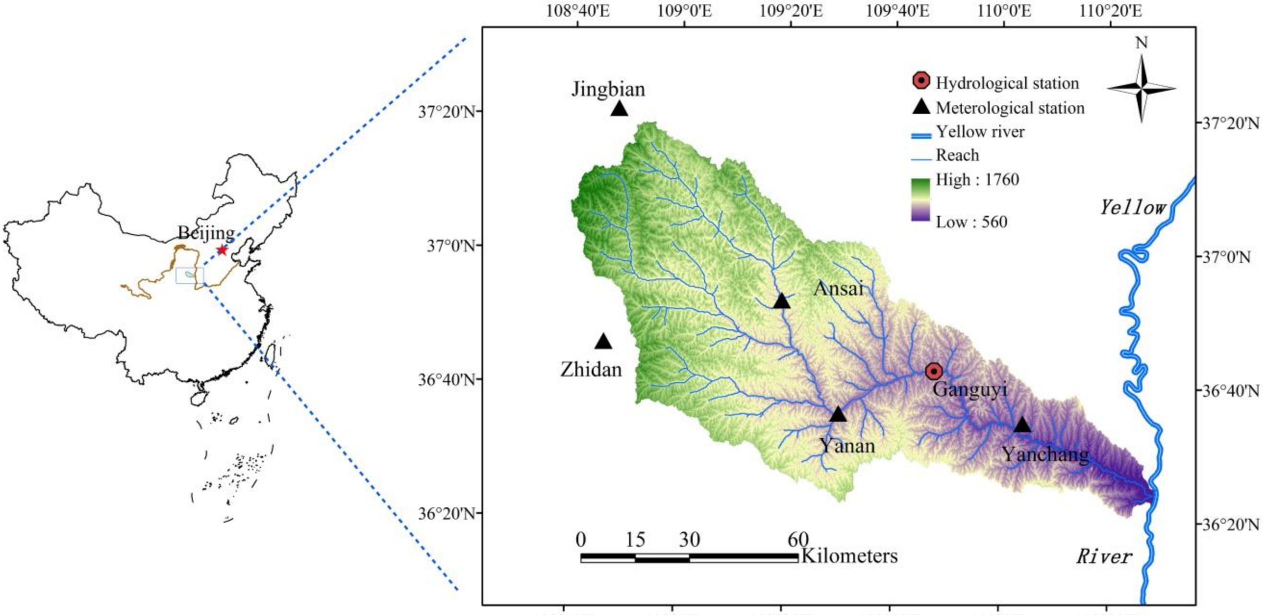

Fig. 1 Map of the location and elevation of the Yanhe basin with the distribution of hydrological station

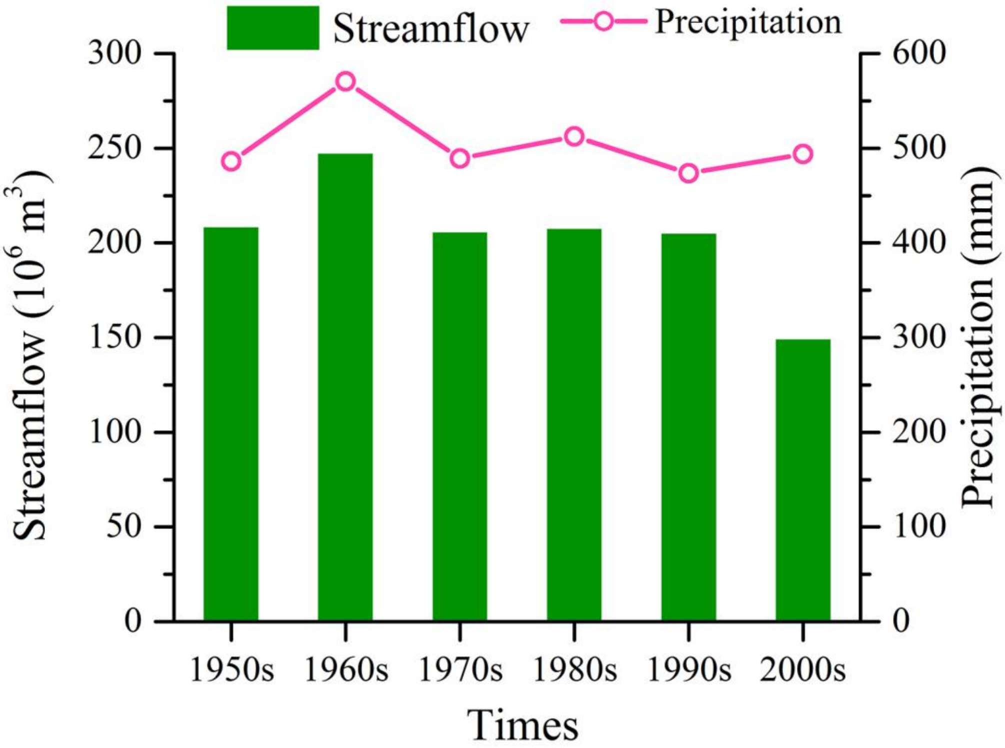

Fig. 2 Precipitation and streamflow changes during different decades in the Yanhe basin

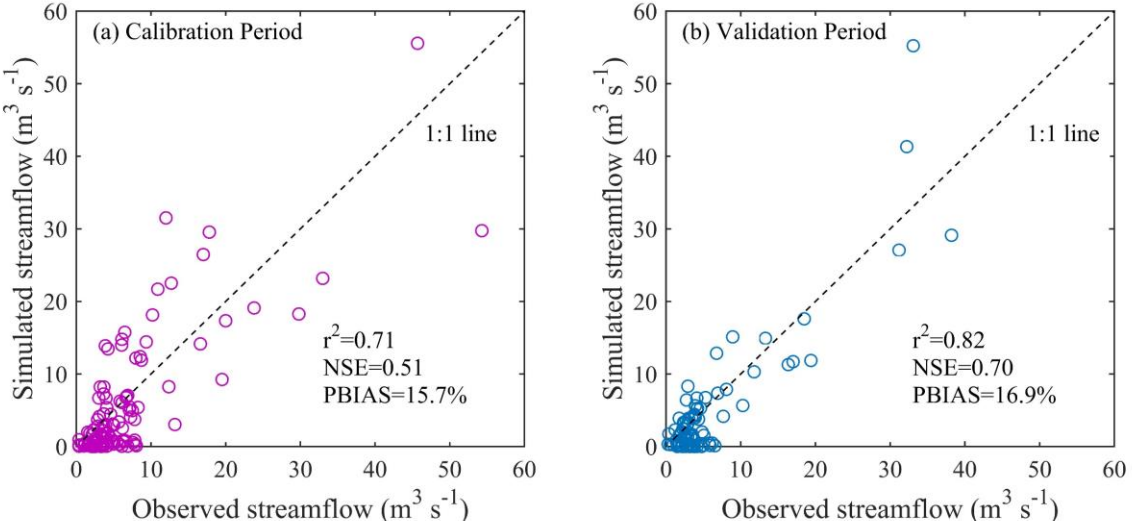

Fig. 3 The model performance in the (a) 10-year (1983-1992) calibration period and (b) 8-year (1993-2000) validation period

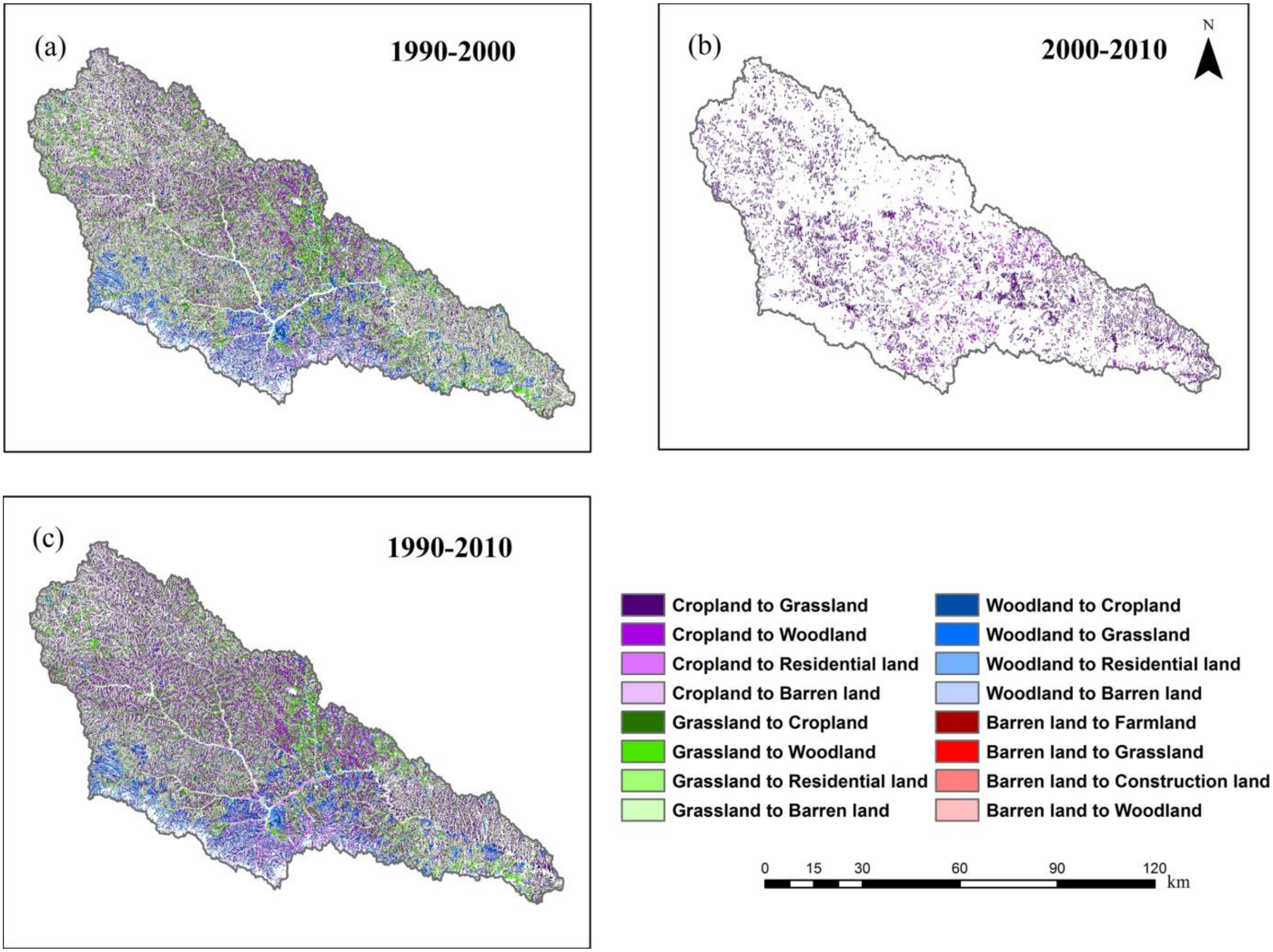

Fig. 4 Land use ~~transitions~~ change from 1990 to 2010 in the Yanhe basin ~~from 1990 to 2010~~

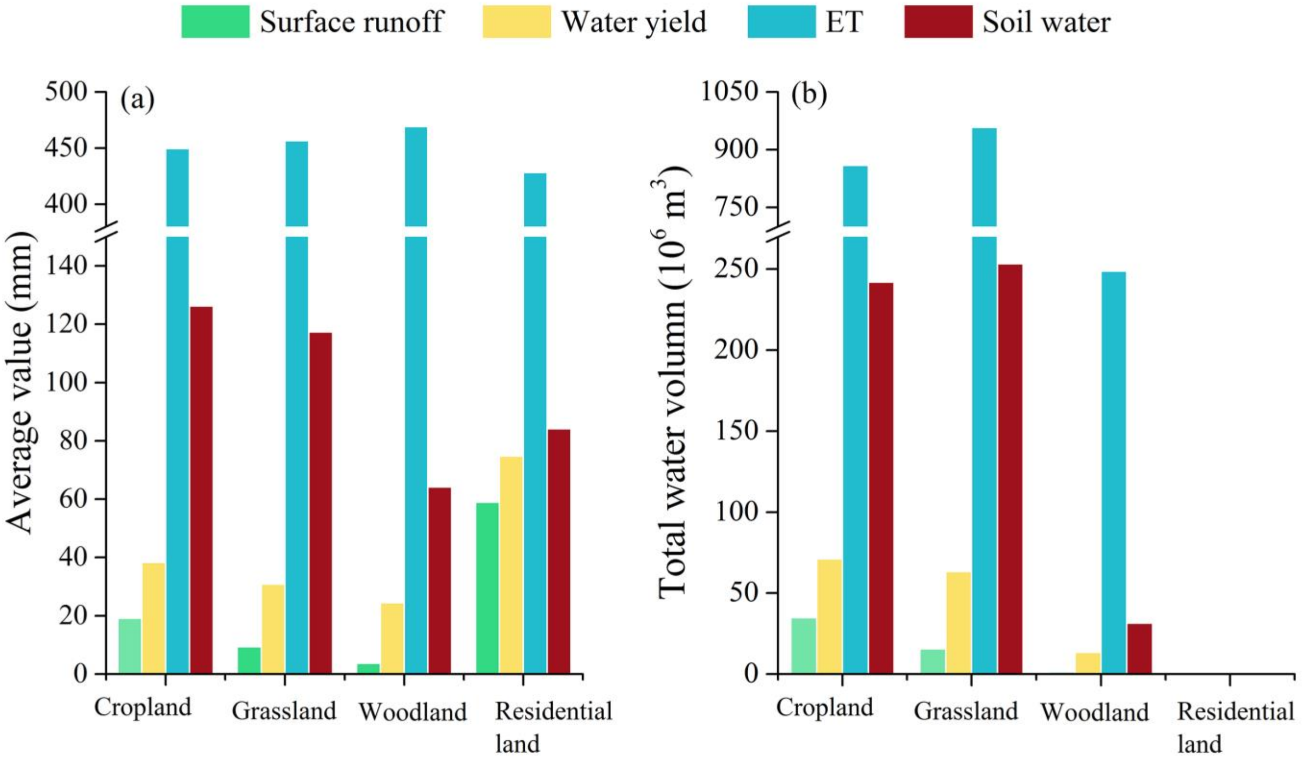

Fig. 5 Calculated a) unit area and (b) total annual hydrological components in the 18-year simulation period (1983-2000) for different land use types in the Yanhe basin

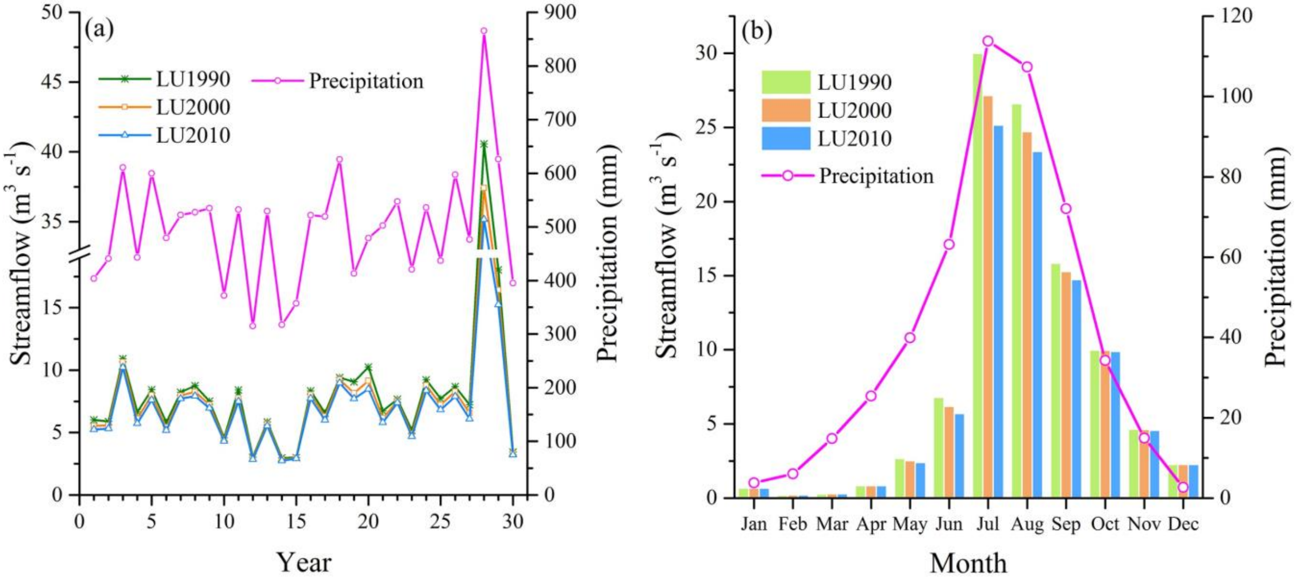

Fig. 6 (a) Simulated annual streamflow and (b) simulated multiyear average monthly streamflow (the data were averaged from1986 to 2015) at the outlet of the Yanhe basin under different land use conditions

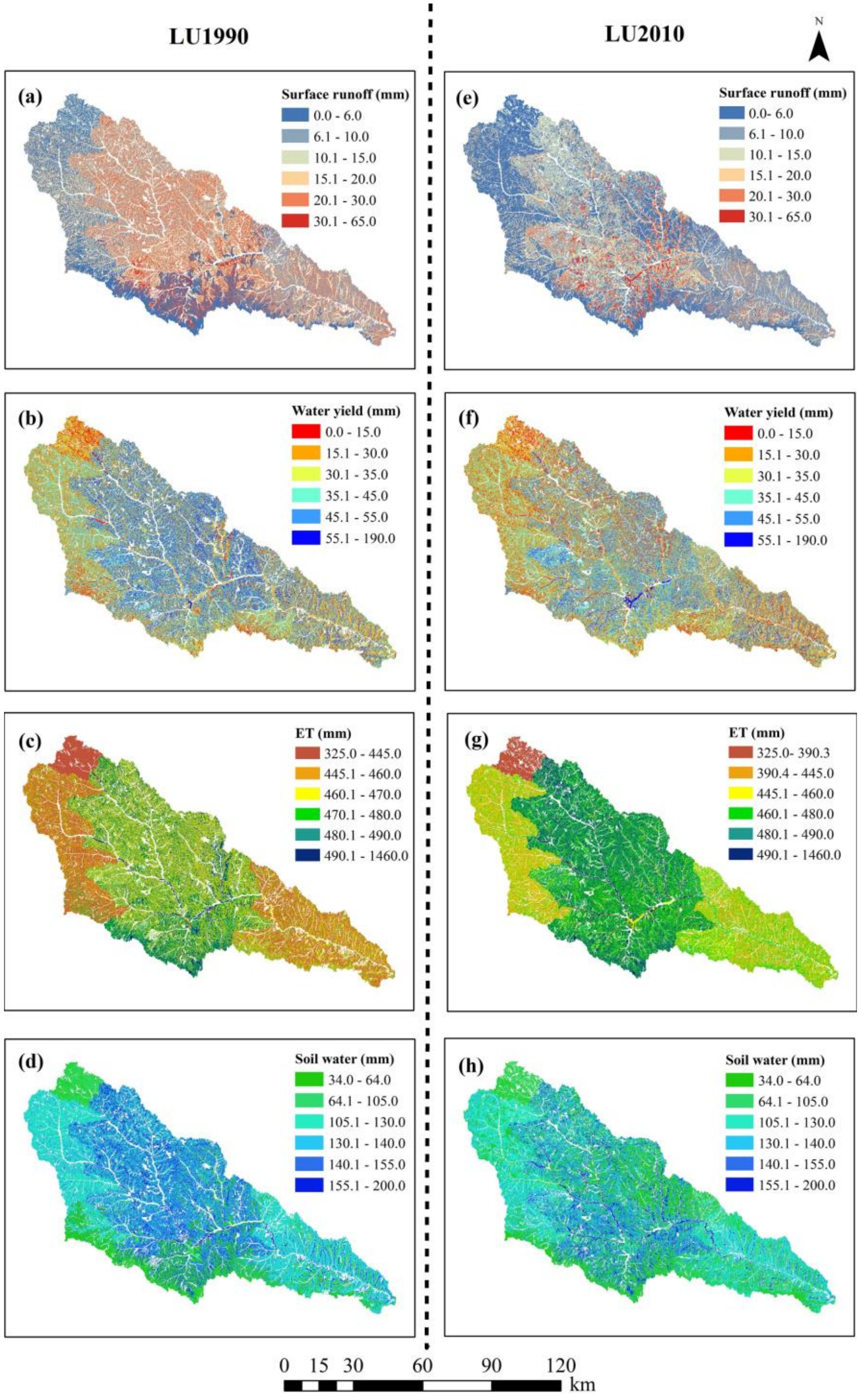

Fig. 7 Simulated spatial distribution of (a) surface runoff, (b) water yield, (c) ET and (d) soil water under land use change between 1990 and 2010

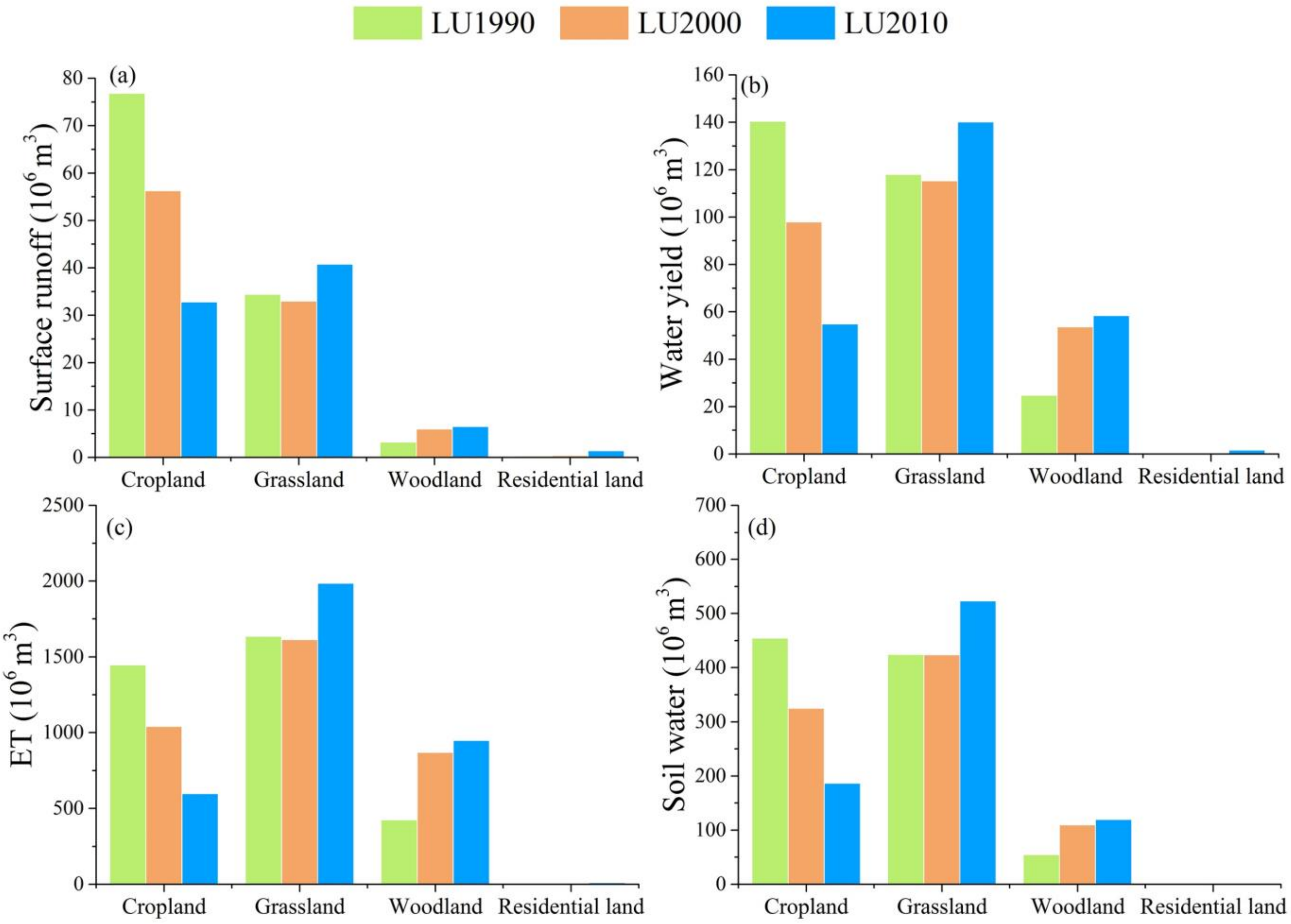

Fig. 8 Calculated average annual total water volume under different land use scenarios

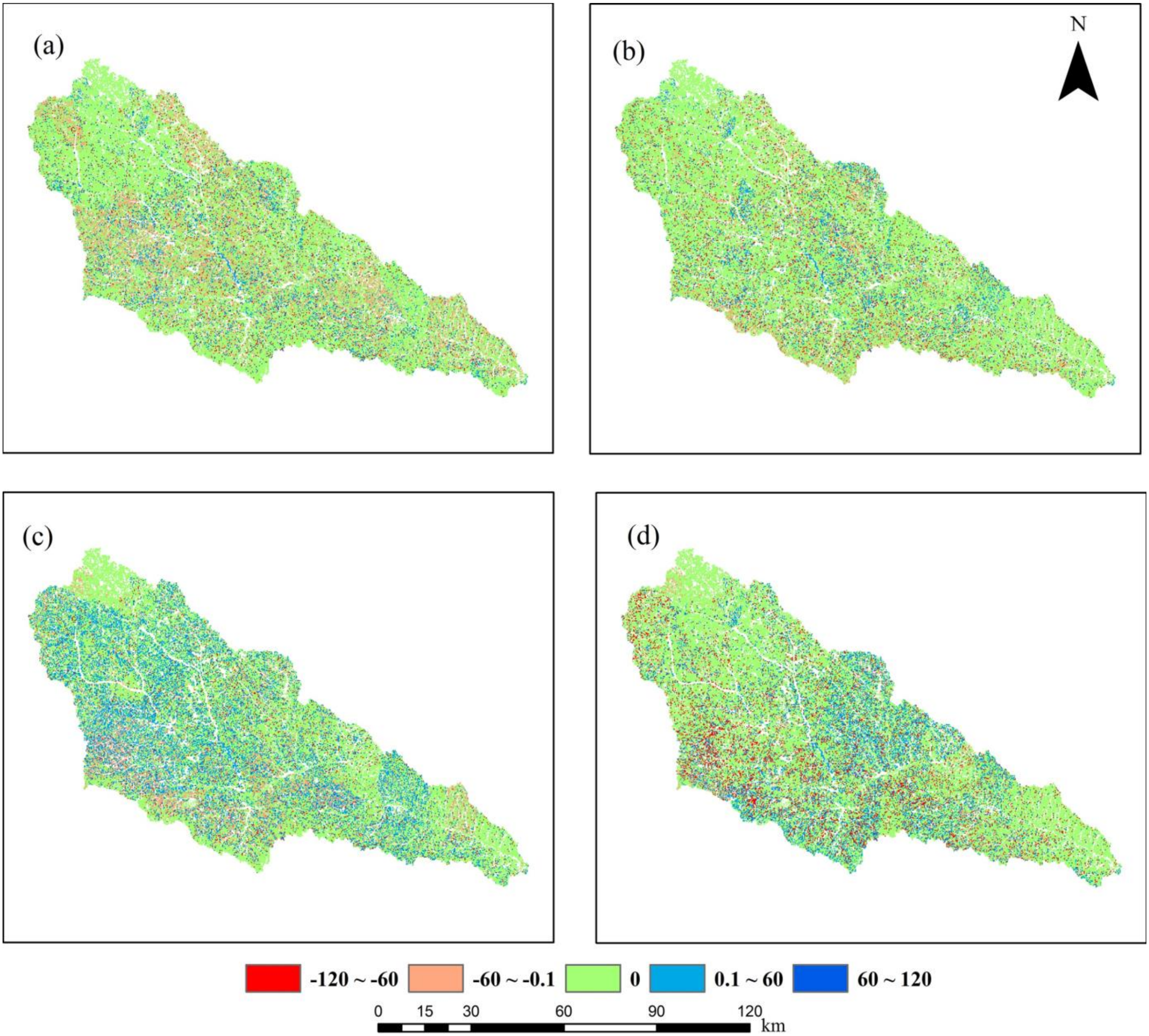

Fig. 9 Calculated soil water difference between the baseline scenario and a) S1, (b) S2, (c) S3 and (d) S4