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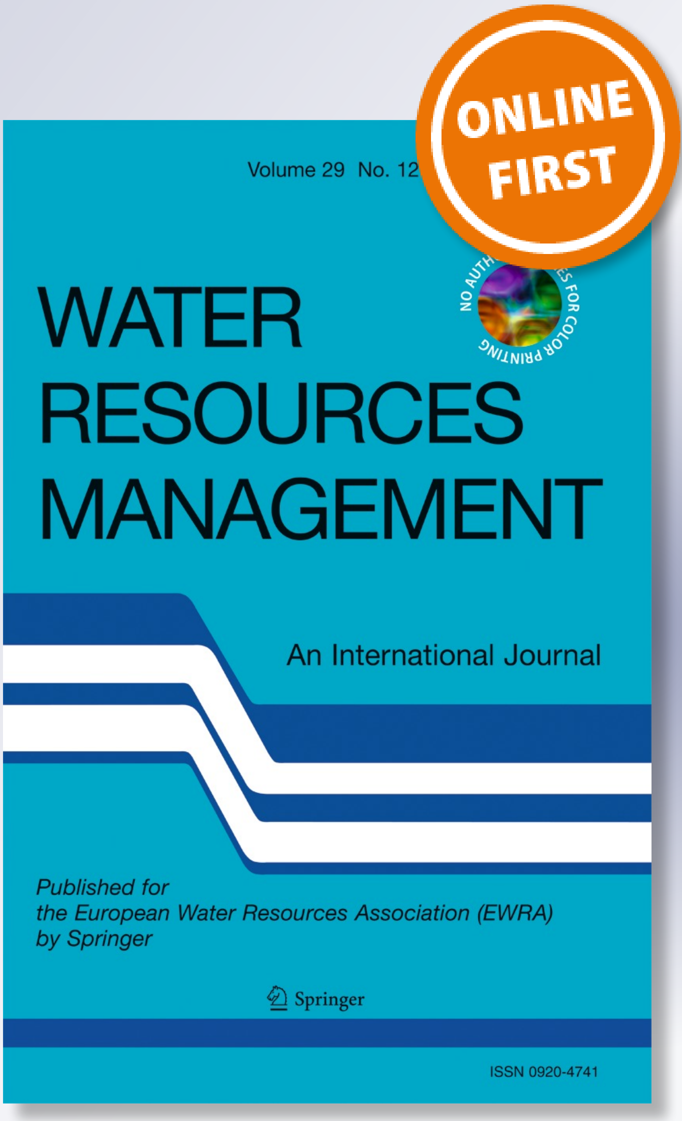
Water Resources Management
An International Journal - Published for the European Water Resources Association (EWRA)

ISSN 0920-4741

Water Resour Manage
DOI 10.1007/s11269-015-1085-9



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Modeling Land-Use and Land-Cover Change and Hydrological Responses under Consistent Climate Change Scenarios in the Heihe River Basin, China

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Received: 4 September 2014 / Accepted: 2 August 2015

Abstract This study investigated land-use and land-cover change (LUCC) and hydrological responses under consistent climate change scenarios (A1B and B1) in the Heihe River Basin (HRB), a typical arid inland river basin in northwest China. LUCC was first projected using the Dynamic Conversion of Land-Use and its Effects (Dyna-CLUE) model. Two cases (Case 1 and Case 2) were then established to quantify the hydrological responses to single climate change and the combined responses to climate change and LUCC with the Soil and Water Assessment Tool (SWAT). The results of LUCC modeling under the A1B and B1 scenarios present distinct regional characteristics and also indicate that the projected future land-use patterns are not appreciably different than the actual map for the year 2000. In Case 1, which only considers the impacts of single climate change, overall, the streamflow at the outlet of the upper HRB is projected to decline, whereas at the outlet of the middle HRB to increase, under both climate change scenarios. Meanwhile, the frequency of occurrence of hydrological extremes is expect to increase under both scenarios. In Case 2, which considers the combined impacts of climate change and LUCC, the changes in streamflow and frequency of hydrological extremes are found to be remarkably consistent with those in Case 1. The results imply that climate change rather than LUCC are primarily responsible for the hydrological variations. The role of LUCC varies with regions in the context of climate change dominated hydrological responses.

Keywords LUCC · Hydrological responses · Climate change · Heihe River Basin · SWAT

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Published online: 14 August 2015

1 Introduction

The observation of temperature increase, extensive snow and ice melting, and sea level rising over the past several decades demonstrates that climate change is undoubtedly a real phenomenon (Rahman et al. 2012). Climate change, which has been recognized as one of the 21st century's most important environmental issues, has a significant impact on hydrology, ecology, agriculture and social-economical systems (Tanzeeba and Gan 2012). Recently, the impact of climate change on hydrological circle has been widely investigated, e.g., Feng et al. (2011), Perazzoli et al. (2013), Xu et al. (2013) and Ashraf Vaghefi et al. (2014). It can be concluded that climate change affects the hydrological cycle profoundly, causing the redistribution of water resources in time and space. In addition to climate change, land-use and land-cover change (LUCC) is another important factor influencing the hydrological behaviors of catchments (Hurkmans et al. 2009; Viola et al. 2014). Several studies have reported on hydrological responses to LUCC with the assumption of constant climatic conditions (e.g. Wijesekara et al. 2012; Baker and Miller 2013; Zhou et al. 2013; Viola et al. 2014). It is found that LUCC plays a key role in controlling the hydrological processes in these studies.

The impacts of climate change and LUCC on hydrological regimes are actually theoretically interlinked and therefore cannot be separated completely (Tong et al. 2012). The combined responses to climate change and LUCC have also been extensively investigated (e.g. Park et al. 2011; Tong et al. 2012; Kim et al. 2013; Shi et al. 2013; Khoi and Suetsugi 2014). However, there are conflicting results regarding how the hydrological responses would be affected when climate change and LUCC are simultaneously considered. Park et al. (2011) and Tong et al. (2012) reported that the combined hydrological responses would be enhanced, which appeared to be opposite to the findings of Shi et al. (2013) and Khoi and Suetsugi (2014). Meanwhile, Kim et al. (2013) showed that the combined responses would be remarkably similar to the responses to single climate change. In this context, more case studies are needed to improve the understanding of combined responses to climate change and LUCC. Moreover, very little research on the combined hydrological responses that considers consistent climate change and LUCC scenarios, where LUCC scenarios are consistent with the specific assumptions of climate change scenarios.

Statistical analysis, paired catchments approach and hydrologic modeling can be employed to assess the hydrological effects of climate change and LUCC (Zhang et al. 2012; Shi et al. 2013). However, the use of the first two methods are often restricted because of strict requirements for long-term observed data and the selection of similar catchments (Elfert and Bormann 2010; Shi et al. 2013). Instead, hydrologic models, especially spatially distributed models, such as Soil and Water Assessment Tool (SWAT), are frequently employed to determine the hydrological impacts of climate change and LUCC.

The Heihe River Basin (HRB) is the second largest inland river basin in the arid region of northwest China (Fig. 1). It has been suffering from a series of water problems which heavily impeded the basin's socioeconomic development and ecological health (Zhang et al. 2015). Thus, sustainable water planning and management is urgently needed for the HRB. However, climate change and LUCC as well as their impacts on hydrological circle have posed vital challenges to local authorities and stake-holders in their aspiration to better harness water resources (Park et al. 2011). An improved understanding of hydrological responses to climate change and LUCC therefore has significant implications for sustainable water development. Based on long-term observed data, many researchers have studied the hydrological impacts of climate change in the HRB through statistical analysis (e.g. Zhang et al. 2007; Wang and Zhang 2010; Nian et al. 2014). However, few studies have investigated the combined

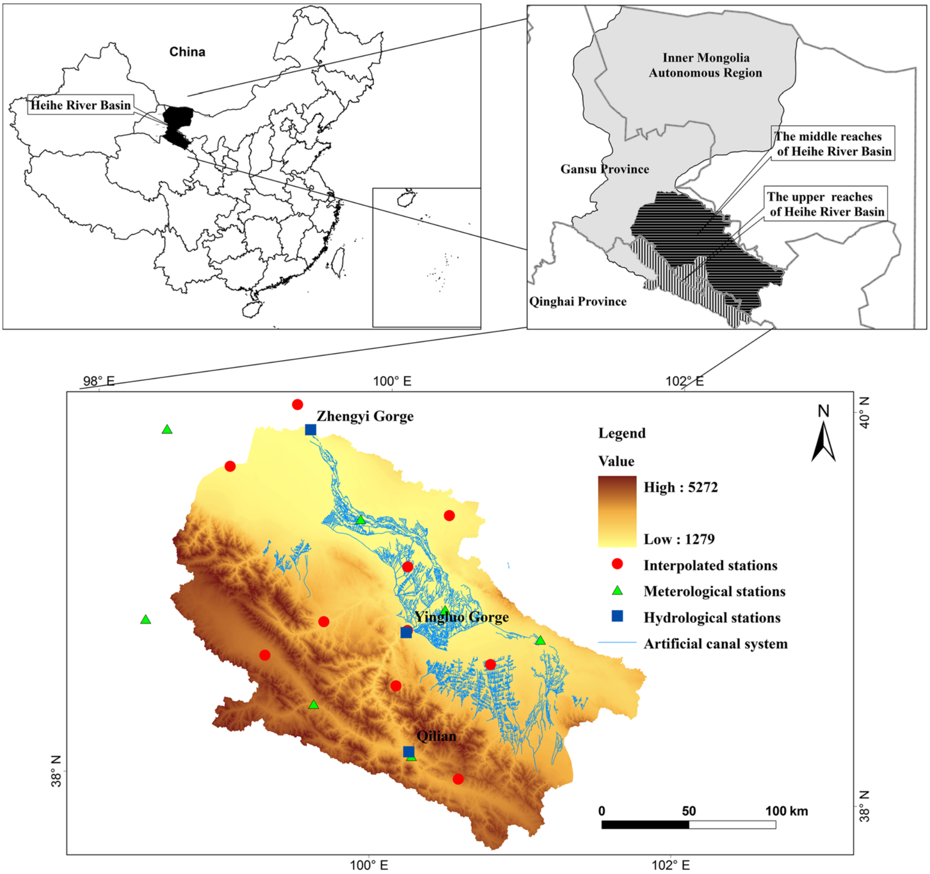

Fig. 1 Location of the study area

hydrological responses to climate change and LUCC, which should be very important because the HRB shares similar water problems as the other arid inland river basins across the world.

Taken the upper and middle HRB as the study area, this study primarily aims to (i) project future land use patterns under climate change scenarios (A1B and B1); (ii) quantify the hydrological responses to single climate change (Case 1), i.e., the changes in streamflow and frequency of hydrologic extremes, and (iii) the combined responses to climate change and LUCC (Case 2) under the A1B and B1 scenarios. The findings of this study can provide useful information for improving water resource management in the HRB as well as other inland river basins with similar characteristics.

2 Materials and Methods

2.1 Study Area

The Heihe River Basin (HRB), which lies between 98° and 101°30’ E and 38°and 42° N, drains an area of approximately 128,000 km^2 and expands across three provinces from south to north, i.e., Qinghai, Gansu and Inner Mongolia. The basin includes three sections: the upper, the middle, and the lower HRB. The upper and middle reaches (Fig. 1) extend from Qilian Mountains to Zhengyi Gorge. As a primary runoff-contributing area, the upper HBR is characterized by mountainous terrains from Qilian Mountains to Yingluo Gorge. The elevations range 2,000–5,500 m; the main vegetation types include alpine forest and grassland; the mean annual precipitation is 250–500 mm; and the mean annual evaporation is approximately 700 mm (Wang and Zhang 2010). As a primary water-consuming area, the middle HRB is characterized by plain oasis extending from Yingluo Gorge to Zhengyi Gorge. The elevations range 1,000–2,000 m; the main vegetation type is artificially planted vegetation; the mean annual precipitation decreases from 250 to 50 mm from south to north; and the annual potential evaporation changes northwards from 2,000 to 4,000 mm (Wang and Zhang 2010). The plain oasis, known as an important grain-producing region in northwestern China, is a highly developed irrigation agriculture zone with an agriculture history of about 2000 years. To effectively utilize and manage available, yet limited water resources, an intensive and advanced artificial canal system for irrigation has been constructed in the plain oasis.

2.2 Dyna-CLUE Model

Land use change modelling was performed using the Dynamic Conversion of Land-Use and its Effects (Dyna-CLUE) model (Verburg and Overmars 2009). The model includes a non-spatial demand module and a spatially explicit allocation module. The non-spatial module calculates the area demands for all land-use types at an aggregate level and the allocation module translates these demands into land use changes at different locations within the study area (Verburg et al. 2002).

The Dyna-CLUE model requires five types of inputs, i.e., land-use demands, location suitability, neighborhood suitability, spatial restrictions and conversion parameters. The land-use demands, which were estimated by trend extrapolation in this study, determine the overall competitiveness of each land-use type (Verburg et al. 2006). The location suitability for each land-use type was estimated by a stepwise logistic regression based on the relations between land use and its driving factors (Verburg et al. 2002). Twelve driving factors including elevation, slope, aspect, soil type, distances to nearest road, to nearest railway, to nearest river, to nearest reservoir, and to nearest residential area, GDP per land area, GDP per capita and population density, were selected. The neighborhood suitability was also determined by a stepwise logistic regression based on the relations between land-use and its enrichment factors (Verburg et al. 2004). The spatial restrictions define areas that are not allowed to change during the simulation period, which include forest and grassland areas with slopes exceeding 25% in compliance with China’s laws. The conversion parameters are composed of conversion elasticity and conversion matrix. The conversion elasticity, which determine the stability of a land use type, were set to 0.8, 0.6, 0.6, 0.9, 1 and 0.4 for cultivated land, forest, grassland, water, built-up land and unused land, respectively, through an error and trail procedure. The conversion matrix is used to describe the possibility of conversions between two land-use types. Conversions from built-up land to any other land-use types and from any other types to water body were restricted.

The land-use data and driving factors used in this study were collected from the Scientific Data Center in Cold and Arid Regions (http://westdc.westgis.ac.cn) and the Statistical Yearbooks of Gansu and Qinghai Province. The land-use data include the land use/cover datasets for the whole HRB in 1986 and 2000. In those datasets, the land-use types were reclassified into six primary types: cultivated land, forest, grassland, water body, built-up land and unused land. The driving data were derived from digital elevation model (DEM) data and maps of roads, railways, reservoirs, rivers and residential areas.

2.3 SWAT Model

Hydrological modelling was performed using the Soil and Water Assessment Tool (SWAT) model. The model was designed to predict the impacts of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soil, land-use and management conditions over long periods (Neitsch et al. 2011). The inputs required for SWAT include DEM, land-use and land-cover data, soil and meteorological data. The meteorological data, including daily precipitation, maximum temperature, minimum temperature, wind speed, relative humidity and solar radiation, were collected from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn/). All other data were obtained from the Scientific Data Center in Cold and Arid Regions. Ten sites (see Fig. 1) with varying elevations were chosen and then interpolated their precipitation using a tool referred to as meteorological distribution system for high-resolution terrestrial modeling (MicroMet) (Liston and Elder 2006). Precipitation at these sites together with that at the real meteorological stations were input to SWAT in hope of better capturing the precipitation distribution in the study area. Considering the impacts of the artificial canal system across the middle HRB, irrigation parameters and the infiltration equations, were adjusted by referring to the work of Lai et al. (2013).

In this study, the SWAT model was first calibrated using the observed streamflow at the Yingluo Gorge (1990–1999) and the Zhengyi Gorge (2000–2004) stations. The model was then validated during the period 2000–2008 at the Qilian station, 2000–2009 at the Yingluo Gorge station and 2005–2009 at the Zhengyi Gorge station. Streamfow data were available at the Scientific Data Center in Cold and Arid Regions. Four metric types, i.e., Nash-Sutcliff efficiency (NSE) (Nash and Sutcliffe 1970), the coefficient of determination (R^2) (Shi et al. 2011), mean absolute error (MAE) and root mean square error (RMSE) (Reusser et al. 2009) were used to fully assess the model's performance.

2.4 Modeling LUCC under Climate Change Scenarios

Two emission scenarios (also known as climate change scenarios), namely A1B and B1, of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SERS) were selected in this study. The A1B scenario (medium emission) describes a future word of very rapid economic growth while the B1 scenario (low emission) describes a convergent world with the same global population growth as in the A1B scenario, but with rapid changes in economic structures toward environmental protection.

The land-use demands of the study area under the A1B and B1 scenarios were set according to the Asian Pacific Integrated Model (AIM) simulation data of 2000–2100 (Morita 1999) in the ASIAP (China and central planned Asia, South and East Asia) region, one of the five regions modelled by AIM. Specifically, the demands for cultivated land, forest and grassland were assumed to follow the projected trends of the corresponding land types, whereas the demand for built-up land was assumed to follow the population trend. Moreover, the area of water body was assumed to be constant after 2000, and the remaining area of the study area was assigned to unused land. Future land-use patterns under the A1B and B1 scenarios were then projected using the Dyna-CLUE model.

2.5 Modeling Hydrological Responses under Climate Change Scenarios

Climatic projections of a general circulation model (GCM), Hadley Centre Coupled Model version 3 (HadCM3), under the A1B and B1 scenarios were selected in this study for its good performance in China (Xu et al. 2002). The basic information about HadCM3 is presented in Table 1. Due to its inherent coarse resolution, a downscaling process is essential for a regional or watershed scale application (Xu 1999). The Delta downscaling method was adopt in this study for its simplicity and advantage of being stable and robust (Boyer et al. 2010). This method has been widely used in the climate change impact studies (Park et al. 2011; Tanzeeba and Gan 2012; Ashraf Vaghefi et al. 2014; Khoi and Suetsugi 2014). Two meteorological variables, namely temperature and precipitation, were downscaled as their changes are primary controlling factors for watershed-scale hydrological processes (Tanzeeba and Gan 2012), in particular in the arid inland river basin. The change fields of mean monthly precipitation (relative change) and mean monthly temperature (absolute change) centered on two 20-year periods (1980–1999, 2011–2030) of HadCM3 were collected from the Data Distribution Centre of IPCC (http://www.ipcc-data.org/). These changes were then employed to adjust the observed data (1980–1999) at the meteorological stations within and around the upper and middle HRB to generate the 2011–2030 climate scenarios.

In this study, two cases were established to quantify the hydrological responses to single climate change and the combined responses to both climate change and LUCC. Meanwhile, a baseline scenario was introduced to serve as a reference scenario assuming that the climate regime will be kept at the level of 1990–2009 and land use at the level of 2000.

Case 1: Hydrological Responses to Single Climate Change The meteorological data (precipitation and temperature) from 2011 to 2030 were assumed to be the projections of HadCM3 and all other inputs and parameters were kept same as those in the baseline scenario. Paired T-tests were performed to compare the simulated results of two time-slices (1980–1999, 2011–2030), for which the meteorological data are mutually corresponding. The target level of significance was α=0.05.

Case 2: Combined Hydrologic Responses to Climate Change and LUCC Both the land-use maps (2015, 2020, 2025 and 2030) and the meteorological data were assumed to be the projections and all other inputs and parameters remained the same as those in the baseline scenario.

Table 1 Basic information about HadCM3

Model	Center, country	Key reference	Vertical resolution	Horizontal resolution	
				Longitude	Latitude
HadCM3	Meteorological Office, UK	Gordon et al. (2000)	19 levels	3.75°	2.50°

3 Results

3.1 Precipitation and Temperature Projections

The precipitation and temperature here refer to the areal precipitation and temperature, interpolated using the Thiessen polygon method. Compared with the baseline scenario, the mean annual precipitation is projected to increase by 33.35 mm and 13.21 mm, respectively, for the time period 2011–2030 under the A1B and B1 scenarios in the entire upper and middle HRB. An increasing trend is also predicted under both scenarios for the mean annual temperature. The results imply a wetter and warmer climate in the near future in the study area, which is in line with the historical trend (Zhang et al. 2012) and the projected trend reported by Wu et al. (2014b).

The projected changes in mean monthly precipitation and temperature relative to the baseline scenario in the upper and the middle HRB are presented in Fig. 2. In the upper HRB, mean precipitation is projected to decrease while mean temperature is anticipated to increase in most months under both climate change scenarios. In the middle HRB, an increase trend of precipitation can be found in most months, especially in June and September, under both scenarios. The changing trends in temperature in the upper and the middle HRB are similar under both scenarios, while they are quite different in precipitation as shown in the left panel of Fig. 2. The inconsistency of precipitation change is possibly closely linked to the difference of geographical characteristics and climatic conditions between the upper and the middle HRB, as well as the uncertainty involved in precipitation projections (Li et al. 2012; Chen et al. 2015). Such inconsistency can also be found in other studies, e.g., Jung and Chang (2011), Xu et al. (2013) and Kopytkovskiy et al. (2015).

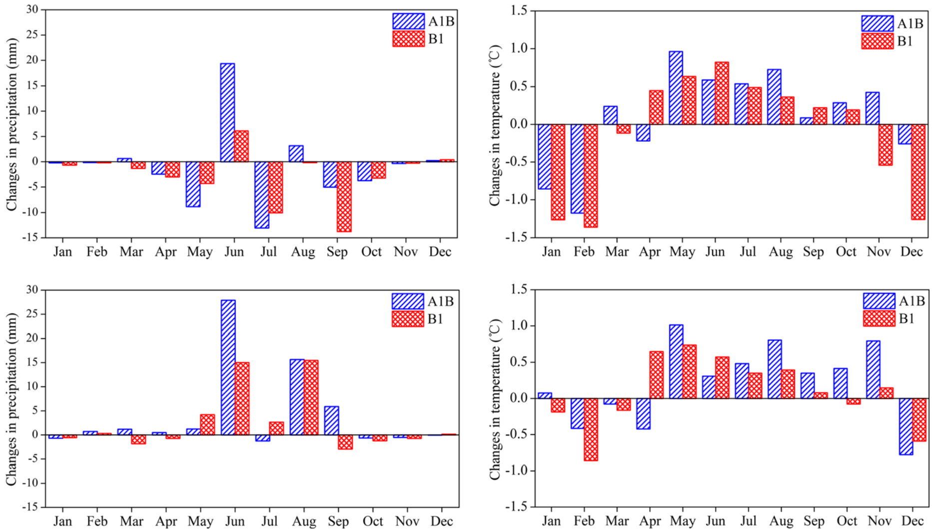

Fig. 2 Changes in mean monthly precipitation (*left*) and temperature (*right*) under the A1B and B1 scenarios in the upper HRB (*top*) and the middle HRB (*bottom*)

3.2 Model Calibration and Validation

The SWAT model was calibrated and validated before using it for scenario simulation. The model evaluation statistics for simulated monthly streamflow at three hydrological stations were summarized in Table 2. At the Yingluo Gorge station which is the outlet of the upper HRB, NSE and R^2 are 0.86 and 0.92, respectively, during the calibration period, and 0.88 and 0.86 during the validation period. As shown in Fig. 3, the simulated streamflow matches well with the observed records. The relatively low agreements from March to May in most years can be explained by the significant impacts of snowmelt and permafrost during this period. At the Zhengyi Gorge station which is the outlet of the middle HRB, NSE and R^2 are 0.63 and 0.69, respectively, during the calibration period and 0.60 and 0.72, respectively, during the validation period. The lower accuracy there is closely related to the complex irrigation canal system across the middle HRB. The validation at the Qilian station shows good performance as well. The RMSE and MAE at all stations are estimated to range from 6.81 to 17.5 m^3/s and 4.94 to 12.15 m^3/s, respectively. Overall, it can be concluded that the SWAT model performs satisfactorily in the study area according to the criteria set by Moriasi et al. (2007).

3.3 LUCC Under Climate Change Scenarios

Figure 4 depicts the actual (2000) and simulated land-use patterns (2015, 2020, 2025 and 2030) in the upper and middle HRB under the A1B scenario. Compared with the actual map for the year 2000, the projected land-use patterns for different years under the A1B scenario are not appreciably different because the changed area of each land-use type is very small relative to the entire study area. Similar results can be found under the B1 scenario. The absolute and relative changes of each land-use type in the upper, the middle and the upper and middle HRB between 2000 and 2030 under the A1B and B1 scenarios are listed in Table 3. The results indicate that LUCC varies with regions in terms of change trend and magnitude. For example, the area of cultivated land shows an increasing trend in the upper HRB but a decreasing trend in the middle HRB under the same scenario. The forest area is found to increase by 1,323 hectares in the upper HRB but by 10,602 hectares in the middle HRB under the A1B scenario. Compared with the A1B scenario, the area of ecological lands, i.e., forest, grassland and water body, is anticipated to be larger under B1, probably due to its emphasis on environmental protection.

Table 2 Model evaluation statistics for simulated monthly streamflow at three hydrological stations in the study area

Metric type	Calibration		Validation		
	Yingluo Gorge (1990–1999)	Zhengyi Gorge (2000–2004)	Yingluo Gorge (2000–2009)	Qilian (2000–2008)	Zhengyi Gorge (2005–2009)
R^2	0.92	0.69	0.88	0.82	0.72
NSE	0.88	0.63	0.85	0.68	0.60
RMSE (m^3/s)	15.32	13.94	17.35	6.81	17.30
MAE (m^3/s)	11.32	10.67	13.74	4.94	12.15

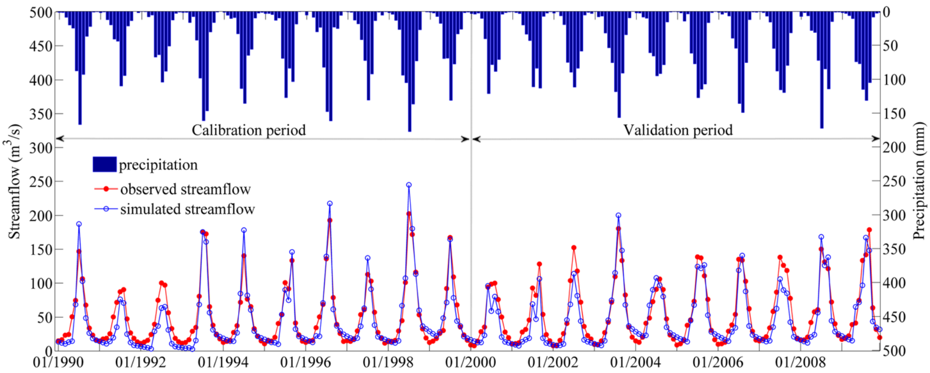

Fig. 3 Observed and simulated monthly streamflow during the calibration and validation periods at the Yingluo Gorge station

3.4 Case 1: Hydrological Responses to Single Climate Change

The top panel of Fig. 5 depicts the changes in mean monthly, seasonal and annual streamflow relative to the baseline scenario at the Yingluo Gorge station, the outlet of the upper HRB, caused by single climate change. Under the A1B scenario, the streamflow is projected to increase in June, August and September by 3.55 to 28.78% and decrease in other months by 1.89 to 24.93%. Under the B1 scenario, however, it is expect to decrease in all months by 0.77 to 28.56%. Except for the summer under the A1B scenario, streamflow shows a decreasing trend in other seasons under both scenarios. Overall, the projected streamflow changes at the outlet of the mountainous upper HRB are basically consistent with those reported by Li

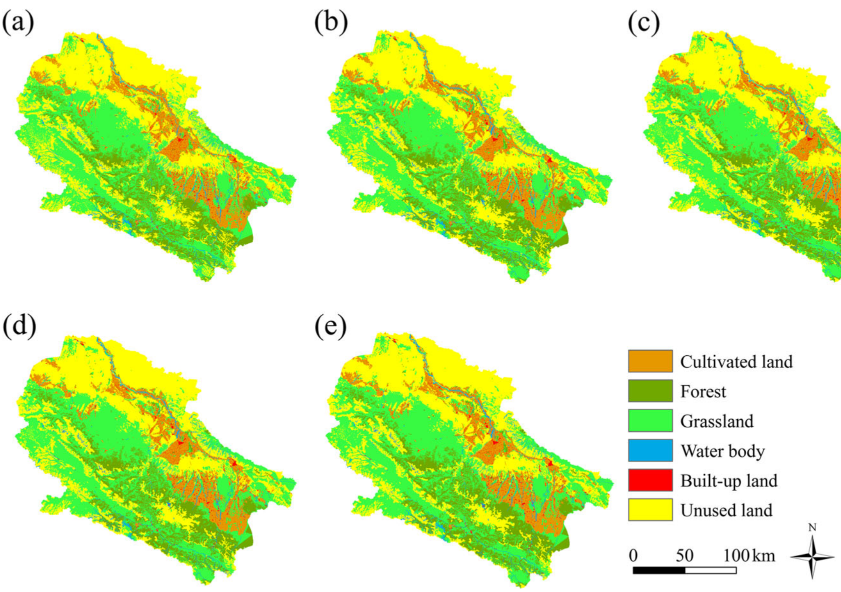

Fig. 4 Land-use patterns in the upper and middle HRB in 2000 **a**, 2015 **b**, 2020 **c**, 2025 **d**, and 2030 **e** under the A1B scenario

Table 3 Absolute (hectare) and relative (in brackets, unit: %) changes of each land-use type between 2000 and 2030 under the A1B and B1 scenarios

Land use type	Upper HRB		Middle HRB		Upper and middle HRB	
	A1B	B1	A1B	B1	A1B	B1
Cultivated land	72 (2.34)	135 (4.39)	−2,376 (−0.61)	−603 (−0.15)	−2,039 (−0.58)	−468 (−0.12)
Forest	1,323 (0.63)	4,581 (2.18)	10,602 (4.12)	18,864 (7.33)	11,925 (2.55)	23,445 (5.02)
Grassland	24,462 (4.89)	28,782 (5.76)	−9,387 (−1.20)	−11,529 (−1.48)	15,075 (1.18)	17,253 (1.35)
Water body	−522 (−2.07)	−495 (−1.96)	459 (0.82)	360 (0.64)	−63 (−0.08)	−135 (−0.17)
Built-up land	2,277 (238.68)	2,439 (255.66)	5,841 (17.68)	5,670 (17.17)	8,118 (23.89)	8,109 (23.86)
Unused land	−27,612 (−11.64)	−35,442 (−14.95)	−5,139 (−0.49)	−12,762 (−1.22)	−32,751 (−2.55)	−48,204 (−3.75)

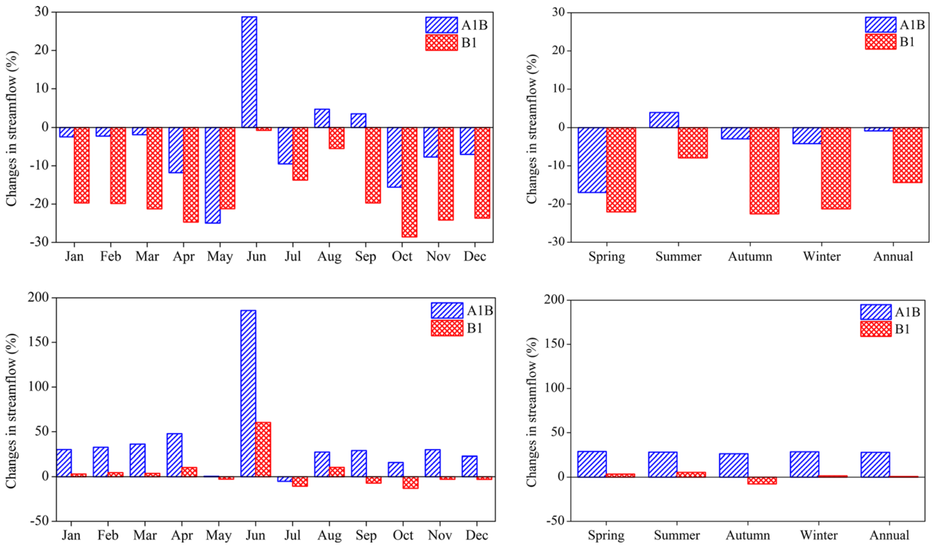

Fig. 5 Relative changes in mean monthly (*left*), seasonal and annual (*right*) streamflow at the outlets of the upper HRB (*top*) and the middle HRB (*bottom*) caused by single climate change under the A1B and B1 scenarios (*Case 1*)

(2007). The changes in streamflow are intimately bound up with the variations of precipitation (Qi et al. 2009). As shown in the top panels of Figs. 2 and 5, the precipitation variations can be generally reflected and amplified in the streamflow changes in most months. The exceptions in other months can be explained by the temperature changes. For instance, the streamflow is projected to decline in June under the B1 scenario regardless of increasing precipitation, possibly in connection with temperature rise, which leads to increase in evapotranspiration and thereafter reduction in streamflow.

The changes in streamflow at the Zhengyi Gorge station, the outlet of the middle HRB, are present in the bottom panel of Fig. 5. Compared with the baseline scenario, the streamflow is projected to decrease by 5.22% in July but increase by 0.38 to 185.71% in other months under the A1B scenario. Under the B1 scenario, it is expect to decrease in May, July and the period September to December while increase in others. Except for autumn under the A1B scenario, streamflow in other seasons under both scenarios shows an increasing trend. On the whole, streamflow at the outlet of the middle HRB is projected to increase under both climate change scenarios, in agreement with the results of Wu et al. (2014b). Under the A1B scenario, the mean annual precipitation is projected to increase by 49.96 mm, resulting in an increase in mean annual streamflow by 27.65%. Under the B1 scenario, it is projected to increase by 29.78 mm, however, leading to a slight increase in mean annual streamflow by 0.76%. The reason is the pronounced reduction of streamflow discharge from the upper HRB, which offsets the rise of streamflow induced by increasing precipitation in the middle HRB.

According to the historical gage data at the Yingluo Gorge station from 1945 and 1990, we defined a year in an extreme drought state when the annual streamflow lower than 1.022×10^9 m^3. Furthermore, an extreme flood is defined as an independent event with daily streamflow higher than 1,050 m^3/s by referring to the historical streamflow records and flood events (Yi et al. 2004). The frequencies of occurrence of hydrological extremes under different scenarios are then counted as in Fig. 6. There are three extreme droughts from 1990 to 2009 under the

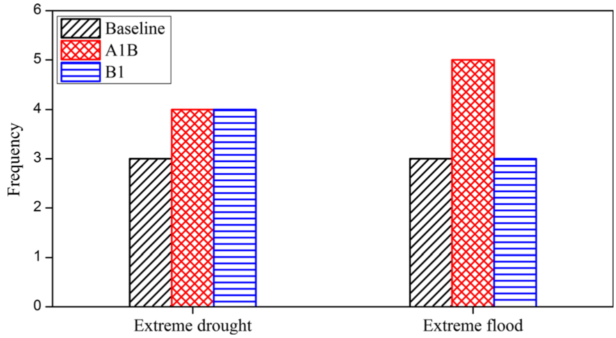

Fig. 6 Frequency of occurrence of hydrological extremes under different scenarios (*Case 1*)

baseline scenario and the number rise to four from 2011 to 2030 under both climate change scenarios. Extreme flood, on the other hand, occurs three times under both the baseline and B1 scenarios, but five times under the A1B scenario. Overall, the frequency of the occurrence of hydrologic extremes is projected to increase under the climate change scenarios, consistent with the results of Wu et al. (2010).

The significance test results for the streamflow simulations between two mutually corresponding periods are shown in Table 4. The changes of annual streamflow and the variations in most months at both outlets successfully pass the test under both scenarios. The failure in some months may be related to uncertainty existed in the hydrological model (SWAT) and the strong natural variation of streamflow.

3.5 Case 2: Combined Hydrological Responses to LUCC and Climate Change

In reality, the observed hydrological responses are combined results of both climate change and LUCC. The top panel of Fig. 7 shows the changes in mean monthly, seasonal and annual streamflow at the outlet of the upper HRB, caused by climate change and LUCC. The changes in streamflow appear to occur in the same direction as those in Case 1. The streamflow changes in Case 2 shown in Fig. 7 (top), which considers both climate change and LUCC, are remarkably similar to those in Case 1 shown in Fig. 5 (top), which only considers climate

Table 4 Paired T-tests for the changes of streamflow between the two periods (1980–1999 and 2011–2030) under the A1B and B1 scenarios (Case 1)

Outlet of the upper HRB													
	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1B	√	√	√	√	√	√	√	×	√	√	×	×	×
B1	√	√	√	√	√	×	√	√	×	√	√	√	√
Outlet of the middle HRB													
	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1B	√	√	√	√	√	√	√	√	√	√	√	√	√
B1	√	√	√	√	√	√	×	×	√	√	×	√	√

'√' means significant while '×' means insignificant at the significant level α=0.05

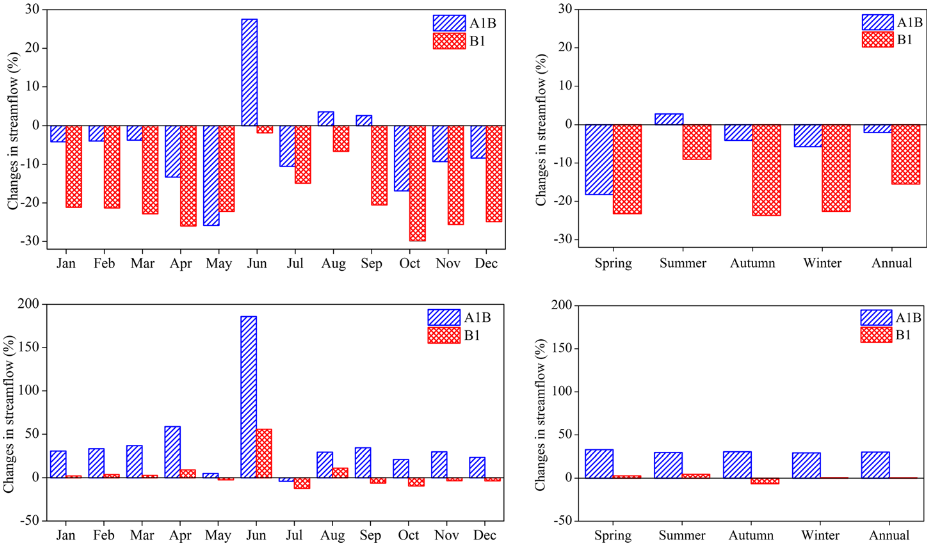

Fig. 7 Relative changes in mean monthly (*left*), seasonal and annual streamflow (*right*) at the outlets of the upper HRB (*top*) and the middle HRB (bottom) caused by climate change and LUCC under the A1B and B1 scenarios (Case 2)

change, suggesting that streamflow change is more sensitive to climate change than to LUCC as reported in other studies (Tu 2009; Khoi and Suetsugi 2014). As a consequence, the frequency of hydrological extremes is found to be same in both cases. A similar study performed in the study area also showed that hydrological processes were more affected by climate change than land use change (Wu et al. 2014b).

The differences in streamflow changes between Case 1 and Case 2 are induced by LUCC. As presented in Section 3.2, the dominant LUCC in the upper HRB include a decrease in unused land and an increase in grassland under both climate change scenarios. Compared with grassland, unused land, i.e. bare land, Gobi and desert, has a weaker capacity of evapotranspiration and consequently a stronger capacity of runoff, owning to lower vegetation coverage. Decreased streamflow will be generated when a large area of unused land is replaced with grassland. As a result, compared with Case 1, either a smaller increase or a larger decrease of streamflow at the outlet of the upper HRB can observed in Case 2 under the same scenario.

The bottom panel of Fig. 7 depicts the percentage changes of streamflow at the outlet of the middle HRB. Similarly, the changes in streamflow (Fig. 7, bottom) behave in the same direction as those in case 1 (Fig. 5, bottom). Under the A1B scenario, the increase in mean annual streamflow is found to be greater in Case 2 than in Case 1. It can be explained by the increase in built-up land and the decline in grassland. Additionally, the area of cultivated land decreases under the A1B scenario, leading to a decreasing demand for irrigation water, and consequently an increase in streamflow. Under the B1 scenario, however, the increase in mean annual streamflow is observed to be smaller in Case 2 than in Case 1, mainly because a large increase in forest and decrease in unused land. Furthermore, the declining streamflow discharge from the upper HRB under the B1 scenario contributes to the drop in streamflow at the outlet of the middle HRB.

4 Discussion and Conclusions

This study investigated the hydrological responses to climate change and LUCC under climate change scenarios (A1B and B1) in the upper and middle HRB by coupling of a land-use change model (Dyna-CLUE) and a spatially distributed hydrologic model (SWAT). The novelty lies in that, as a new case study in a typical arid inland river basin, not only hydrological responses to single climate change but the combined responses to consistent LUCC and climate change scenarios were investigated. To differ from the methodology in other existing studies where LUCC and climate change were projected separately, this study established LUCC scenarios consistent with climate change scenarios. The findings can provide a reference for local authorities and stakeholders in better management of land and water resources in the HRB as well as other arid inland river basins across the world which share similar water problems.

Simulations of LUCC under both the economic oriented A1B scenario and the environmentally friendly B1 scenario reveal that the projected future land-use patterns are not appreciably different than the actual pattern in 2000 and that the LUCC presents distinct regional characteristics. In Case 1, which only considers the impacts of single climate change, decreasing streamflow is generally projected at the outlet of the upper HRB, whereas increasing streamflow at the outlet of the middle HRB, under both climate change scenarios. The frequency of occurrence of hydrological extremes is estimated to increase under both scenarios. In Case 2, which considers the combined impacts of climate change and LUCC, the changes in streamflow discharge from the upper and the middle HRB are found to be noticeably similar to those in Case 1. It implies the hydrological variations are more sensitive to climate change than to LUCC.

Although climate change dominates the hydrological variations in future, LUCC still plays an important role in influencing the hydrological cycle. Under the A1B scenario, the changes in mean annual streamflow discharge from both the upper and the middle HRB are found to be enhanced by LUCC. Under the B1 scenario, the variations in mean annual streamflow are modelled to be strengthened as well in the upper HRB, while weakened in the middle HRB. In this context, LUCC can not only enhance but also weaken the hydrological impacts induced by climate change. It is also supported by the well-designed two case studies, Case 1 and Case 2, the latter including additional LUCC impacts with others intact. Comparing the results of the cases, the difference is not pronounced. The major reasons include relatively small absolute changes in land-use and land-cover compared with the entire study area, and the tradeoff caused by the role of LUCC, i.e. the LUCC-induced positive and negative impacts might offset each other, resulting in an unapparent changes in streamflow at the final outlet.

The findings of the hydrological impacts of climate change imply management hints for the local watershed, especially for the upper HRB where few human activities have been involved (Zhang et al. 2015). This study shows a decreasing streamflow discharge from the upper HRB under both climate change scenarios, which may raise the awareness of the local water source managers. As we mentioned in Section 2.1, the middle HRB, where millions of people are sustained, is a primary water-consuming area, accounting for approximately 90% of the total water use from the Heihe River. Due to little precipitation and high evapotranspiration, water use in this area heavily depends on the streamflow discharge from the upper area. Consequently, together with the ever-increasing water demands from agricultural, industrial and domestic sectors, declining streamflow induced by climate change will put much stress on water resources utilization in the middle HRB, which have already beyond the red line of water sustainability (Wang et al. 2009). As the largest water consumer, the agriculture will be firstly impacted (Wu et al. 2014a). Other consumers, such as industry, residents and ecosystem, will be threatened as well. Traditional approaches to counter water stress will be challenged and it necessitates the research of integrated water management based on scientific modeling.

In this study, although the hydrological responses to climate change and LUCC were successfully examined, there is still space for improvement. The uncertainty linked to GCMs, greenhouse gases emission scenarios, downscaling method, hydrological model and its parameters, needs to be further investigated and quantitatively assessed. Furthermore, one implicit assumption in this study is that the calibrated parameters remain valid and optimal for future land use and climatic conditions. This might not hold, as Merz et al. (2011) argued, the parameters may potentially vary with varied climatic conditions. An in-depth analysis regarding transferability of parameter is therefore needed in further study. In addition, a number of reservoirs have been built in the upper HRB since 2000. However, the hydrological impacts of reservoirs were not considered, which may bring some biases to the results.

Acknowledgments This work was financially supported by the National Natural Science Foundation of China (No. 91125006 and 91125005). The authors thank the Scientific Data Center in Cold and Arid Regions and the China Meteorological Data Sharing Service System for providing the data. The authors also would like to extend their gratitude to the anonymous reviewers for their valuable suggestions to this paper.

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