



# Adapting Water Scarcity for River Basin: Optimization of Land Uses

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**Abstract**

Water scarcity is a hot issue in river basin management, especially in ecologically fragile areas with arid climate, such as the Heihe River Basin (HRB) in Northwest China, where water availability is at the core of sustainable socioeconomic development and ecological conservation and the effects of land use changes on the hydrological process are crucial to rational allocation of water resources. In this chapter, first, we identified that the severity of water scarcity problems can be associated with imbalance between water supply and demand, irrational water consumption structure and low water efficiency, deficient systems and institutions for water management, as well as unreasonable water allocation scheme. Further, we investigated the hydrological responses to land use changes in the upper and middle reaches of the HRB based on scenario analysis. In one case, the results indicated that the forest land has “sponge” effects on the water resource in the upper reach of the HRB; in the other case for the upper and middle reaches, the results showed that the forest land and grassland will expand with increase in water utilization ratio, and further the quick-response surface runoff would decrease significantly due to forest and grassland expansion, which may cause an overall decreasing trend of the water yield. This indicated that water resources should be reasonably allocated for different land use demand, which is critical for sustainable development. The results of this chapter will be informative to decision-makers for sustainable water resource and land management.

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**Keywords**

Water scarcity · Water constrain · Water yield · Surface runoff · Forestry change · Land use changes · Hydrological process · SWAT · DLS · Heihe River Basin

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**Introduction**

Water is one of the most critically limited resources for sustainable development and natural ecosystem conservation, especially in the arid and semiarid regions (Vörösmarty et al. 2000). Its scarcity is further triggered by the unsustainable use, rapid population growth, and economic development, which results in deterioration of the natural ecosystem, land degradation, and decrease in agricultural production.

In view of this, the issue of water scarcity and stress have increasingly attracted more attention, and how to improve water provision to adapt for water scarcity becomes a key issue in the river basin management in order to reconcile water availability and demand. The water resource management and land use patterns are intrinsically linked. On the one hand, the provision of water resources is closely related with the hydrological processes, which are considered to be affected mainly by climate and land use/cover changes in the river basins (Al-Bakri et al. 2013). Better understanding of the impact mechanism of climate and land use/cover changes on hydrological processes is crucial for sustainable water resource management. At a catchment level, forest cover and agricultural cultivation have significant

impacts on the water resources and can affect the availability of water for other users. While climate and land use/cover change interact with each other, it is important to apply consistent climate or land use conditions when trying to investigate the separate impacts of land use/cover change and climate change on the hydrological processes (Bierwagen et al. 2009). For example, Van Ty et al. (2012) and Kim et al. (2013) investigated the impacts of climate and land use/cover change on hydrological processes, respectively, and their results showed that both changes in climate and land use/cover have significant impacts on streamflow in the basins. On the other hand, water resource is the determinant factor that will affect the land use structure since different land use types have different water demands (Deng et al. 2014) and land use/cover change in arid region is strongly restricted by water resources. For example, Li et al. (2011) found that after the implementation of the water allocation scheme in the HRB between Gansu Province and Inner Mongolia in 2000, water use in the middle reach region was further limited, which significantly affected the land use structure changes in the middle reach region of the HRB. Besides, for long-term water resource planning and management, scenario analysis has become an efficient method to predict the responses of hydrological process to climate and land use/cover change. For example, Menzel et al. (2009) designed two intermediate land use/cover change scenarios, with projected developments ranging between optimistic and pessimistic futures (with regard to social and economic conditions in the region) and climate conditions remaining unchanged; the simulation results showed that both increase and decrease of water availability depend on the future pattern of natural and agricultural vegetation and the related dominance of hydrological processes.

The HRB, as a typical inland river basin located in the semiarid region of Northwest China, is facing increased water scarcity issues, which have become the major bottleneck of socioeconomic development and ecological security, especially where agricultural production and natural ecosystems are closely linked and compete for the water use. The water from the Heihe River is important to agricultural production and ecosystem stabilization in the middle and lower reaches of the HRB and is highly sensitive to climate change and human activities in this area. The climate in the HRB has remained in a relatively stable warm-wet state since the 1960s and has not experienced strong changes due to global warming (Qin et al. 2010). Therefore, human activities, such as land use changes and economic development, have become the dominant driver of changes in the water resources of the HRB over the last 60 years. Especially between the 1960s and 1990s, with the rapid expansion of farmland, a large increase in the quantity of water used for irrigation had directly lead to the decrease in the amount of water for ecosystems, resulting in devastating environmental and ecological problems in the arid river basin (Hu et al. 2015).

In this chapter, we firstly aim to identify the water scarcity condition of the HRB; following, in order to come up with adaptation strategies that may release the pressure from water scarcity and minimize the water conflicts between agricultural production and natural ecosystems from the perspectives of land use optimization, we investigated the relationship between water availability and land use changes in

the typical area of the basin: we firstly analyzed the effects of forestation on the hydrological process in the upper reach of the river basin, which is the water source area of the whole basin and crucial to protecting water resources; further taking the upper and middle reaches of the HRB as the study area, we aimed to investigate the changes in the hydrological processes under different land use scenarios based on the degrees of water constraints. The research results in this chapter are meant to provide valuable information and implications for future sustainable water and land management in the HRB.

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## Identification of Water Scarcity in the Heihe River Basin

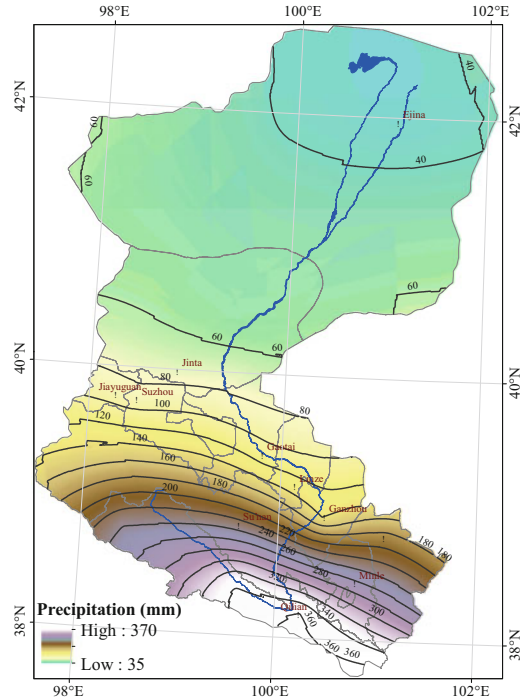
Water plays an important role in economic development and ecological balance of the HRB, especially in the middle and lower reaches. During the 1960s–1990s, intensive agricultural activities in the middle reaches and lack of effective coordinated water management system have drastically reduced the amount of water that flows into the lower reach. As a result, the rivers and lakes dried up intensively in the lower reach, the groundwater table declined, and the level of water mineralization increased, leading to substantial deterioration of the ecosystems (Deng and Zhao 2015). In addition, along with the rapid climate and land use/cover changes, water scarcity and stress faced by the HRB increasingly becomes severe and thus is a critical issue that should be addressed for sustainable development.

## Water Scarcity with Imbalance Between Water Supply and Demand

Water scarcity is a long-standing and widespread problem in the HRB, with the characteristic of unevenly temporal and spatial water distribution. There are a series of reservoirs (1 large reservoir, 9 medium-sized reservoirs, and 89 small reservoirs) in the basin, and the total capacity is 416.9 billion m<sup>3</sup>. Influenced by topography, altitude, and atmospheric circulation at different scales, the spatial distribution of precipitation is extremely uneven in the middle and lower reaches. Generally, the annual average precipitation decreases from the southeast to the northwest (Fig. 1). The maximum precipitation zone mainly concentrated in the upper reach with an altitude of 2200–3000 m and an annual precipitation of 400–750 mm. In contrast, the minimum precipitation zone is the desert area of Ejina, which administratively belongs to the Inner Mongolia, with an annual precipitation of only 15–50 mm.

Aside from precipitation, the available water resource mainly depends on the amount of water from the upper and middle reaches, supplied by springs, subsurface flow, and solid glacier in the Qilian Mountain. There are 298 million m<sup>3</sup> of water resource formed by ice and snow melting from the Qilian Mountain, accounting for 8% of the total amount of runoff. However, due to irrational human activities that seriously changed the landscape structure and composition in the upper reach of the HRB, available water resources inevitably reduced. It has been concluded that the yearly based rate of glacial retreating was around 0.60% in the HRB from the 1960s to 2010,

**Fig. 1** Spatial distribution of the average precipitation (mm) in the HRB for the year 1960–2006 (Reprinted from Deng and Zhao (2015) with permission of Advances in Meteorology)



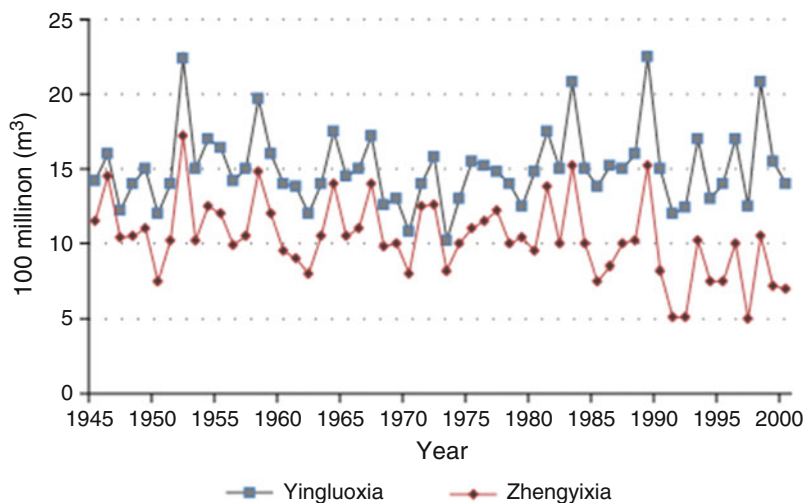
and this speed was significantly faster than that of the Tian Shan Mountain (0.49%/a), Geladaindong (0.05%), and Naimona'nyi region (0.26%) (Huai et al. 2014).

Meanwhile, water demand in the HRB has increased considerably over the past half century. Since 1949, the Chinese government has paid much attention to the development of irrigation infrastructure, and by 1985, the number of reservoirs (the small plain reservoirs and embankments with a volume less than 100,000 m<sup>3</sup> are not accounted) in the middle reaches had reached 95, and the total storage capacity had been up to 360 million m<sup>3</sup>, more than 20 times of that in 1949. As a result, the hydrology changed radically in the middle reach, which was highlighted by the fact that the utilization rate of surface water increased by 19 times, the area of irrigated oasis expanded by 89.5%, and the area of desertification land increased by 4–11% since the year 1949. Along with utilization of the surface water, the groundwater was also extensively explored, and the number of motor-pumped well had doubled from 1985 to 1994 (Wang and Cheng 1998). The groundwater table had been steadily decreasing due to the overpumping and the decreasing of recharges. In fact, there is a very close interconnection between the surface runoff and groundwater in the HRB because of the water distribution characteristics of the HRB, which partly determined the hydrological process. Last but not least, as the intermediate linkage between the surface water and the groundwater, the volume of springs also showed a decreasing trend. In addition, the average reducing rate had increased by 6.8% in 1981–1991 compared to 1960–1980 (Wang and Cheng 1998).

Consequently, the exploitation on surface runoff water and groundwater had dramatically changed the hydrological situation of the HRB during the long historical period. All the 33 tributaries in the middle reach no longer joined into the main stream of the Heihe River since the 1980s and gradually disappeared and formed some independent irrigation oasis. The water volume of the runoff through the Zhengyixia hydrological station decreased sharply in recent decades, from 1.19 billion  $\text{m}^3$  in the 1950s to merely 691 million  $\text{m}^3$  in the 1990s, and the mainstream became a seasonal river in the downstream of the Zhengyixia station (Fig. 2). In this arid and semiarid river basin region, large-scale development of irrigation agriculture induces dramatic increase of water demand. The excessive water consumption by humans has resulted in continued environmental deterioration, which has become a serious threat to sustainable development.

### Irrational Water Consumption Structure with Low Water Efficiency

Currently, the overall water consumption of all sectors in the HRB is about 3.36 billion  $\text{m}^3$ , among which industrial and domestic water consumption is fairly less and agricultural water use accounts for about 95%, posing a great threat to the ecological water consumption. Taking the year 2000 as an example, the annual water consumption in the HRB was 2.65 billion  $\text{m}^3$ , among which the farmland irrigation consumed 2.03 billion  $\text{m}^3$ ; the water consumption in the forestry, stock raising, and fishing sector was 489 million  $\text{m}^3$  in total; the industrial water consumption was 86 million  $\text{m}^3$ ; the livestock water consumption was 15 million  $\text{m}^3$ ; the human living



**Fig. 2** Change of the surface runoff through the Yingluoxia hydrological station in the upper reach and the Zhengyixia hydrological station in the middle reach (Reprinted from Deng and Zhao (2015) with permission of *Advances in Meteorology*)

consumption was 32 million m<sup>3</sup> (including urban public consumption); and the urban environment water consumption was 2 million m<sup>3</sup>. In terms of the spatial distribution of water consumption, the water consumption in the upper and lower reaches accounts for 2.3% and 13.6%, respectively, while the water consumption in the middle reach accounts for 84.1% of the total. The water consumption is high in the middle reach because human and economic activities mainly concentrate in this region, which results in high water consumption in the counties located in the middle reach, including Shandan, Minle, Linze, and Gaotai (Table 1).

The irrigation agriculture in the middle reach of the HRB has greatly contributed to the increase of food production historically and supported the large number of population of the Northwest China. In the HRB, large-scale development of irrigation agriculture induces dramatic increase of water demand, agricultural water use accounted for about 94% of the total social and economic water consumption in the year 2006, but the water efficiency and the water productivity were very low. Therefore, agricultural water-saving strategies are necessary in terms of water resource management. However, due to people's unawareness of implementation of water-saving projects, as well as the restriction on the crop types, planting technologies, crop rotation, land management patterns, and unguaranteed maintenance costs, the water-saving renovation projects cannot be effectively promoted, and the water demand for farmland irrigation is hard to decrease. This phenomenon is extremely predominant in the middle reach of the HRB, where there are lots of irrigation gates and plain reservoirs and high technical irrigation engineering and exploitation of groundwater cannot be supported. All of these lead to low water efficiency and lower GDP output of per unit of water, which further accelerate the water scarcity problems.

### **Deficient Systems and Institutions for Water Management Along with Unreasonable Water Allocation Scheme**

In the inland river basin, improving the water security and efficiency is of great significance, which can guarantee the supply of water for livelihood and production. The water efficiency in the HRB is beyond the satisfactory level. The deficiency of systems and institutions for water management as well as the unreasonable water allocation scheme are the primary cause of the huge water consumption in agriculture.

There are two main kinds of management strategies for community irrigation in the HRB, including the collective management strategy and Water User Associations (WUAs) management strategy. For the collective management strategy mode, village leaders are in charge of the village water allocation, channel maintenance, water charges, and other relevant issues to fulfill their water management duties. In contrast, WUAs are independent water management organizations that take over the village leaders to be responsible for water allocation, channel maintenance, water charges, and other relevant issues in a specific village. In terms of the policies and measures on water demand management, there are three modes, including water

**Table 1** Statistics of county-level water consumption (1000 m<sup>3</sup>) in the HRB, 2000

Region	Domestic living in cities	Domestic living in countryside	Industry	Farmland irrigation	Forest and fishing	Stock raising	City environment	Total
Qilian	417.8	353.3	1246.0	7815.6	5154.6	3305.9	38.8	18331.9
Shandan	1435.5	2702.9	15573.0	214360.0	20214.3	1300.0	138.5	255724.2
Minle	1968.3	3099.6	8771.0	404498.1	27034.0	1162.3	183.5	446716.7
Ganzhou	6371.4	6086.4	28222.1	640706.5	49352.0	4312.6	723.0	735774.0
Linze	1300.6	1993.0	13102.8	380011.4	57492.0	1109.6	119.1	455128.4
Gaotai	1591.5	2103.8	8609.9	278336.0	45154.0	1367.5	148.0	337310.7
Sunan	335.2	279.4	2434.4	24108.0	13844.4	1134.2	32.9	42168.6
Jinta	461.7	684.2	4669.2	68783.4	21100.0	418.4	41.0	96157.7
Ejina	390.9	62.9	2981.1	10136.5	249421.0	810.7	78.2	263881.2
Total	14272.8	17365.5	85609.4	2028755.5	488766.3	14921.0	1503.0	2651193.5



price, water ticket, and water right. For the water price mode, the government would charge some fees for water services. For the water ticket mode, the farmers need to purchase water tickets from village leaders or WUAs before the farmland irrigation activities. The water right mode refers to the water right card issued to farmers to guarantee their water consumption rights.

Since 1992, a series of water resource allocation and management policies have been implemented in China to alleviate the conflicts between natural water shortage and the high water consumption (Cai 2008). In 1997, the Heihe River Basin Bureau was established for special management of water resource in the HRB. With the support of scientific research from Chinese scholars, it has adjusted the water resource allocation schemes among the HRB for five times. Unfortunately, different counties have their own management focuses and time schedules, which lead to another form of water waste.

The difficulty for a rational water allocation scheme is also on by due to the fact that the supply volume and the annual distribution of water in the lower reaches are completely subjected to the human activities in the middle reaches. In the long history, people living in the middle reaches performed irrigation agriculture (settled culture), and the people living in lower reaches performed nomadic husbandry. Even though conflicts on water use between the middle and lower reaches has a history of 200 years, it reached an unprecedented situation. Since 1950s, intensive agricultural practices in the middle reaches have resulted in drastic environmental degradation in the lower reaches. In addition, Heihe River dries up in May, June, and July and is flooded from August to October, and the water volume would reduce and even stops flowing sharply in December till the next March or April. Consequently, there is a prominent contradiction between the water supply and demand over time and space, which is deteriorated by the fact that the high water demanding just happens in the dry periods (Wang and Cheng 1998).

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## **Water Resource Availability and Land Use/Cover Change**

The HRB has been facing serious water scarcity problems, as water and land resources in the arid inland river basin have been intensively used due to population increase and economic expansion. In this section, we aim to investigate the impact of land use/cover changes on water resource availability for sustainable water resource management in the HRB. The main economic activity in the HRB is traditional agriculture, which is mostly concentrated in irrigated oasis regions in the middle reaches. Such an economic pattern necessitates a close relation between water resources and land use in the HRB. It has been long recognized that changes in land use and land cover are important factors affecting water circulation and the spatial-temporal variations in the distribution of water resources. Such impacts on hydrological processes are reflected in fluctuations in the supply-and-demand relation of water resources, which in turn will significantly affect the ecosystem, environment, and economy (Wang et al. 2007). With the continuous exploitation of both water and land resources in the middle reach, the runoff in the lower reach

had been decreasing, and terminal lakes had dried up, resulting in a series of severe eco-environment problems in the HRB (Hu et al. 2015). The effects of land use/cover changes on the runoff process in the upper and middle reaches of this arid inland river basin are a key factor in the rational allocation of water resources to the middle and lower reaches. Thus, it is critical to clarify how land use/cover changes impact the hydrological processes in such an arid inland river basin to promote effective measures for sustainable water and land resources management in the HRB.

### **Water Yield Variation Due to Forestry Change in the Head-Water Area of the Heihe River Basin, Northwest China**

The HRB is the second largest inland river basin in China, which can be divided into the upper, middle, and lower reaches, differing significantly in their natural and socioeconomic characteristics. For example, the average annual precipitation in the upper, middle, and lower reaches are 200–600 mm, less than 200 mm, and less than 50 mm, respectively, while the annual evaporation ranges from 500 mm in the upper reach to over 3000 mm in the lower reach (Feng et al. 2001).

The water resource in this basin mainly originates from the Qilian Mountains in the upper reach of the HRB, where the grassland and forest are the main land use types, accounting for about 21% and 50% the total land area, respectively. The relationship between forests and water resources is a critical issue which must be accorded with high priority. A key challenge faced by the land, forest, and water managers is how to maximize the wide range of forest benefits without detriment to water resources and ecosystem functions. To address this challenge, there is an urgent need for a better understanding of the interactions between forests/trees and water, also for awareness raising and capacity building in forest hydrology and for embedding this knowledge and the research findings in policies. Forestation in the upper reach of the basin is deemed as the most effective measure to enhance water availability for agriculture, industrial, and domestic uses (Singh and Mishra 2012). A quantitative assessment of the hydrological effects of forestation, especially on the water yield, is therefore crucial for improving the forestation and water resource management to guarantee the sustainable water and land management within the arid or semiarid regions.

The hydrological effects of forestation of degraded land in the dry region have important implications for local and regional hydrological services, but such issues have been relatively less studied when compared to the issue of impacts of forest conversion (Yu et al. 2013). Scientists from forestry and environmental science disciplines emphasized the significance of forests in regulating runoff and controlling soil erosion (Huaxing et al. 2009; Chen et al. 2010), while scientists from other fields, for example, geography, climatology, and agriculture, argued that forests only have limited effects on water budgets and controlling flood (Yu et al. 2013). Overall, the relationship between forestation/reforestation and water yield is still a controversial issue. A central concept in the “traditional” view of the role of forests is the

“sponge” effect of the tree roots, forest litter, and soil. It has been ever claimed that the tree roots soak up water during wet periods and release it slowly and evenly during the dry season to maintain water supplies (Myers 1983). The debate was endless because there were no convincing field data from research on forest hydrology, especially in China. Most literature suggested that the effects of forestation on annual flow are largely on the base flow, which is an important component of annual water yield for most forested watersheds. Some may conclude that forests increased base flow because the trees help to increase infiltration (Scott et al. 2004), while others may argue that forests used more water and thus reduced the base flow (Wang et al. 2014). However, the hydrological consequences of forestation on degraded lands are not well studied in the forest hydrology research (Huaxing et al. 2009; Wang et al. 2014).

Catchment parameters have great influence on responses of the water budget and runoff to forestation. The magnitude of effects of forestation on annual water yield varies as a function of vegetation, climate, soil, and management practices (Calder 2003). Hydrological models, for example, the soil and water assessment tool (SWAT), allow for simulating the hydrological effects of these catchment parameters, which can help to understand the effects of forestation on water yields in the entire basin. The SWAT has been widely used in the water quantity and quality assessments at a wide range of scales and environmental conditions (Faramarzi et al. 2009; Castillo et al. 2014) and has also been successfully used to simulate the hydrological processes in the small upstream watershed of the HRB (Yao et al. 2009). In this section, the SWAT model, which includes the components such as soil and vegetation, is used to analyze the effects of forestation on the water yield.

## Data and Methodology

SWAT is a semi-distributed hydrological model based on geography and natural hydrological processes at the watershed scale. SWAT subdivides an entire watershed into sub-watersheds connected with a river network and into smaller units that is called hydrological response units (HRUs). Each HRU represents a combination of land use, soil, and slope. HRUs are assumed to be nonspatially distributed with no interaction or dependency (Neitsch et al. 2011). Major model components of SWAT include weather, hydrology, temperature and properties of soil, plant nutrients and growth, pesticides, bacteria, and land management (Neitsch et al. 2011). The meteorological variables in SWAT include precipitation, temperature, wind speed, solar radiation, and relative humidity in daily or sub-daily time steps. The model uses readily available inputs efficiently for computing the large watersheds and is capable of simulating long-term yields for determining impacts of land management practices (Arnold et al. 1999). SWAT allows a number of different physical processes to be simulated in a basin. The hydrological routine of SWAT actually and also potentially consists of discharge, snow melting, and evapotranspiration.

We aim to address the processes related to vegetation interception, infiltration, transpiration, and evaporation in the dry watersheds, and the corresponding data used in the model are presented in Table 2. The 30 m resolution Landsat TM images in 1980 were downloaded from the US Geological Survey (USGS) website

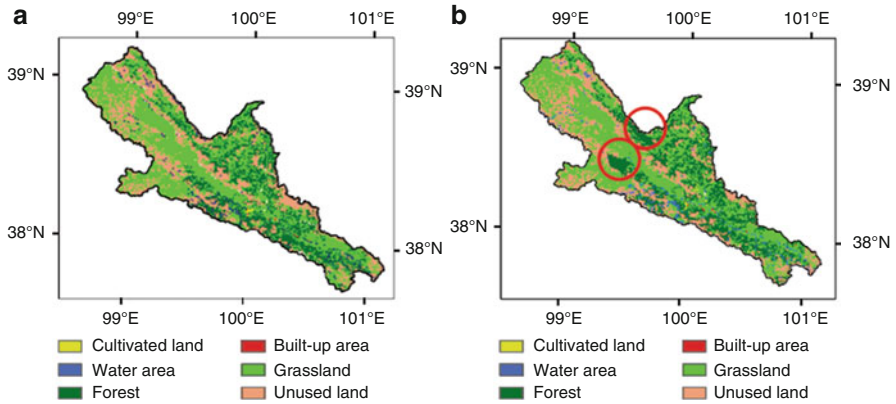
**Table 2** Data used and sources information (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

Data type	Data source	Scale	Description
DEM	Shuttle radar topography mission (SRTM)	90 m	Elevation
Soil	Regional database ( <a href="http://westdc.westgis.ac.cn/">http://westdc.westgis.ac.cn/</a> )	1: 1000000	Soil-plant-atmosphere-water (SPAW) field and pond hydrology model was used to calculate some parameters
Weather	China Meteorological Administration (daily)		13 meteorological stations
Hydrological observation	Hydrologic yearbook (daily)		4 hydrological stations
River flow	Data Center of Chinese Academy of Science	1: 250000	River network diversion

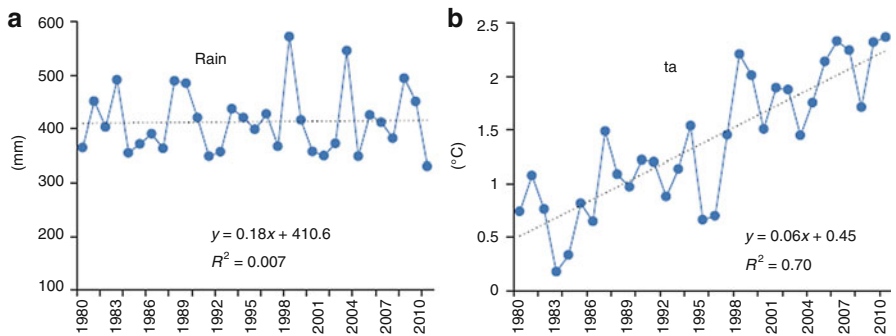
(<http://earthexplorer.usgs.gov/>) for mapping the land cover types in the upper reach of the HRB in 1980. The collected images have already been georeferenced, and we radiometrically corrected them using the calibration utility for Landsat in ENVI 4.7 software package. The preprocessed images were subsequently clipped with the boundary of the study area. Supervised classification method was used to classify the land cover types in 1980. The Chinese Land Resource Classification System, from Data Center of Chinese Academy of Sciences, was used as the classification scheme to categorize the pixels of the image (Deng et al. 2008). The classification system includes cultivated land, forest land, grassland, water, urban and/or built-up area, and unused land. Further, a baseline scenario of forestation was designed on the basis of the land cover in 1980, in which the forestry proportion is 21%. Then a scenario was established with the simulated land cover data in 1980, in which the forest area increases by 12% compared to the actual land cover data in 1980. The regions with land use conversion are mainly located in the middle and western part of the study area (Fig. 3). The precipitation data of Qilian weather station was also used to analyze the trend of precipitation. From 1980 to 2010, the precipitation showed a significantly upward trend, increasing at an average rate of  $1.79 \text{ mm year}^{-1}$ , and the annual average temperature significantly increased by  $0.06 \text{ }^{\circ}\text{C year}^{-1}$  (Fig. 4).

### Impacts of Forestation on Water Yield

We simulated the effect of forestation on water yield using the SWAT model which couples the vegetation and physical processes. The SWAT model was calibrated based on the daily observation data records of 1980–1990 from Yingluoxia hydrological station, which is an outlet of the upper reach area, and the simulation results were validated with the daily observation records of 1990–2000. Some parameters were updated after the calibration. The Nash-Sutcliffe coefficient ( $E_{ns}$ ) and coefficient of determination ( $R^2$ ) of 0.72 and 0.70 and 0.80 and 0.79 for the calibration and



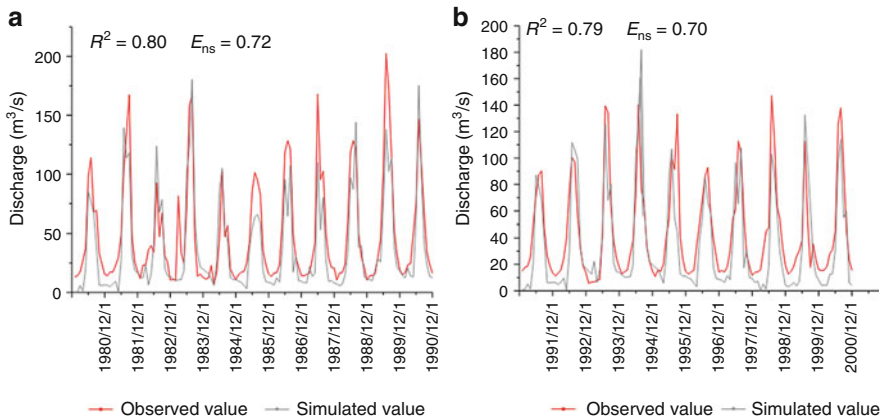
**Fig. 3** The land use map in the upper reach of the HRB: (a) 1980 and (b) scenario-based simulated map (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)



**Fig. 4** The change trend of precipitation and temperature at Qilan meteorological station during 1980–2010 (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

validation period, respectively, showed that the SWAT model performed well in simulating the hydrological process in the upper reach area of the HRB (Fig. 5). The two coefficients of validation period were lower than the calibration period, the reason being that we used the land use map of the year 1980. Moreover, comparing the simulation results with the observation records from Yingluoxia hydrological station, we failed to reject the significance of the parameters of the SWAT model, indicating the model is suited for simulating the water balance in the upper reach area of the HRB.

The intervals of the most sensitive parameters were identified, and the most appropriate values are eventually shown in Table 3. The temperature lapse rate (TLAPS) is the most sensitive parameter, and it is directly related to the melting process of snow and glacier. Snow melting occurs mostly from March to June in a sub-watershed. The snow-melting factor on June 21 was parameterized to be SMFMX, which is the maximum melting rate; any increase of SMFMX drives



**Fig. 5** The calibration and validation of monthly discharge at the Yingluoxia hydrological station, observed versus simulated using the SWAT (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

**Table 3** Ranges and values of the most sensitive parameters in SWAT model (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

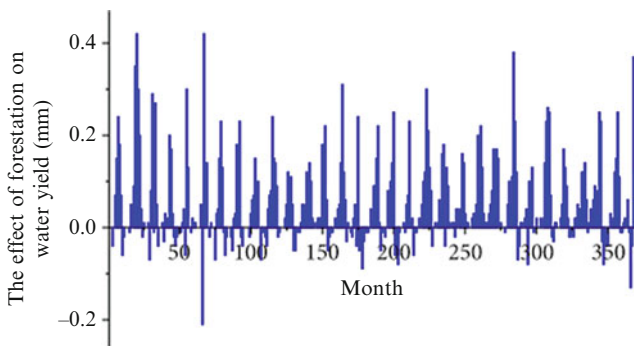
Parameters	Descriptions	Ranges	Values
CN <sub>2</sub>	SCS curve number	-20%~20%	+6.32%
Sol_k	Saturated hydrological conductivity	-20%~20%	+11.56%
Escno	Evaporation compensation factor	0~1.0	0.83
SFTMP	Snowfall temperature	-2.0~2.0 °C	0.9 °C
Sol_z	Depth from soil surface to bottom of layer	-20%~20%	+3.65%
Sol_Awc	Available soil water content	-20%~20%	-0.35%
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	0~500 mm	306.5
ALPHA_BF	Base flow alpha factor	0.00~1.00	0.07

rapid snow melting. The snow temperature lag factor TIMP is also linked with SMFMX because it is based on the previous situation. Along with TIMP surface water lag time, SURLAG plays an important role in influencing the model performance as a melted snow routing process is related to the geology of the watershed, where the melted water mainly flows to the surface runoff covering the impervious rock formations. SMTMP is sensitive since it indicates the starting and ending of snow and glacier melting, the availability of snow melting on a specific day, and the model-simulated streamflow, especially their peak values that are significantly influenced by the variation of SMTMP. Some parameters were updated after the calibration, and both calibration of the model and validation of the simulation results show that the model performed well in simulating the runoff variation due to glacier melting and climate change in upper reach of the HRB.

Streamflow production may be related to the differences in climatic pattern, meteorological conditions, species composition, canopy structure, and morphological

characteristics of tree leaves, branches, and bark. Canopy rainfall interception varied from 14.7% to 31.8% of total rainfall, depending on the stand characteristics of different land cover type. Forest canopy interception was also affected by rainfall characteristics, which generally decreases with the rainfall amount and intensity. Evapotranspiration (ET), including physical evaporation and biological transpiration, is a significant component of forest water budgets, ranging from 80% to 90% of the total rainfall in the region. As expected, the actual amount of ET raised due to the increase of temperature and rainfall, whereas the amount of ET is relatively low in the mountainous watershed. ET from a forest is generally higher than that from pasture or bare land. However, ET is about 600 mm in the forest cover in the upper reach area of the HRB, which is far lower than that in those regions covered by grassland or unused land. The ET/PET ratio of native grasslands was the fastest to decline, followed by pine woodlands, shrub lands, alfalfa, and croplands. Pine woodland's low ET/PET ratios were mainly caused by its higher runoff due to soil compaction resulting from soil desiccation.

Previous studies have shown that the effect of forestation on water yield may differ among regions due to the difference in the topography, soil properties, and climate conditions (Deng et al. 2010). The simulation results in this study suggest that the monthly average water yield has generally increased under the forestation scenario, with an increment of 15.7 mm during 1980–2010 (Fig. 6). The increase of water yield mainly occurred in summer, while the decrease of water yield was mainly in winter. This may be due to the water conservation function of the forests. The study area is located in the mountain area having an altitude of approximately 3000 m, about 600 mm annual rainfall and a generally very high slope with the forests intercepting a large proportion of rainfall. The forest has a more powerful conservation function compared to the grassland, and it is more difficult to generate runoff in the forest than in the grassland. The results of the two simulation experiments show that the monthly average runoff decreased by 22.12 mm when the forest area increased during 1980–2010. In addition, the simulation results show that the interflow declined dramatically, the monthly average value of which decreased by approximately 500 mm during 1980–2010. This may be due to the difference in the



**Fig. 6** The difference of water yield between forestation scenario and baseline during 1980–2010 (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)



moisture infiltration of the forests and grasslands. The surface roots of forests can absorb more surface moisture and keep the shallow soil moist, and that of grasslands are generally very shallow, thus promoting the infiltration of rainfall into the soil.

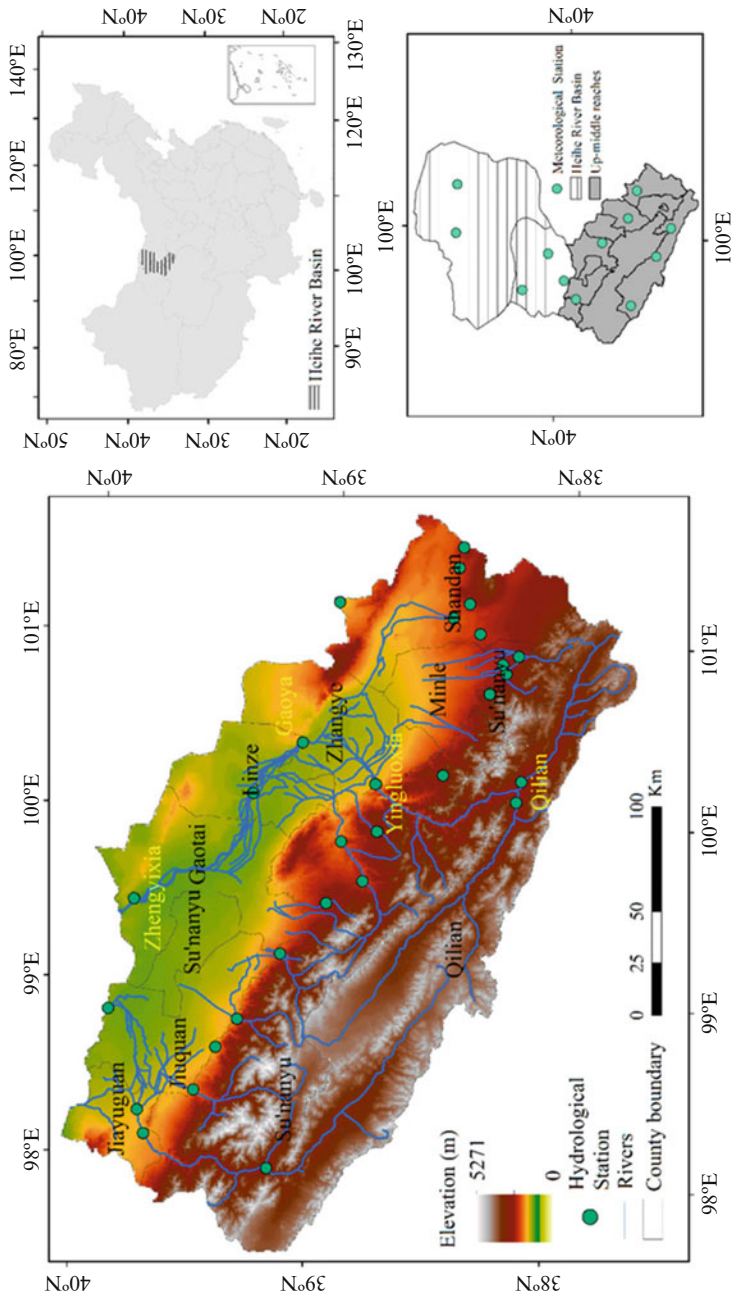
The results of this study on the relationship between forestation and water yield differ from that obtained in some other studies. For example, Scott et al. (2004) showed that forestation can cause a reduction in water yield. However, the belief is based on the assumption of a constant relationship between precipitation and ET; that is, a reduced ET can logically lead to a gain of water yield. However, if this assumption is not true or if the relationship between precipitation and ET varies over time and space, the simple logic may be not tenable. Besides, forestation practices may cause the decrease of annual water yield due to the increase of ET. For any statistical tests, streamflow data must be first naturalized to account for other water uses. Moreover, the majority of the statistical studies are experiments at the plot scale, whereas there are few watershed-scale studies. Therefore, using ET information to infer water yield may not always be correct.

It is difficult to accurately simulate the hydrological processes because they are influenced by a myriad of biophysical factors. The results of this study suggest that the effect of forestation on water yield is area specific and forestation has positive effects on the water yield in the mountainous area. Several inferential studies have also demonstrated the uncertainty and variability of forestation on potential hydrological responses across China due to the large differences in climate and soil conditions (Wei et al. 2005). At the same time, most studies have focused on understanding whether forests are important in influencing water protection and soil erosion, and almost none of them have aimed at determining what percentage of forested land in a watershed or a landscape must be protected in order to minimize negative impacts on water resources. This question is important and must be answered in order to provide reference information for designing and implementing sustainable water and forest management practices.

## **Water Resources in Response to Land Use Change in the Middle and Upper Reaches of the Heihe River Basin**

The HRB covers an area of approximately 130,000 km<sup>2</sup>, which can be divided into three parts: (a) the upper reach region, including most part of Qilian County of Qinghai Province and some parts of Sunan County, where the supply of water mainly comes from the Qilian Mountains in the upper reach; (b) the middle reach region, including Zhangye city (Zhangye district, Sunan, Gaotai, Linze, Minle, and Shandan county) and Jiuquan and Jiayuguan cities, which is the main water consumption area as an irrigation agriculture economic zone; and (c) the lower reach region, including parts of Jinta county and Ejin Banner of Inner Mongolia Autonomous Region, which is mainly dominated by the desert animal husbandry (Fig. 7). Among the three parts, the upper reach is the main source of water, while the middle reach region (especially Zhangye city) is a highly developed irrigation agriculture zone in the HRB, with an agricultural history of about 2000 years, where about 90%





**Fig. 7** Geographic location of the upper and middle reach of the HRB (Reprinted from Li et al. (2015) with permission of Sustainability)

of the available surface water are used for agricultural irrigation, leading to strong competitions for water between irrigation agriculture and natural ecosystems (Hu et al. 2015). In this case, we selected the upper and middle reach as the study area to detect the impacts of scenario-based land use/cover change on hydrological process, with the aim of figuring out the relationship between water availability and land use changes, and the optimal land use for adapting to water scarcity.

## Model Inputs

In this section, we aim to investigate the relationships between water resource availability and land use changes, mainly based on the clarification of the hydrological process responses to land use changes that are simulated with different water constraint scenarios. We apply the SWAT model within the upper and middle reaches of the HRB to quantify the corresponding hydrological processes. The following inputs were prepared and used for the simulation.

### 1. Topographic and Soil Data

The topographic data include elevation, slope and aspect, flow direction, and flow accumulation. The topographic data were obtained from a digital elevation model (DEM) of Shuttle Radar Topography Mission (SRTM) with 90 m resolution. The soil data mainly include soil texture, soil depth, and soil drainage attributes. The soil data with the resolution of 1 km were derived from the Harmonized World Soil Database (HWSD) provided by the Environmental and Ecological Science Data Center for West China (WestDC) (Table 4).

### 2. Hydrometeorological Data

To simulate the daily hydrological processes with the SWAT model, meteorological data are required, including daily precipitation, minimum and maximum air temperatures, solar radiation, wind speed, and relative humidity. In general, the historical daily meteorological observation data sets of the HRB were collected from meteorological stations maintained by China Meteorological Administration (CMA) (Table 6). The meteorological data were obtained from 12 meteorological stations located within the HRB, and the data were available for 1980–2010. In addition, the historical hydrological data for the SWAT model calibration and validation, including the river flow data and discharge data of the hydrological stations, were obtained from the People's Republic of China Hydrological Yearbook-Inland Rivers Hydrological Data. The hydrological data of 2007 and 2008 were used for SWAT calibration and validation, respectively (Table 4).

### 3. Land Use Data

The historical land use data with a resolution of 1 km used in this study were derived from the database of the Resources and Environment Scientific Data Center, Chinese Academy of Sciences (Table 4). The land use data covers four periods: the late 1980s, mainly including the data from 1986 to 1989; the middle of the 1990s, including the data from 1995 to 1996; the late 1990s, including the data from 1999 to 2000; and the late 2000s, including the data from 2005 to 2008. In the late 1990s, the Chinese Academy of Sciences organized 8 research

**Table 4** Input data used in the SWAT model (Reprinted from Li et al. (2015) with permission of Sustainability)

Data	Data sources	Information	Date/period	Description
Digital elevation models (DEM)	Shuttle radar topography mission (SRTM) <a href="http://srtm.csi.cgiar.org/">http://srtm.csi.cgiar.org/</a>	Raster, 90 m	2000	
Land use	Resources and environment scientific data center (RESDC), Chinese Academy of Sciences	Raster, 1 km	2000, 2008	Including six land use types
Soil data	Environmental and ecological science data Center for West China (WestDC) <a href="http://westdc.westgis.ac.cn/">http://westdc.westgis.ac.cn/</a>	Raster, 1 km	1995	Parameters including saturation, texture, and hydraulic condition are calculated using a soil-plant-atmosphere-water (SPAW) field and pond hydrology model
Meteorological data	China Meteorological Administration (CMA)	Daily	1980–2010	Daily temperature and precipitation data from the weather stations at Tuole, Yeniugou, Qilian, Shandan, and Zhangye
Hydrological data	People's republic of China hydrological yearbook-inland rivers hydrological data	Daily	2007, 2008	Discharge data, at hydrological stations Zhengyixia and Yingluoxia
Glacier	Environmental and ecological science data Center for West China (WestDC) <a href="http://westdc.westgis.ac.cn/">http://westdc.westgis.ac.cn/</a>	Raster, 1 km	2000	Attributes including width, length, and depth

institutions, comprising about 100 scientists, to conduct its second nationwide land cover and land use classification project. The research team developed the national land use database by visual interpretation and digitalization based on remotely sensed digital images by the US Landsat TM/ETM satellite with a spatial resolution of 30 m. Further the interpretation of TM images and land cover classifications was validated through extensive large-scale field surveys. After the ground truthing, the results showed that the average interpretation

accuracy for land cover classification were higher than 90% for each period (Liu et al. 2014). The land use data used in this study were composed of six land use types, including cultivated land use, forest land, grassland, water area, built-up land, and unused land. We adopted the land use data of years 2000 and 2008, among which the land use data of the year 2008 were adopted for the accuracy assessment of the simulation with the Dynamic Land System (DLS) model. Land use properties were obtained directly from the SWAT model database, and the glacier data were obtained from WestDC (Table 4).

## Scenario-Based Land Use Simulation

### 1. Land Use Scenarios

Facing water scarcity, it is of great significance to integrate water and land use management. In the HRB, contradictions among water and land resource utilization for agricultural production, economic development, and ecological construction will be an outstanding issue for a long period in the future. The water constrains will be the key factor of land use/cover changes in the basin. Especially, in the middle reach region, which is characterized by irrigation agriculture, the water supply is critical to the regional development. According to the “water allocation scheme” in the HRB, the water amount for the middle reach will be strictly controlled to assure the supply of water for ecosystem conservation in the lower reach region. In this regard, it is urgent to improve the water utilization ratio in the middle reach; the water availability will be increased if the water utilization ratio were improved, which will significantly influence the land use pattern. Thus, we aim to detect how water resource constrain will affect the land use pattern and further how such land use/cover change will affect the hydrological process.

Particularly, Zhangye city covers about 90% of the middle reach, and more than 80% of artificial oasis, 92% of the population, 83% of GDP, and 95% of the arable land of the HRB concentrated in the Zhangye city (Shi et al. 2011). The water resource in Zhangye city is the main constrain of the socioeconomic development. According to the water amount from the upper reach of the Heihe River, Zhang et al. (2007) designed three scenarios of available water amount used in Zhangye city, which are  $18.0 \times 10^8 \text{ m}^3$ ,  $26.5 \times 10^8 \text{ m}^3$ , and  $35.0 \times 10^8 \text{ m}^3$ , respectively, related to 68%, 100%, and 132% of water utilization ratio, with circulation and repeat utilization between surface water and groundwater taken into account within the study area. In each scenario, the water resources for ecological utilization are considered according to ecological environmental conditions and total amount of available water, designed as  $2.636 \times 10^8 \text{ m}^3$ ,  $4.967 \times 10^8 \text{ m}^3$ , and  $7.625 \times 10^8 \text{ m}^3$ , respectively. Further aiming to maximize the total socioeconomic utility of water resources, the changing trend of six land use types from 2001 to 2020 under three water resource constraint scenarios using linear programming was calculated, with the constraint conditions of water quantity, total land areas, total population, and macro-scheme of regional development and ecological balances in Zhangye city.

In this section, taking the land use data of the year 2000 as baseline, we simulated the land use till the year of 2020 under the three land use structure change scenarios which correspond to three water utilization ratios (low-level water utilization ratio scenario (S1), middle-level water utilization ratio (S2), and high-level water utilization ratio (S3)).

## 2. Land Use Simulation

The DLS model is a collection of programs that simulate the pattern changes in land uses by conducting scenario analysis of the area of land use/cover change (Deng 2011). The model analyzes causes of the dynamics of land use patterns, simulates the process of land use/cover change, and assists land use planning and land management decisions. The DLS model can export a macroscopic pattern change map of land uses at high spatial and temporal resolution by estimating the effects of changes in the spatial pattern of driving factors, formulating land use conversion rules and scenarios of land use change and simulating dynamic spatiotemporal processes of land use/cover change. The simulation process includes the analysis on driving mechanism, scenario design, and spatial allocation of land cover, and the DLS model has been proved to be robust to simulate the land cover change at the pixel scale (Deng et al. 2010).

The analysis of the driving factors aims to estimate the statistical relationship between land use pattern successions and driving factors, which theoretically provides the response function for each land use types. All the driving factors are endowed with corresponding weights according to certain principles which can be assumed not to change during a short period, while the driving factors vary with time. In this case study, after collinearity diagnosis, we selected 17 driving factors to conduct the logistical regression analysis and got the relationships between the frequency of each land use type and the driving factors (Table 5). The results showed that the 17 driving factors can reasonably explain the spatial patterns of the six land use types. Specifically, the driving factors at the significant level and the driving mechanisms were different for each land use types. For example, the change of cultivated land was significantly driven by 16 driving factors, while the changes in the water area and built-up land were significantly affected by less driving factors. For each land use type, we selected those specific significant driving factors for land use pattern simulation. Base on the driving mechanism, spatial disaggregation module in the DLS model can spatially explicitly convert the land demands into land use/cover change at various locations of the study area under different scenarios.

## 3. Performance of the DLS Model

Land use change models have widely been used to analyze the possible land use dynamics, which helps to support land use management and relevant policy-making. For further scientific application of land use change models, results obtained from these models are often assessed by comparing the simulated and actual spatial land use patterns, and one of the most commonly used methods is the Kappa coefficient of agreement (Congalton 1991). As land use datasets are

**Table 5** Relationships between the frequency of each land use type and the driving factors base on logistical regression (Reprinted from Li et al. (2015) with permission of Sustainability)

Driving factors	Cultivated land	Forest land	Grassland	Water area	Built-up land	Unused land
Slope	$-2.95 \times 10^{-3***}$	$1.15 \times 10^{-3***}$	$-0.49 \times 10^{-3***}$	$-0.74 \times 10^{-3***}$	$-1.44 \times 10^{-3***}$	$0.20 \times 10^{-3***}$
Aspect	$-1.52 \times 10^{-5***}$	$0.22 \times 10^{-5}$	$0.13 \times 10^{-5}$	$-0.33 \times 10^{-5}$	$-0.59 \times 10^{-5}$	$0.22 \times 10^{-5**}$
Elevation	$-2.54 \times 10^{-3***}$	$-0.47 \times 10^{-3***}$	$0.039 \times 10^{-3}$	$-0.73E-05***$	$-2.07E-05***$	$1.29E-05***$
Rain	$-1.32 \times 10^{-3***}$	$-0.93 \times 10^{-3***}$	$0.546 \times 10^{-3***}$	$-0.17 \times 10^{-3}$	$0.59 \times 10^{-3}$	$-0.88 \times 10^{-3***}$
Sun radiation	$-1.9 \times 10^{-2***}$	$-0.52 \times 10^{-2***}$	$0.15 \times 10^{-2***}$	$-0.69 \times 10^{-2***}$	$-0.28 \times 10^{-2}$	$-0.24 \times 10^{-2***}$
>0 °C accumulated temperature	$-0.0426 \times 10^{-4}$	$1.45 \times 10^{-4***}$	$1.48 \times 10^{-4***}$	$-2.007 \times 10^{-4***}$	$-0.93 \times 10^{-4}$	$-1.72 \times 10^{-4***}$
>10 °C accumulated temperature	$-2.02 \times 10^{-4***}$	$-2.36 \times 10^{-4***}$	$-1.55 \times 10^{-4***}$	$1.40 \times 10^{-4***}$	$0.32 \times 10^{-4}$	$2.88 \times 10^{-4***}$
Soil depth	-0.11***	0.07***	-0.027***	0.092***	-0.089	-0.0099*
Soil organic	-1.09**	2.52***	0.42	-0.83	-3.08	-1.47***
Soil pH	-0.72***	-0.25***	0.039	-0.20	-0.17	0.036
Population density	$1.97 \times 10^{-4*}$	$-9.45 \times 10^{-4***}$	$-1.4 \times 10^{-4}$	$4.58 \times 10^{-4}$	$0.50 \times 10^{-4}$	$7.00 \times 10^{-4***}$
GDP	$2.74 \times 10^{-3***}$	$-8.30 \times 10^{-3***}$	$-7.66 \times 10^{-3***}$	$-4.52 \times 10^{-3***}$	$7.72 \times 10^{-3***}$	$-24.05 \times 10^{-3***}$
Distance to express way	$-5.60 \times 10^{-2***}$	$-1.80 \times 10^{-2***}$	$-0.66 \times 10^{-2***}$	$0.33 \times 10^{-2}$	$-1.86 \times 10^{-2***}$	$1.20 \times 10^{-2***}$
Distance to highway	$1.2 \times 10^{-2***}$	$0.41 \times 10^{-2***}$	$-0.46 \times 10^{-2***}$	$0.38 \times 10^{-2}$	$0.45 \times 10^{-2}$	$0.69 \times 10^{-2***}$
Distance to province way	$-0.83 \times 10^{-2***}$	$-1.714 \times 10^{-2***}$	$-0.25 \times 10^{-2***}$	$-1.39 \times 10^{-2***}$	$0.52 \times 10^{-2}$	$1.09 \times 10^{-2***}$
Distance to water source	$-0.73 \times 10^{-2***}$	$1.42 \times 10^{-2***}$	$1.35 \times 10^{-2***}$	$-1.06 \times 10^{-2***}$	$0.19 \times 10^{-2}$	$-1.22 \times 10^{-2***}$
Distance to province capital	$-0.95 \times 10^{-2***}$	$-01.26 \times 10^{-2***}$	$0.55 \times 10^{-2***}$	$-0.15 \times 10^{-2***}$	$-1.42 \times 10^{-2***}$	$-0.59 \times 10^{-2***}$
Cons	71.36	4.73	-2.35	8.38	22.94	2.71

t statistics in parentheses: \* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

**Table 6** The contingency table of actual and simulated land use in 2008 (Unit: %) (Reprinted from Li et al. (2015) with permission of Sustainability)

Actual land use in 2008	Simulated land use in 2008						Total
	1	2	3	4	5	6	
1	8.3	0.0	1.2	0.3	0.7	1.1	11.6
2	0.2	5.9	2.8	0.1	0.0	0.8	9.8
3	1.4	2.6	25.2	0.4	0.1	5.2	34.8
4	0.3	0.0	0.4	0.3	0.0	0.5	1.7
5	0.6	0.0	0.0	0.0	0.2	0.1	0.9
6	1.1	1.3	5.2	0.5	0.1	33.0	41.2
Total	11.9	9.9	34.8	1.6	1.1	40.6	100

**Table 7** Accuracy of DLS land use simulation results assessed with Kappa statistics (Reprinted from Li et al. (2015) with permission of Sustainability)

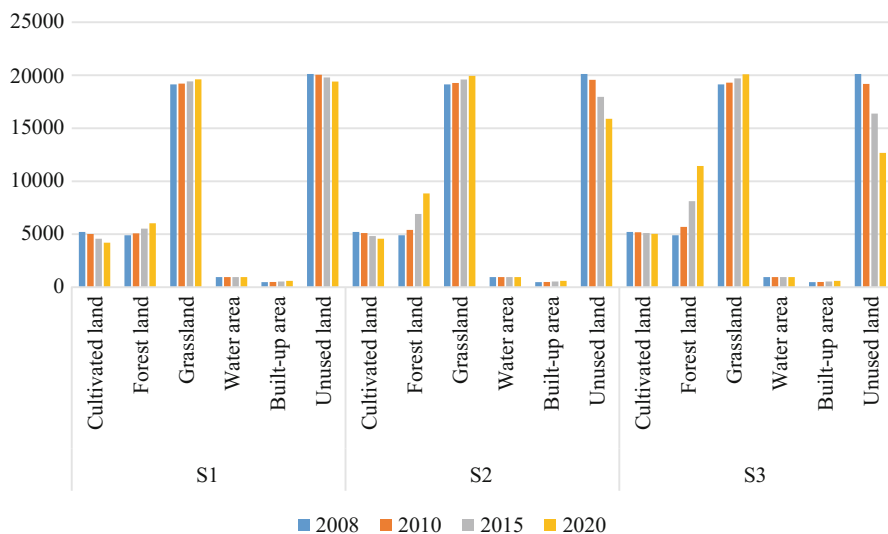
Agreement	Expected agreement	Kappa	Std. err.	Z	Prob >Z
72.83%	31.25%	0.605	0.003	182.830	0.000

categorical, Kappa can be used for accuracy assessment of the results of spatial simulation models (Hagen-Zanker and Lajoie 2008). In this study, the land use data of 2000 was used as the base data to simulate the land use data of 2008, and the agreement between simulated and actual land use pattern of 2008 was accessed using the kappa coefficient.

Table 6 gives the contingency table from the comparison of the actual and simulated land use of 2008, and the fields indicate the fraction of cells that occupies a particular land use type. Based on Table 6, the agreement and Kappa value were calculated, the results shown in Table 7 indicated that the agreement between the actual and simulated land use pattern is 72.83%, and the corresponding Kappa is 0.605. According to the classification criterion based on Kappa coefficient (Saraux et al. 2013), the Kappa value above 0.6 indicated that the agreement between the actual data and simulation results was good, and the DLS model was suitable for simulating the spatial pattern of land use in the upper and middle reaches of the HRB.

#### 4. Simulated Land Uses

Grassland, forest land, cultivated land, and unused land are the four major land use types in the upper and middle reaches of the HRB. Under the three water utilization ratio scenarios, the changing trend of the land uses are shown in Fig. 8 and Table 8. It mainly shows that the increase of water utilization ratio will mitigate the decrease of cultivated land. The increase of forest land and grassland shows a positive relationship with the water utilization ratio. As for the built-up land, it will expand more significantly if the water resource is more strictly restricted. In other words, with lower water availability, to get the optimal utilization and maximum utility, water resources will be more diverted to built-up land. In addition, the unused land greatly decreases along with the increase of water utilization ratio.



**Fig. 8** Land use structure changes under S1, S2, and S3 scenarios (Reprinted from Li et al. (2015) with permission of Sustainability)

Figure 9 shows the land use patterns under each scenario for 2008–2020, which was simulated with the DLS model based on logistic regression analyses in Table 5. During the simulation processes, the land use structure data of the whole Zhangye city was applied as the input data, and the development-restricted areas and other counties were taken as restricted region. The simulation results indicated that land use/cover change in the arid area is strongly constrained by water resources, especially for the forest lands. The land use/cover change during 2008–2020 was mainly dominated by substantial expansion of forest land and grassland and the shrinkage of the cultivated land and unused land, which would exert significant impacts on water quantity in this basin.

## Impacts of Land Use Change on Hydrological Process

### 1. SWAT Model Calibration and Validation

The SWAT model was performed on a daily time step to predict the impacts of land use/cover change on water flow. In the SWAT model, a basin is divided into multiple subbasins, which were then further divided into two or more hydrological response units (HRUs) on the basis of unique combinations of land use, soil, and slope class. These HRUs are defined as homogeneous spatial units characterized by similar geomorphological and hydrological properties (Neitsch et al. 2011). To generate the HRUs, we used two slope classes (0–25% and >25%), and we also used a threshold of 25% for slope class and 38 soil types. That is, slope classes and soil types that covered more than 25% of a subbasin area would become their own HRUs. Furthermore, we incorporated land use/cover into the SWAT model to generate the HRUs, as the study



**Table 8** Simulated areas of land use types under different scenarios (Unit: km<sup>2</sup>) (Reprinted from Li et al. (2015) with permission of Sustainability)

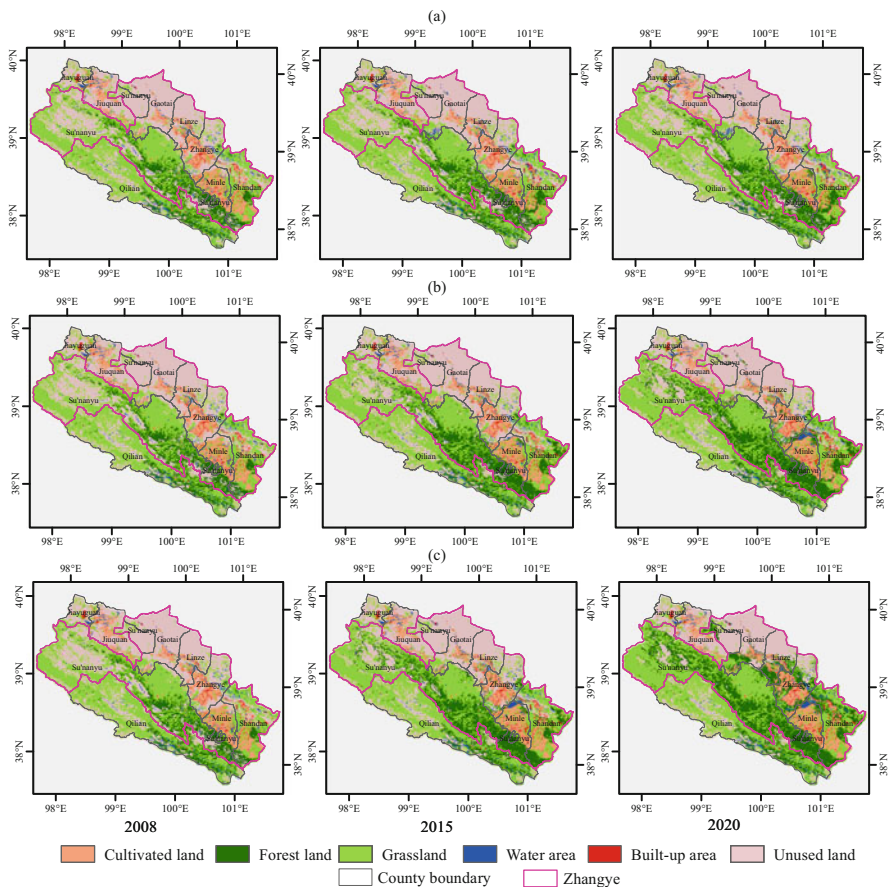
Land use types	2008	2020					
		S1		S2		S3	
		Area	Percent change (%)	Area	Percent change (%)	Area	Percent change (%)
Cultivated land	5217	4413	-15.4	4807	-7.9	5217	0
Forest land	4894	6031	23.2	8807	80	11,420	133.3
Grassland	19,135	19,525	2	19,866	3.8	20,029	4.7
Water area	957	917	-4.2	923	-3.6	911	-4.8
Built-up land	500	601	20.2	588	17.6	573	14.6
Unused land	20,113	19,329	-3.9	15,825	-21.3	12,666	-37

selected multiple HRUs in a subbasin to simulate and the HRU threshold is determined by the threshold percentage of land use/cover over subbasin area (5%) and soil over land use area (10%). Finally, 113 subbasins and 1171 HRUs were generated in the upper and middle reaches of the HRB. For each subbasin, a modified soil conservation service (SCS) curve number (CN) method, which integrates a slope factor, was applied to simulate the surface runoff (Wu et al. 2015a).

The SWAT model was calibrated for streamflow at the subbasin level for 2005–2007 based on the daily observed streamflow from Yingluoxia hydrological station in the upper reach of the HRB, where human activities are not intensive. With the first 2 years (2005–2006) used as a warm-up period, which were not considered in the calibration analysis, the data of 2007 were actually applied to calibrate the model. Validation of the model was conducted using the data of 2008. The model performance was evaluated using goodness-of-fit statistics such as the Nash and Sutcliffe model efficiency coefficient ( $E_{ns}$ ) and the coefficient of determination ( $R^2$ ). Figure 10 shows the calibration and validation results. During the calibration period, the  $E_{ns}$  was 0.88, and the value of  $R^2$  between the simulated and observed daily streamflows was 0.87. During the validation period, the  $E_{ns}$  was 0.87, and the value of  $R^2$  was 0.89. The simulated streamflow was considered to be accurate for values of  $E_{ns} > 0.75$  (Motovilov et al. 1999). These results suggest that the calibrated model can accurately simulate the streamflow in the HRB and confirm that the calibrated model with the set of optimized parameters can be used to examine the responses of hydrological processes to land use/cover change in the upper and middle reaches of the HRB.

## 2. Effects of Land Use Changes on Hydrological Processes

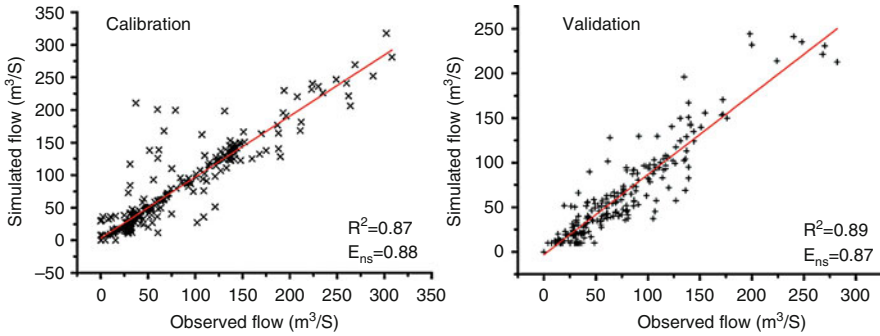
The influence of land use/cover change on the hydrological processes is a key factor in the rational allocation of water resources in the study area. It has been



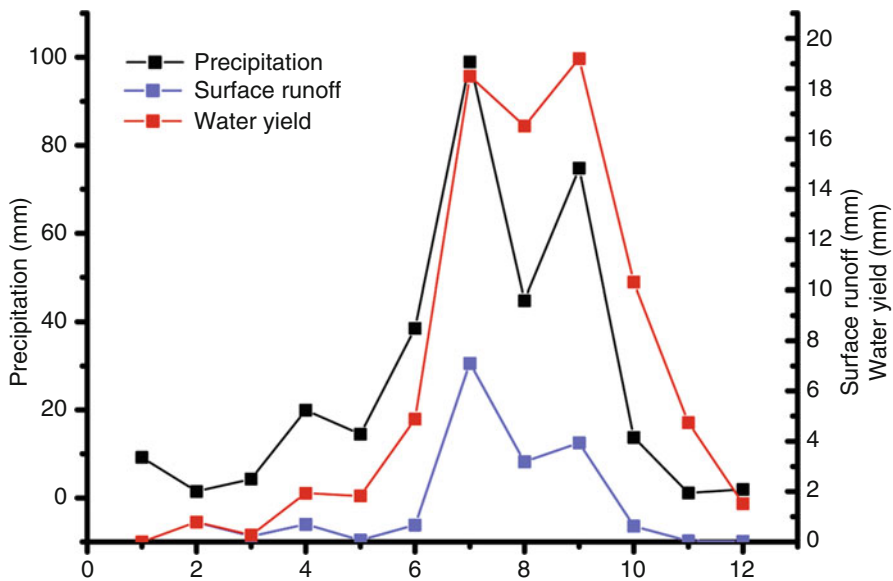
**Fig. 9** Simulate land use patterns under the (a) S1 scenario, (b) S2 scenario, and (c) S3 scenario in the upper and middle reaches of the HRB for the years 2008, 2015, and 2020 (Reprinted from Li et al. (2015) with permission of Sustainability)

widely reported that land use/cover change can affect the quantity of water resources. The data of Zhengyixia hydrological station located at the outlet of middle reach were used to examine the impact of land use/cover changes on hydrological processes. We choose surface runoff and water yield to analyze the impacts of land use/cover change. The monthly average values of the surface runoff, water yield, and precipitation were calculated (Fig. 11). The results showed that the impacts of land use/cover change on the surface runoff and water yield varied with the precipitation and seasons, and the changing trend of surface runoff and water yield were similar to that of the precipitation.

The simulated surface runoff and water yield in 2020 under the three scenarios were compared to the corresponding values in 2008 (the baseline year). Figure 12

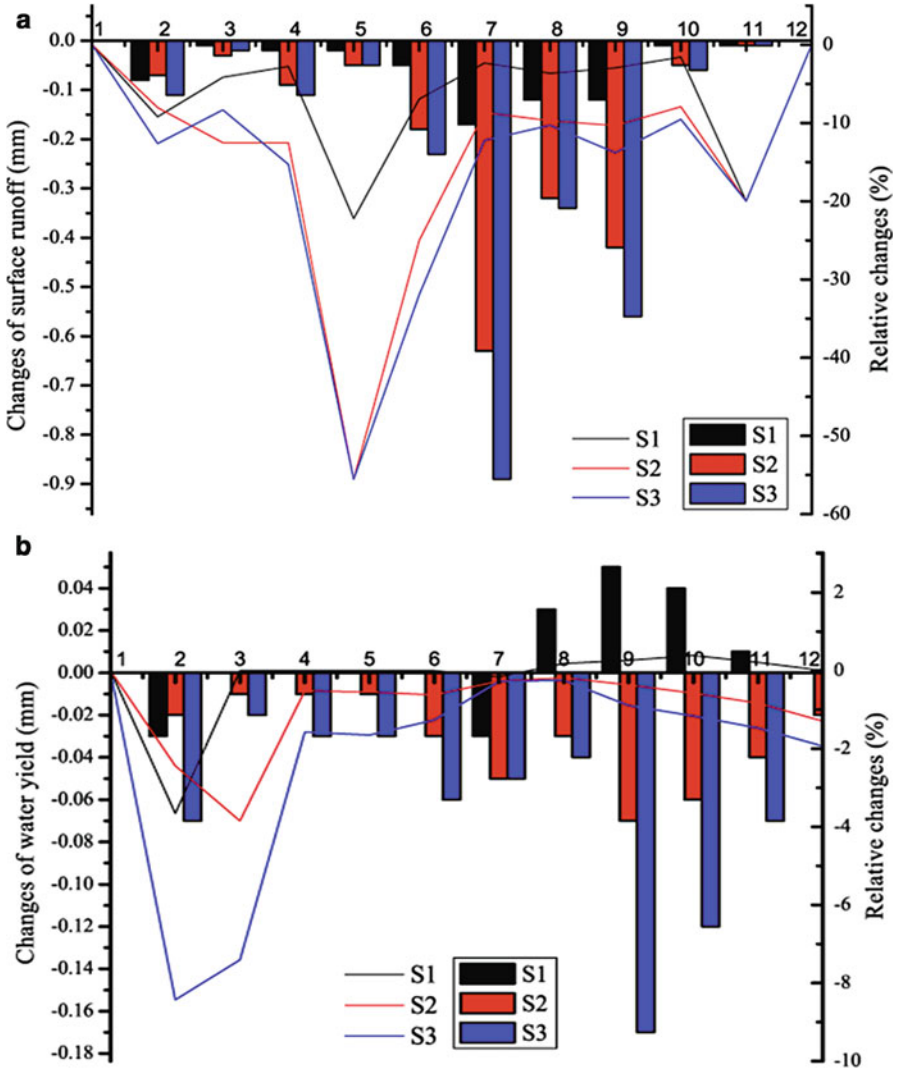


**Fig. 10** Scatter plot of observed and simulated flow for the calibration and validation periods (Reprinted from Li et al. (2015) with permission of Sustainability)



**Fig. 11** Multi-year averaged monthly precipitation, surface runoff, and water yield in the upper and middle reaches of the HRB (Reprinted from Li et al. (2015) with permission of Sustainability)

shows the changes in monthly surface runoff and water yield under different land use/cover change scenarios. Surface runoff is one of the major pathways contributing to the water yield. The monthly quick-response surface runoff showed a decreasing trend, with the relative changes ranging from  $-55.5\%$  to  $-1.6\%$  (Fig. 12a) under the three scenarios. The water yield would increase in May and June and decrease in all other months in scenarios S2 and S3, while the water yield will increase during August to November in scenario S1 (Fig. 12b). The overall changing trend of the surface runoff is consistent with the water yield in scenarios S2 and S3, both revealing a decreasing trend due to land use/cover change.



**Fig. 12** Changes in monthly surface runoff (a) and water yield (b) under S1, S2, and S3 scenarios for the year 2020 relative to 2008 (Reprinted from Li et al. (2015) with permission of Sustainability)

The major causes of the decrease in surface runoff are the expansions of forest land and grassland. There is a broad agreement among researchers that the streamflow change is likely to be caused by different kinds of forestry activities, such as afforestation, which may lead to lower runoff generation and reduction of water yield. Sahin and Hall analyzed empirical data from 145 sites around the world and found that increase in scrub cover decreased annual runoff, and a reduction in deciduous hardwood cover leads to an increase in runoff (Huang et al. 2003).

Yin et al. (2009) identified the order of runoff rate of different land use types as unused land > cultivated land > grassland > forest land. In this case study, forest land and grassland land were mainly converted from unused land, which inevitably led to the reduction of surface runoff, and the more intensive forest land and grassland expansion are, the more the reduction and fluctuation of surface runoff. As shown in Fig. 12a, surface runoff reduced most significantly under the S3 scenario, especially in July, August, and September, when the precipitation is much more intensive and the impacts of land use/cover change on the absolute runoff amount changes will be significantly higher.

As for the water yield, the scenario S1, with less grassland and forest land expansion compared to scenarios S2 and S3, showed an increasing trend of the water yield during August to November even though the surface runoff is decreasing. Different land use types have different characteristics of the soil water infiltration, and the infiltration rate of forest land is higher than grassland and unused land (Liu et al. 2013). As both surface runoff and base flow are the major two parts contributing to water yield, with unused land being converted to grassland and forest land, the infiltration will increase and further lead to an increase of base flow. The impacts of vegetation coverage on the base flow are complex. On the one hand, infiltration rates increased strongly with the increase in vegetative coverage, leading to more generation of base flow (Loch 2000). On the other hand, vegetation evaporation and transpiration will consume a large amount of water, and vegetation coverage change will alter and improve the water storage capacity of soil, which is not conducive to supplement the base flow (Li 2000). In addition, vegetation roots, especially the larger deep-rooted vegetation that increased absorption, may make base flow absorbed by vegetation, and consequently, the water yield declines (Walker et al. 1993). The smaller the rainfall and rainfall intensity, the greater the capacity of vegetation to intercept precipitation. During July to October, the rainfall is much larger than for other months, leading to a lower capacity of vegetation to intercept precipitation. Under S1 scenario, the vegetation coverage density is much lower than that under S2 and S3 scenarios, resulting in less decrease of surface runoff and less absorption of vegetation, and the positive effect on base flow overwhelmed the negative effect on surface runoff, finally resulting in an increase in the water yield during August to November under S1 scenario (Fig. 12b). While under the S2 and S3 scenarios, with much higher vegetation coverage, the negative impacts on surface runoff overwhelmed the positive impacts on base flow, finally leading to the increase of water yield. In particular, during the winter season (October to December), the decrease of water yield is even larger than the decrease in surface runoff, which means that the base flow during the winter season has also been negatively affected by the forest and grassland expansion in the basin.

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## Summary

Water scarcity and stress have attracted increasing attention as water is one of the most critical limited resources for sustainable development of the world. The HRB, a typical arid inland river basin in Northwest China, had experienced serious water

scarcity problems particularly during the 1960s–1990s, resulting from the extensive human activities and lack of effective management system, and consequently suffered a substantial deterioration of the ecosystem. In the HRB, there exist imbalances between the water supply and demand, with the characteristic of irrational water consumption structure, low water efficiency, and uneven temporal and spatial water distribution. In order to deal with the water scarcity problems, it is of great significant to consider the relationships between land use changes and water availability for sustainable water management.

Water resource constraints are a critical factor affecting land use demand for socioeconomic development and ecological conservation and further resulting land use/cover change, which will affect the water supply through influencing the hydrological processes. Understanding the interactions between water resources and land use change is crucial for sustainable water resource and land use management. The upper reach of the HRB is crucial for the basin's water supply, as it is the water source area of the whole basin. In the upper reach region, it is of high priority to identify the relationship between forests and water yield. It is shown that there was a significant positive relationship between forestation and water yield in the upper reach of the HRB during 1980–2010. The annual water yield increased by 1.31 mm when the forest cover increased by 1%, and the surface runoff reduced 1.84 mm for every 1% increase in the forest cover, which indicated that the forest land has “sponge” effects on the water resource in the mountainous watershed. Further, we chose the upper and middle reaches of the HRB, which is the major region of water consumption, to clarify the relationship between water availability and land use changes. First, we examined the possible land use/cover changes under different water utilization levels, with the higher water utilization ratio implying more water available for socioeconomic development and ecological conservation, which can further ease the decreasing trend of cultivated land in the irrigation agriculture area and stimulate the expansion of forest land and grassland. Further, based on the simulated land use data with unchanged climate conditions, we conducted quantitative analyses of the impacts of land use/cover change on the surface runoff and water yield in the upper and middle reaches of the HRB for the year 2008–2020. The results indicated the surface runoff and water yield both changed when there was forest and grassland expansion. The impacts of land use/cover change on hydrological processes is complex, and the surface runoff showed a decreasing trend along with increasing forest land and grassland under the three scenarios, while the water yield generally showed a decreasing trend. Exceptionally, the water yield showed an increasing trend during August to November under S1 scenario, in which the expansion of forest land and grassland was much lower than that under S2 and S3 scenarios, and the decreasing trend in water yield under S3 scenario is significantly higher than that under the S1 and S2 scenarios. With the higher water utilization ratio and the aim to maximize the socioeconomic utility of water resources, the higher water availability would lead to the expansion of forest land and grassland, which will in return exert negative impacts on the water yield, resulting in less water availability. This indicates that even if the water utilization ratio increases, the unreasonable allocation of water resources may exert negative impacts on the

water resource, and therefore it is very necessary to reasonably allocate the water resources for different land use demand.

The water and land use planning should consider not only the current socio-economic utility of water resources but also the future possible response of hydrological processes to the land use/cover change, and it is essential to carry out integrated water and land use management and consider the responses of hydrological process to land use/cover change resulted from water and land use management. The long-term water resource planning should be flexible and adaptable to changes due to these responses, and there is still considerable potential to improve the integrated modeling and analyses of water resources in the HRB and other basins with similar conditions.

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