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Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China

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SUMMARY

Land use and climate are two main factors directly influencing catchment hydrology, and separation of their effects is of great importance for land use planning and water resources management. Using the SWAT (Soil and Water Assessment Tools) model, we assessed the impacts of land use change and climate variability on surface hydrology (runoff, soil water and evapotranspiration) in an agricultural catchment on the Loess Plateau of China. Results indicated that SWAT proved to be a powerful tool to simulate the effect of environmental change on surface hydrology. The Nash–Sutcliffe model efficiency (Ens), Percent bias (PBIAS) and ratio of root mean square error to measured standard deviation (RSR) for annual flow was 0.87, 4.0%, 0.36 during calibration period and 0.87, 2.5%, 0.36 during validation periods, respectively. During 1981–2000, about 4.5% of the catchment area was changed mainly from shrubland and sparse woodland to medium and high grassland, and climate changed to warmer and drier. The integrated effects of the land use change and climate variability decreased runoff, soil water contents and evapotranspiration. Both land use change and climate variability decreased runoff by 9.6% and 95.8%, respectively, and decreased soil water contents by 18.8% and 77.1%. Land use change increased evapotranspiration by 8.0% while climate variability decreased it by 103.0%. The climate variability influenced the surface hydrology more significantly than the land use change in the Heihe catchment during 1981–2000; therefore, the influence of climate variability should be considered and assessed separately when quantifying the hydrological effect of vegetation restoration in the Loess Plateau.

Introduction

Land use and climate are two important factors influencing hydrological conditions. For example, land use change can result in change of flood frequency (Brath et al., 2006; Crooks and Davies, 2001), severity (De Roo et al., 2001), base flow (Wang et al., 2006), and annual mean discharge (Costa et al., 2003), while climate variability can change the flow routing time, peakflows and volume (Changnon and Demissie, 1996; Prowse et al., 2006). However, non-linear relationships, multiple causation, lack of mechanistic understanding and lag effects together limit our ability to diagnose causes (Allan, 2004). Hence, distinguishing effects of land use changes from concurrent climate variability poses a particular challenge (Lioubimtseva et al., 2005; Tollan, 2002). As this information is important for land use planning and water resources management, it is necessary to quantify the extent to which land use change and climate variability influence the hydrological conditions.

To assess the hydrological effects of environmental change, several methods were developed, which mainly fall into three groups: paired catchments approach, time series analysis (statistical method) and hydrological modeling. Paired catchments approach is often considered as the best method to compensate for climate variability in small experimental catchments. However, it is difficult to be applied to catchments other than small catchments, for it is difficult to find two similar medium or large-sized catchments and even the same catchment may change greatly at different stages (Lorup et al., 1998). Time series analysis is a statistical method that is easy to realize, but it can only analyze the hydrological effects of environment change simply because it lacks of physical mechanism. Hence, there is a need for use of a more comprehensive and physically based tool in order to obtain as much information as possible from limited existing data. Hydrological models provide a framework to conceptualize and investigate the relationships between climate, human activities and water resources (Jothityangkoon et al., 2001; Leavesley, 1994), among which distributed hydrological models have important applications because

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they relate model parameters directly to physically observable land surface characteristics (Legesse et al., 2003).

With the above methods, a series of research results were achieved on the hydrological response to environmental change. At different spatial and temporal scales, the prevailing variables and the extent to which land use and climate affect the hydrological condition often vary. Spatially, land use impacts on peak flows were generally most pronounced at small scales, such as on a patch, field or hillslope (Tollan, 2002); however, the impact of land use change on the annual water balance was relatively small at large catchment scales due to compensating effects in a complex catchment (Fohrer et al., 2001). Temporally, the short-term impacts of land use change and climate variation could often be seen on the peak runoff rate while the long-term impacts were more apparent on the average-annual runoff (Brath et al., 2006; Costa et al., 2003; Prowse et al., 2006). The combined effects of land use and climate variability were also studied. For example, the effects of land use change on river flows were more evident in the arid climates, where the low river flows were more sensitive to land use change (Bultot et al., 1990; Naef et al., 2002).

The Loess Plateau is situated in north China, and occupies an area of 430,000 km^2. It is covered with highly erodible aeolian deposits. It has a semiarid to sub-humid climate with most precipitation falling in summer months largely in forms of heavy storms. Canopy cover degree is generally low, and land use is predominantly cultivated croplands and improved grasslands. The Yellow River, which has highest sediment concentration in the world (Xu, 2002), runs through the Loess Plateau. Due to frequent large rainfall storms in summer months, steep landscape, low vegetable cover, and highly erodible loessial soil, the Loess Plateau has become one of the most severely eroded areas in the world (Zhang and Liu, 2005).

Since 1950s, a series of conservation measures including replanting trees and improving grasslands were implemented to control soil erosion and maintain agricultural productivity. These measures improved vegetation coverage, altered land use patterns, and resulted in changes in surface hydrology. For instance, Liu et al. (2003), based on the simulated results of the SWAT's model, concluded that climate variation decreased runoff by 109% while land use change increased runoff by 10% in the source region of the Yellow River during 1980–1990. Hessel et al. (2003) used a soil erosion model of Limburg Soil Erosion Model (LISEM) to simulate the effects of land use and management strategies for reducing runoff and erosion rates in the Danangou catchment in the Loess Plateau, and reported 5–15% decreases in runoff volume and soil erosion amounts by implementing conservation measures under the present land use pattern. However, a 40–50% decrease for discharge and 50–60% decrease for soil loss were predicted if the land use pattern was changed according to the slope-steepness-based conservation strategies. Huang and Zhang (2004) found that mean annual surface runoff and baseflow decreased by 32% during1967–1989 due to the implementation of conservation practices in the Jialuhe River catchment after removing the contribution of precipitation variation. Mu et al. (2007) statistically separated the impacts of precipitation and land use change in the HeLong region of the Yellow River from 1950s, and reported 29% and 71% decreases in runoff caused by changes in precipitation and land use, respectively. As reported above, runoff changes in the Loess Plateau were the results of both changes in precipitation and human activities. However, different opinions still exist on the extent of the total runoff change as well as to what extent each factor can influence that change.

Though hydrological effects of land use change and climate variation occur at all spatial scales, studies at regional and local scales are more relevant to provide important information to local economical and societal developments and environment protection (Lahmer et al., 2001). The objective of this study was to quantify the impacts of past land use change and climate variability on surface hydrology (runoff, soil water contents and evapotranspiration) in the Heihe catchment in the Loess Plateau and to provide decision-makers information they need to promote vegetation restoration, water resources management and sustainable development.

Materials and methods

Catchment description

The Heihe River flows eastward through the Huating, Chongxin, Lingtai and Jingchuan Counties of the Gansu Province before discharging into the Jinghe River in the Changwu county of the Shanxi Province (Fig. 1). The Heihe catchment is located between 106°.29′–107°.47′E and 35°.03′–35°.19′N, and the elevation is about 1000–2500 m. The drainage area is about 1506 km^2 and is composed of two main kinds of terrains: tableland and gully. The soil is predominantly silt loam with silt content greater than 50% (two soil series: Heilutu and Huangmiantu). The mean annual precipitation ranges from 522 mm to 608 mm with 54.0–57.5% falling in July through September, and the mean annual temperature ranges from 6.3 to 11.7 °C. The land use mainly includes three types, i.e. farmland, woodland and grassland, as the area of farmlands are always more than 50%, the catchment is a typical agricultural one.

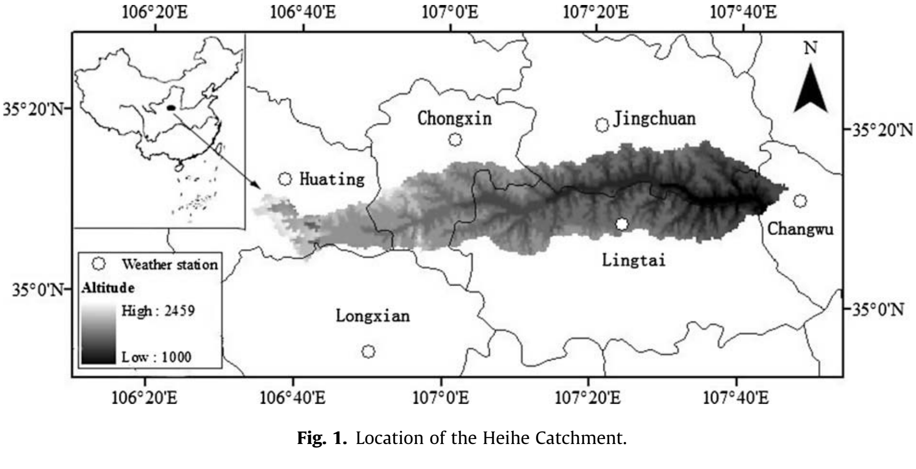

Fig. 1. Location of the Heihe Catchment.

SWAT description

SWAT is a watershed-scale, physically based distributed hydrological model developed to predict the impact of land management practices on hydrologic and water quality response of complex watersheds with heterogeneous soils and land use conditions (Arnold et al., 1998). The model partitions a watershed into subwatersheds and organizes input information for each subwatershed into the following categories: climate, hydrologic response units (HRUs), ponds/wetlands, groundwater, and the main reach draining each subwatershed. As a process-based model, SWAT can be extrapolated to a broad range of conditions that may have limited observations; therefore, it is widely used to study the impacts of environmental change (e.g. Bouraoui et al., 2004; Chaplot, 2007; Eckhardt and Ulbrich, 2003; Rosenberg et al., 2003). The SWAT provides several options when simulating hydrologic processes, which can be chosen by users based on their data availability. For example, infiltration can be simulated with the Curve Number or Green-Ampt method and potential evapotranspiration (PET) with Hargreaves, Priestley-Taylor, or Penman–Monteith equation.

Data collection

Topographic, land use/cover, soil and hydro-meteorological data required by SWAT for this study were generated or collected as follows. The DEM (1:250,000), soil types map (1:500,000) and land use maps (1:100,000) of 1985 and 2000 were provided by the Environmental and Ecological Science Data Center for West China. Soil properties were obtained from the Chinese Soil Database of the Institute of Soil Science, and land use properties were directly from the SWAT model database. The runoff data of the Heihe River were obtained from the Scientific Database of the Yellow River Hydrology which included annual data during 1972–2000 and monthly data during 1972–1987. The meteorological data during 1972–2000 were collected from the China Meteorological Administration (CMA), which included daily data of precipitation, maximum and minimum temperature, solar radiation, humidity, wind speed and direction for six weather stations in or near the Heihe catchment.

Methodology

SWAT calibration and validation

After preparing the necessary maps (landuse, soil, DEM) and database files (climate, soil properties, etc.), a new SWAT project was built for the Heihe watershed. Through delineating subwatershed and creating HRU (Hydrological Response Unit), the SWAT project can simulate the water balance of the Heihe watershed. Curve Number and Priestley-Taylor equations were chosen for simulation of infiltration and potential evapotranspiration in this study, respectively. However, model calibration and validation are necessary to improve SWAT performance.

Model calibration is usually carried out by adjusting values of model parameters, but SWAT model has a large number of parameters, therefore, identification of the sensitive parameters to improve the calibration efficiency is necessary. LH-OAT (Latin Hypercube sampling based on One Factor at a Time) method (van Griensven et al., 2006), which is incorporated in SWAT as an extension, was used to identify parameters that have a significant influence on model simulations. LH-OAT starts with taking N Latin Hypercube sample points for N intervals, and then varying each LH sample point P times by changing each of the P parameters one at a time. The method operates by loops and each loop starts with a Latin Hypercube point. Around each Latin Hypercube point j, a partial effect $S_{i,j}$ for each parameter e_i is calculated as:

$$S_{i,j} = \left| \frac{100 * \left(\frac{M(e_1,\ldots,e_i * (1+f_i),\ldots,e_p) - M(e_1,\ldots,e_i,\ldots,e_p)}{[M(e_1,\ldots,e_i * (1+f_i),\ldots,e_p) + M(e_1,\ldots,e_i,\ldots,e_p)]/2} \right)}{f_i} \right|$$

where $M(\ldots)$ refers to the model functions, f_i is the fraction by which the parameter e_i is changed (a predefined constant) and j refers to a LH point. A final effect is calculated by averaging these partial effects of each loop for all Latin Hypercube points. The final effects can be ranked with the largest effect being given rank 1 and the smallest effect being given a rank equal to the total number of parameters. Thus the impacts of each parameter on the model results can be quantified and the most sensitive parameters can be identified.

After identifying the sensitive parameters, model calibration can be carried out. Annual runoff of 1972–1987 and land use map of 1985 were used for model calibration, and annual runoff of 1988–2000 and land use map of 2000 for model validation. Though the measured monthly runoff data was only from 1972 to 1987, they were split into two periods for calibration (1972–1980) and validation (1981–1987) of SWAT to further improve the performance of SWAT. It should be noted that calibration for stream flow is first done for average annual conditions. Once completed, the calibrated values are used as first approximation and are fine-tuned using monthly records (Neitsch et al., 2002) until the simulated results are acceptable according to the model evaluation guidelines.

Nash–Sutcliffe model efficiency (Ens), Percent bias (PBIAS) and root mean square error-observations standard deviation ratio (RSR) (Moriasi et al., 2007) were used to assess the predictive power of the SWAT model. The equations were given as follows:

$$\mathrm{Ens} = 1 - \sum_{i=1}^{n} (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})^2 \bigg/ \sum_{i=1}^{n} (Q_{\mathrm{obs}} - \mathrm{mean}(Q_{\mathrm{obs}}))^2$$

where Q_{obs} and Q_{sim} is the measured and simulated data, respectively, and n is the total number of data records. The optimal value of Ens is 1.0. As Ens approaches 1.0, the model simulates the measured data more accurately. When Ens is negative, the model is a worse predictor than the measured mean.

$$\mathrm{PBIAS} = \sum_{i=1}^{n} (Q_{\mathrm{obs}} - Q_{\mathrm{sim}}) \bigg/ \sum_{i=1}^{n} Q_{\mathrm{obs}}$$

The optimal value of PBIAS is 0. Low-magnitude values indicate accurate model simulation; positive values indicate model underestimation bias; and negative values indicate model overestimation bias.

$$\begin{aligned} \mathrm{RSR} &= \mathrm{RMSE}/\mathrm{STDEV}_{\mathrm{obs}} \\ &= \sqrt{\sum\nolimits_{i=1}^{n} (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})^2} \bigg/ \sqrt{\sum\nolimits_{i=1}^{n} (Q_{\mathrm{obs}} - \mathrm{mean}(Q_{\mathrm{obs}}))^2} \end{aligned}$$

RSR varies from the optimal value of 0, which indicates zero RMSE or residual variability and therefore perfect model simulation, to a large positive value. The smaller RSR, the better the model simulation performs.

Analyzing the climate trend

A non-parametric method, i.e. Mann–Kendall test was used to analyze the monotonic trend of annual and monthly precipitation and mean temperature from six weather stations. The Mann–Kendall test statistic is given as follows (Partal and Kahya, 2006; Xu et al., 2003):

$$Z = \begin{cases} (S-1)/\sqrt{Var(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ (S+1)/\sqrt{Var(S)} & \text{if } S < 0 \end{cases}$$

in which

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \operatorname{sgn}(x_k - x_i)$$

$$\operatorname{sgn}(x_k - x_i) = \begin{cases} +1 & \text{if } (x_k - x_i) > 0 \\ +1 & \text{if } (x_k - x_i) = 0 \\ +1 & \text{if } (x_k - x_i) < 0 \end{cases}$$

$$Var(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] \Big/ 18$$

where the x_k and x_i are the sequential data values, n is the length of the data set, the notation t is the extent of any given tie and Σt denotes the summation over all ties. The null hypothesis H_0, i.e. there is no trend in the dataset, is accepted if $-Z_{1-a/2} \leqslant Z \leqslant Z_{1-a/2}$.

Kendall slope is another very useful index in Mann–Kendall test, which quantifies the magnitude of the monotonic trend and is given as

$$\beta = \operatorname{Median}\left(\frac{x_i - x_j}{i - j}\right), \quad \forall j < i$$

in which $1 < j < i < n$. The estimator β is the median over all combination of record pairs for the whole data set. A positive value of β indicates an ‘upward trend’, and a negative value of β indicates a ‘downward trend’.

Evaluating the effect of land use change and climate variability

To evaluate the effect of land use change and climate variability on hydrology, the approach of one factor at a time was used (i.e., changing one factor at a time while holding others constant). Meteorological data of the two time-slices of 1981–1990 and 1991–2000 were selected, and each time-slice included one land use map. The land use maps of 1985 and 2000 were used to represent the land use patterns of 1980s and 1990s for the two time-slices, respectively. The calibrated SWAT model was run for each of the four combinations of two time-slices and two land use maps (called four scenarios hereafter). The influences of the land use change and climate variability were quantified by comparing the SWAT outputs of the four scenarios as follows:

- S1: 1985 land use and 1981–1990 climate.
- S2: 2000 land use and 1981–1990 climate.
- S3: 1985 land use and 1991–2000 climate.
- S4: 2000 land use and 1991–2000 climate.

Results and discussion

Land use change

The dominant land use types of the Heihe catchment were farmlands and medium grassland (Table 1), which accounted for about 90% of the entire area (89.4% and 92.3% for 1985 and 2000, respectively). There were two main trends of land use changes during 1985–2000: the decrease of forest and the increase of grassland and construction land (areas for residence, traffic, industry and mining). Compared with 1985, woodland, shrubland and sparse woodland of 2000 decreased by 4.3, 26.2 and 23.6 km^2, respectively; while high and medium grasslands and construction land of 2000 increased by 8.6, 46.4, and 2.2 km^2, respectively; Farmland and water body changed little compared to their baselines of 1985.

Table 2 lists the main land use conversions. Overall, the land use types of the Heihe catchment changed little from 1985 to 2000, and only about 4.5% of the entire catchment underwent type conversions. There were mainly eight type changes whose areas were more than 1 km^2 (Table 2). The changes fell into two groups: one was the mutual conversion between woodland and grassland, the other was the conversion of farmland to other land use. Different land use pattern should have different effects on rainfall-runoff relationships. For example, the conversion of grassland to woodland would decrease runoff, and a decrease in woodland and an increase in construction land would increase runoff.

Climate variability

Taking $P = 0.1$ as the significant level, the monotonic trends of annual precipitation and temperature were different. According to the Kendall slopes, annual precipitation for all weather stations tended to decrease during 1972–2000; however, the trend was significant only for one station. In contrast, annual mean temperature increased significantly for five weather stations (Table 3). The change trend can be analyzed in details from monthly data (Tables 4 and 5). Precipitation for September and December decreased significantly, and mean temperature for February, July and September increased significantly, with precipitation and mean temperature of other months changed insignificantly. The above results suggested that climate in the Heihe catchment was getting warmer and drier. Specifically speaking, compared with 1981–1990, annual

Table 2
Major conversions of land use in the Heihe catchment during 1985–2000.

Land use change types	Changed area, km^2	Percent change of converted landuse, %
Shrubland to medium grassland	27.7	43.5
Sparse woodland to medium grassland	15.4	28.1
Sparse woodland to high grassland	8.6	15.7
Woodland to medium grassland	6.6	57.2
Medium grassland to woodland	2.3	0.5
Medium grassland to shrubland	2.1	0.5
Farmland to construction land	2.0	0.2
Farmland to medium grassland	1.5	0.2

Table 1
Change of land use structure in the Heihe catchment during 1985–2000.

	Farmland	Woodland	Shrubland	Sparse woodland	Other forest land	High grassland	Medium grassland	Low grassland	Water	Construction land
1985										
Area, km^2	878.4	11.6	63.7	54.6	1.2	8.5	468.5	6.0	0.3	13.0
% area	58.3	0.8	4.2	3.6	0.1	0.6	31.1	0.4	0.0	0.9
2000										
Area, km^2	875.2	7.3	37.5	31.1	1.3	17.1	514.9	6.0	0.3	15.2
% area	58.1	0.5	2.5	2.1	0.1	1.1	34.2	0.4	0.0	1.0
Change										
Area, km^2	−3.2	−4.3	−26.2	−23.5	0.1	8.6	46.4	0	0	2.2
% area	−0.2	−0.3	−1.7	−1.5	0	0.5	3.1	0	0	0.1

Table 3
Mann–Kendall test statistic for annual precipitation and mean temperature of six weather stations during 1972–200.

Weather station	Precipitation			Mean temperature		
	β	Z	P	β	Z	P
Changwu	−3.416	−0.994		0.025	1.557	*
Chongxin	−1.729	−0.450		0.035	2.570	**
Huating	−2.571	−0.807		0.007	0.281	
Jingchuan	−3.509	−0.957		0.022	1.519	*
Lingtai	−2.963	−1.182		0.040	2.532	**
Longxian	−4.528	−1.557	*	0.029	2.120	**

(*) Means significant at $p < 0.1$. (**) Means significant at $p < 0.05$.

precipitation of 1991–2000 decreased about 18% and annual mean temperature increased about 6 °C in the Heihe catchment.

Such climate variability would possibly influence hydrological processes. For example, the precipitation decrease and temperature increase during September would decrease runoff significantly owing to a decrease of water supply and an increase of evapotranspiration, because precipitation of September accounts for about 17% of the annual precipitation and mean temperature is relatively high (about 16 °C). Besides, a temperature increase of July would possibly increase evapotranspiration and subsequently decrease soil water and runoff because mean temperature of July is the highest (22 °C) in a year. Similar conclusions about climate changes were reported, by Liu et al. (2008) and Zhao et al. (2008).

Calibration and validation of SWAT

The LH-OAT parameter sensitivity analysis procedure showed that CN2, ESCO, SOL_AWC and ALPHA_BF parameters were more sensitive to input changes than other parameters. These sensitive parameters were optimized using the autocalibration extension of SWAT2005 to calibrate the model in this study. The final values of these parameters are shown in Table 6.

Model was calibrated well to the measured annual runoff depth, and the calibrated model performed well for the validation data (Figs. 2 and 3). The measured and simulated average-annual runoff depths during the calibration period (1972–1987) were 54.2 and 52.0 mm, respectively. The Ens, PBIAS and RSR for the period were 0.87, 4.0% and 0.36, respectively. The measured and simulated average-annual runoff depths during the validation period (1988–2000) were 36.7 and 38.3 mm, respectively. The Ens, PBIAS and RSR for the period were 0.87, 2.5%, 0.36, respectively. The SWAT performance for annual runoff for both calibration and validation periods was very good, based on the performance criteria given by Moriasi et al. (2007).

The Ens, PBIAS and RSR of the calibration period (1972–1980) for monthly runoff were 0.65, 5.4% and 0.59, respectively, indicating SWAT performance was good according to Moriasi et al. (2007). The Ens, PBIAS and RSR of the validation period (1981–1987) for monthly runoff were 0.53, 10.7% and 0.69, respectively, suggesting SWAT performance was satisfactory (Moriasi et al., 2007). Although SWAT performance for monthly runoff was not as good as annual runoff, results showed that its performance was still

Table 4
Mann–Kendall test statistic for monthly precipitation of six weather stations during 1972–2000.

Month	Changwu			Chongxin			Huating			Jingchuan			Lingtai			Longxian		
	β	Z	P	β	Z	P	β	Z	P	β	Z	P	β	Z	P	β	Z	P
Jan	0.013	0.207		−0.013	−0.226		0	−0.056		−0.002	−0.09	**	−0.006	−0.08		−0.028	−0.471	
Feb	−0.022	−0.188		−0.009	−0.169		0.045	0.338		−0.051	−0.582		−0.082	−0.432		0	0	
Mar	0.104	0.338		0.009	0.056		−0.029	−0.094		0.065	0.375		0.234	0.844		0.162	0.563	
Apr	−0.225	−0.750		−0.031	−0.075		−0.334	−0.657		−0.052	−0.169	**	−0.433	−0.581		−0.208	−0.319	
May	−0.267	−0.431		−0.671	−0.825		−0.120	−0.188		−0.308	−0.319	**	−0.369	−0.713		−0.140	−0.131	
Jun	0.846	1.294	*	0.924	1.444	*	0.923	0.807		0.418	0.506		0.9	1.107		0.523	0.769	
Jul	−1.374	−1.294	*	−0.013	0		−0.440	−0.169		−1.254	−0.863		−0.769	−0.356		−1.075	−0.657	
Aug	0.362	0.281		0.364	0.244		−0.071	−0.131		0.641	0.581	**	0.321	0.206		−0.337	−0.206	
Sep	−1.739	−1.932	**	−2.373	−2.607	**	−2.744	−2.795	**	−1.958	−2.007	**	−1.928	−2.157	**	−2.588	−2.589	**
Oct	0.206	0.356		0.156	0.375		0.184	0.244		0.194	0.338		0.146	0.206		0.202	0.244	
Nov	−0.146	−0.657		−0.091	−0.469		−0.052	−0.244		−0.055	−0.131		−0.121	−0.375		−0.087	−0.338	
Dec	−0.117	−1.278		−0.103	−1.673	**	−0.070	−1.393	*	−0.073	−1.748	**	−0.1	−1.241		−0.055	−1.907	**

(*) Means significant at $p < 0.1$. (**) Means significant at $p < 0.05$.

Table 5
Mann–Kendall test statistic for monthly mean temperature of six weather stations during 1972–2000.

Month	Changwu			Chongxin			Huating			Jingchuan			Lingtai			Longxian		
	β	Z	P	β	Z	P	β	Z	P	β	Z	P	β	Z	P	β	Z	P
Jan	0.001	0.056		0.014	0.657		−0.020	−1.182		−0.006	−0.206		0.027	0.994		0.009	0.469	
Feb	0.061	1.519	*	0.066	1.669	**	0.029	0.807		0.059	1.744	***	0.072	1.632	*	0.056	1.426	*
Mar	0.012	0.319		0.007	0.244		−0.020	−0.657		0.002	0.019		0.014	0.544		0.004	0.169	
Apr	0.011	0.244		0.026	0.581		−0.022	−0.863		0.005	0.113		0.019	0.581		0.015	0.506	
May	0.033	1.107		0.033	1.107		0.009	0.206		0.019	0.694		0.041	1.369	*	0.043	1.369	*
Jun	−0.003	−0.094		−0.009	−0.469		−0.026	−1.032		−0.013	−0.769		−0.011	−0.244		−0.007	−0.356	
Jul	0.034	1.782	**	0.041	1.895	**	0.016	0.694		0.035	1.932	**	0.047	2.007	**	0.050	1.782	**
Aug	−0.013	−0.338		0.008	0.206		0.001	0.056		−0.006	−0.206		0.022	0.863		0.003	0.131	
Sep	0.056	2.907	**	0.064	3.283	**	0.027	1.764	**	0.055	2.757	**	0.079	3.395	**	0.065	3.320	**
Oct	−0.013	−0.469		0.010	0.356		−0.005	−0.169		−0.006	−0.300		0.023	0.694		0.019	0.657	
Nov	−0.019	−0.431		0.007	0.206		−0.008	−0.319		−0.018	−0.581		0.014	0.581		0.001	0.019	
Dec	0.057	1.744	**	0.066	1.895	**	0.046	1.407	*	0.037	1.107		0.075	2.195	**	0.050	1.989	**

(*) Means significant at $p < 0.1$. (**) Means significant at $p < 0.05$.

Table 6
The final values of the sensitive parameters.

No	Name	Description	Range	Initial value	Adjusted/last value
1	CN2	Initial SCS CN II value	35–98	Default/initial	−7
2	ESCO	Soil evaporation compensation factor	0–1	0.95	0.6
3	SOL_AWC	Available water capacity	0–1	Default/initial	+0.05
4	ALPHA_BF	Baseflow alpha factor [days]	0–1	0.0294	0.0129

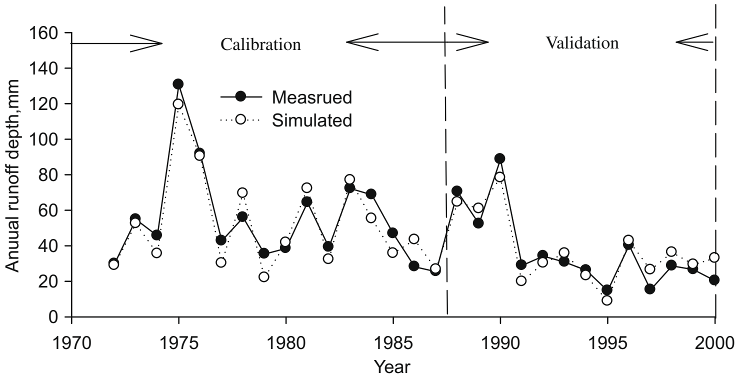

Fig. 2. Observed and simulated annual runoff depth of the Heihe catchment during 1972–2001.

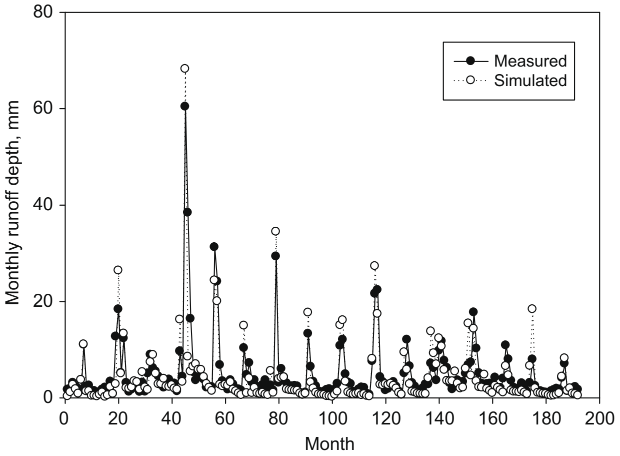

Fig. 3. Observed and simulated monthly runoff depth of the Heihe catchment during 1972–1987.

satisfactory, implying that SWAT was applicable to the Heihe catchment.

Hydrological effect of land use change and climate variability

Impact on runoff

Table 7 shows the annual mean runoff simulated by SWAT under different land use and climate. The simulated results rather than the measured data were used to compare the hydrological effects for all four hypothetical scenarios. Compared with S1, simulated runoff in S4 decreased by 27.6 mm, which represented the combined effects of land use change and climate variability. The contrast between S1 and S2 indicated the influence of land use change between the two periods. The land use change decreased runoff by 2.6 mm, which accounted for 9.6% of the total change (27.6 mm). The contrast between S1 and S3 indicated the influence of the climate variation. The climate variation decreased runoff by 26.4 mm, which accounted for about 95.8% of the total runoff reduction. The above results showed that land use change and climate variability during 1980s and 1990s both decreased runoff, but the contribution of climate variability was far greater than that of land use change. It should be pointed out that the summation of the measured runoff reductions caused by both climate variability and land use change (28.9 mm) was slightly greater than the simulated combined effect of S4 (27.6 mm) due to the interactions between the climate variability and land use change represented in the SWAT model.

Impact on soil water and evapotranspiration

Table 8 shows the results of soil water contents and evapotranspiration (ET) simulated by SWAT under the four scenarios as presented in section 3.4.1. Results showed that land use change and climate variability both decreased soil water contents, and the percent contributions were 18.8% for the land use change and 77.1% for the climate variability. The combined effect of land use change and climate variability (S4) decreased evapotranspiration by 49.6 mm. The climate variability decreased ET by 51.1 mm while the land use change increased ET by 4 mm, accounting for −103% and 8% of the total combined effect of 49.6 mm, respectively.

Table 7
Simulated average-annual runoff depth under different climate and land use.

Scenarios	Land use	Climate	Measured, mm	Simulation, mm	Simulated change, mm	Percent, %
S1	1985	1981–1990	55.5	56.1	–	–
S2	2000	1981–1990	–	53.5	−2.6	−9.6
S3	1985	1991–2000	–	29.7	−26.4	−95.8
S4	2000	1991–2000	26.6	28.6	−27.6	−100

Table 8
Simulated average annual soil water and evapotranspiration under different climate and land use.

Scenarios	Land use	Climate	Precipitation, mm	Soil water			Evapotranspiration		
				Simulation, mm	Change, mm	Percent, %	Simulation, mm	Change, mm	Percent, %
S1	1985	1981–1990	608.3	176.2	–	–	533.0	–	–
S2	2000	1981–1990	608.3	164.9	−11.2	−18.8	537.0	4.0	8.0
S3	1985	1991–2000	509.6	130.1	−46.1	−77.1	481.9	−51.1	−103.0
S4	2000	1991–2000	509.6	116.4	−59.8	−100.0	483.4	−49.6	−100.0

Discussion

Generally speaking, woodland produced lower runoff volumes and soil water contents but more evapotranspiration than other land use types. This was true only when canopy cover of the woodland was above a certain threshold level. Huang et al. (1999) compared the hydrological behaviors of one forest catchment with an adjacent grassland catchment in the Loess Plateau, and found the woodland was no better than grassland in conserving water when the canopy cover of woodland was less than grassland. This finding corroborated the measured runoff data in the Heihe catchment. During 1981–2000, conversion of shrubland and sparse woodland (low cover) to medium or high cover grassland (Table 2) directly decreased runoff and soil water contents while increased evapotranspiration in the high cover grassland. In addition to the effects of land use cover, climate variability in the Heihe catchment was a major factor, which tended to be warmer and drier during 1981–2000 and directly led to decreases in runoff, soil water and evapotranspiration (Tables 7 and 8).

Under the combined effects of land use change and climate variability, hydrological condition of the Heihe catchment changed greatly, and different factors had different influences on the hydrological condition. The climate variation played a more pronounced role than land use change in influencing surface hydrology in this catchment. Thus, when planning for ecological restoration and conservation, climate variation should be considered in evaluating the suitability of plant species and the rationality of their spatial structure.

Conclusions

SWAT proved to be a useful tool for assessing the effects of environmental changes including land use change and climate variability in the Loess Plateau. The Nash–Sutcliffe model efficiency (Ens), Percent bias (PBIAS) and root mean square error-observations standard deviation ratio (RSR) for annual flow was 0.87, 4.0%, 0.36 for calibration period and 0.87, 2.5%, 0.36 for validation periods, respectively, indicating SWAT's performance in the Heihe watershed was very good. During 1981–2000, about 4.5% of the catchment area changed mainly from shrubland and sparse woodland to medium and high cover grassland, and climate became warmer and drier. The combined effect of these changes decreased runoff, soil water contents and evapotranspiration. Land use change and climate variability both decreased runoff and soil water contents (percent contributions were 9.6% and 95.8% for runoff, and 18.8% and 77.1% for soil water, respectively). Land use change increased (percent contribution was 8.0%) while climate variability decreased (percent contribution was 103.0%) evapotranspiration.

Overall, climate variability influenced surface hydrology more significantly than land use change in the Heihe catchment during 1981–2000. Thus, the influence of climate variability should be separated when assessing the hydrological effects of vegetation restoration in the Loess Plateau. Land use change influenced the hydrology slightly in this study, possibly because the extent of the land use change was relatively small. However, with considerable changes in land use patterns and vegetation cover in other areas of the Loess Plateau, the effect of land use change deserves more attention when evaluating the impacts of vegetation restoration on water resources, hydrological processes, and ecosystems.

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