Integrated assessment of the impacts of climate variability and anthropogenic activities on river runoff: a case study in the Hutuo River Basin, China

Abubaker Omer, Weiguang Wang, Amir K. Basheer and Bin Yong

ABSTRACT

Understanding the linear and nonlinear responses of runoff to environmental change is crucial to optimally manage water resources in river basins. This study proposes a generic framework-based hydrological model (Soil and Water Assessment Tool (SWAT)) and two approaches, to comprehensively assess the impacts of anthropogenic activities and climate variability on runoff over the representative Hutuo River Basin (HRB), China. Results showed that SWAT performed well in capturing the runoff trend in HRB; however, it exhibited better performance for the calibration period than for the validation. During 1961–2000, about 26.06% of the catchment area was changed, mainly from forest to farmland and urban, and the climate changed to warmer and drier. The integrated effects of the anthropogenic activities and climate variability decreased annual runoff in HRB by 96.6 mm. Direct human activities were responsible for 52.16% of runoff reduction. Climate (land use) decreased runoff by 45.30% (2.06%), whereas the combined (land use + climate) impact resulted in more runoff decrease, by 47.84%. Land use–climate interactive effect is inherent in HRB and decreased runoff by 1.02%. The proposed framework can be applied to improve the current understanding of runoff variation in river basins, for supporting sustainable water resources management strategies.

Key words | environmental change, integrated assessment, interactive effect, runoff, SWAT

Abubaker Omer
Weiguang Wang (corresponding author)
Amir K. Basheer
Bin Yong
State Key Laboratory of Hydrology-Water
    Resources and Hydraulic Engineering,
Hohai University,
Nanjing 210098,
China
E-mail: wangweiguang006@126.com

INTRODUCTION

Over the past decades, the runoff in many regions around the world has significantly decreased. Human activities and climate variability are regarded as the two driving factors for the runoff changes (e.g., Nijssen et al. 2001; Bao et al. 2012). Thus, it is very important to understand and quantitatively evaluate the effects of these factors on runoff (Jiang et al. 2012). However, the interactions between these factors have a confounding effect that makes inferring causation difficult to achieve at a sufficient scale (Bogena et al. 2005; Zhang & Schilling 2006). For instance, the conversion of forest to crop land and extensive urbanization are observed to affect the exchange of moisture and heat between terrestrial and atmospheric components and hence change local and regional surface temperatures and rainfall patterns (Wang et al. 2010; Miller & Cotter 2013). Climate change, in turn, exerts a dominant control on the predominant vegetation types, land use practices and their spatial characteristics (Brovkin 2002; Tao et al. 2015). Moreover, a definite coupling is observed between the climatic variables and land surface processes such as consumptive water use in irrigation schemes (e.g., Qian et al. 2013; Awan et al. 2016). In spite of this, most previous studies have assessed impacts of climate variability and/or human activities and associated hydrological changes in isolation (e.g., Li et al. 2009; Jiang et al. 2012; Wang et al. 2013). An implication of the lack of integrated analysis associated with these studies is likely to lead to either over- or under-estimation of the potential effects.

In recent years, a number of studies have pointed out that human activities and climate variability are inter-related with each other and are not readily separable. For example, Liu & Xia (2004), conducted a semi-quantitative analysis to explore the reason for the runoff reduction in the Haihe River Basin, and they noted that interaction between climate variability and human activities is inherent in the study basin and plays an important role in runoff decline. A similar study by Xu *et al.* (2013) in the Luan River Basin indicated that the sum of all contributions of the driving factors to decrease river flow in the study watershed could be less than 100% due to the cross impacts between the contributing factors. Zheng *et al.* (2009) studied the impact of climate and land surface changes on streamflow in the headwaters of the Yellow River Basin. They noted that the major uncertainty related to the study is the assumption that climate and land surface are independent factors. More recent studies by Wang *et al.* (2014), El-Khoury *et al.* (2015), and Yan *et al.* (2015) reported that the individual and combined effects of land use and climate variability on runoff are determined by how these factors are defined with different extents of interaction effects.

To assess the hydrological effects of human activities and climate variability, several methods have been used, which can be categorized into four groups: experimental paired catchment method (e.g., Scott *et al.* 2000), statistical methods (e.g., Tian *et al.* 2009), climate sensitivity analysis approach (e.g., Liu & Xia 2004), and distributed hydrological models. However, among these techniques, the distributed hydrological models are by far the most appealing tools to carry out impact assessment studies (Mango *et al.* 2011). These models provide a distributed framework that takes physically observable land surface characteristics and meteorological conditions into account (Refsgaard & Knudsen 1996). Among the distributed hydrological models, the basin-scale Soil and Water Assessment Tool (SWAT) is widely used for evaluating changes in hydrologic regime in response to land use/land cover alterations and climate variability (e.g., Fan *et al.* 2010; Du *et al.* 2013; Singh *et al.* 2015).

As a typical mountainous basin that is heavily influenced by environmental change, the Hutuo River Basin (HRB) is used in this study as a proxy to conduct integrated assessment of the impacts of climate variability and human activities on river runoff. It is located in north China, occupies an area of 15,900 km^2 and supports 4.29 million people. The Hutuo River is the largest tributary in the mid portions of the Haihe river catchment, which plays a key role in the sustainable development of the economy and ecology of China (Peng *et al.* 2012). Over the past few decades, the basin has endured influential, frequent droughts and serious water shortages causing severe environmental problems (Liu & Xia 2004). Climatic variability and human activities have negatively affected the hydrological processes and, consequently, water resources in the basin (Tian *et al.* 2009; Wang *et al.* 2013). Rapid socio-economic development has led to an increase in water demand, whereas climate variability and land use change have an impact on water availability. However, nonlinear relationships, multiple causation, lack of mechanistic understanding together limit researchers' ability to diagnose causes (Allan 2004; McIntyre *et al.* 2014). In order to address and meet these challenges, integrated assessment approaches are needed which take into account the interactive effects of the driving factors on river runoff. The present study addresses this issue through systematic investigation, considering both the separated and complex-coupled natural and human influences.

The main objective of this study is to explore the separated and interactive impacts of climate variability and anthropogenic activities on river runoff over the representative HRB. To this end, a generic framework, based on a hydrological model (SWAT) and two simple approaches, is proposed. The main research work involved: (1) isolating quantitatively the impacts of three main processes, i.e., direct human activities, climate variability and land use change on runoff; (2) estimating the interactive effect of climate variability and land use change on the river runoff.

MATERIALS AND METHODS

Study area

The HRB is a headwater mountainous sub-basin of the Haihe River catchment, originating from Taixi Mountain in Shanxi Province and flowing eastward to join the Haihe River at Xianxian County in Hebei Province (Wang *et al.* 2011).

HRB is situated in north China in the upstream region of the Gangnan reservoir, with a drainage area of 15,900 km^2. It is located between longitudes 112.14–113.93 °E and latitudes 38.02–39.47 °N, with an elevation of 127–3,059 m above mean sea level (Figure 1). The climate in the study area is semi-arid, characterized by a cold–dry winter and summer monsoon rainfall. The precipitation is temporally and spatially distributed at intervals of an annual average ranging from 454 to 584 mm, and about 75% of the rainfall occurs in July and September. The mean annual temperature over the basin is about 8 °C. The typography of the basin consists of four main categories: terrain, plains, hills, and mountains. The main land use types in the basin are grassland, forest, and farmland.

Model description

SWAT is a conceptual basin-scale, continuous-time semi-distributed hydrological model, developed by the United States Department of Agriculture (USDA) to predict the impact of land management practices on watershed hydrology, agricultural chemicals, and sediment yields (Arnold

Figure 1 │ Location of the study area, gauging station, and weather stations.

et al. 1998). SWAT divides a watershed into a number of sub-basins related to stream networks in the basin. Based on the input information, SWAT arranges in each of the sub-watershed the following categories: climate, hydrologic response units (HRUs), groundwater, ponds/wetlands, and the main reach draining each sub-watershed. Then the model captures the underlying physical processes at small lumped land areas within the sub-basin (HRUs) that comprise unique land cover, soil, slope attributes and management combinations. The distributed framework of SWAT serves to conceptualize the relations between climate variability and human activities and their synchronic effects on the hydrological process.

Data

The required input data for the SWAT model, including topographic, climatic, soil and land use data, in this study were collected or processed as follows. Topography of the watershed was defined by digital elevation model (DEM) clipped out from the Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Data (http://srtm.csi.cgiar.org/).

60 m Landsat Multispectral Scanner (MSS) and 30 m Thematic Mapper (TM) images for three different dates (26 June 1974, 26 May 1984, and 6 May 2000) were selected to generate land use and land cover data of the study area. The Landsat images were obtained from the Global Land Cover Facility (http://glcf.umd.edu/data/landsat/) and Earth Explorer site (http://earthexplorer.usgs.gov/). The selected images are sufficiently long enough apart from each other (10–16 years) and obtained within the same season (a maximum of 30 days from each other) to detect the potential land use changes and consequent catchment responses.

The soil data (1,000 m × 1,000 m) of the study area were extracted from the FAO GeoNetworkportal (Figure 2). The soil physical properties were obtained from mwswat-WaterBase (http://www.waterbase.org/index.html) and then imported to the SWAT model geodatabase.

Observed metrological data at Yuanping and Wutaishan stations during 1961–2000 were collected from the China Meteorological Administration (CMA), including daily records of maximum and minimum temperature, precipitation, wind speed, sunshine duration, and relative humidity. Monthly and annual runoff data of the same
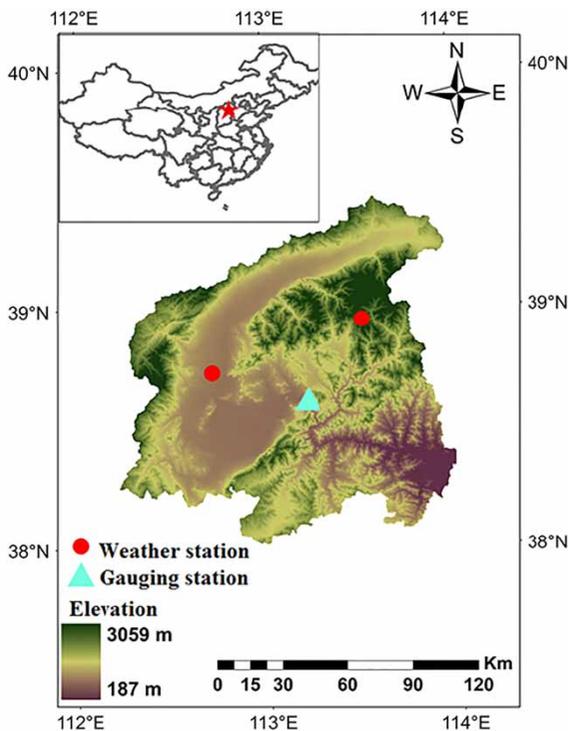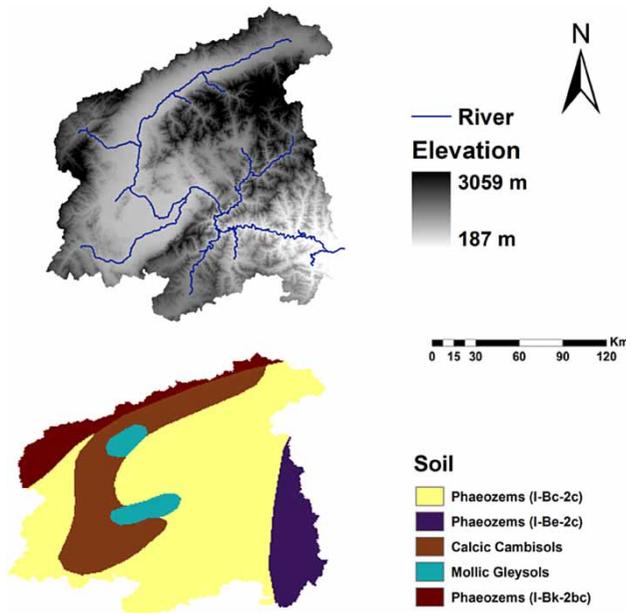
Figure 2 | DEM and soil types in HRB.

period were obtained for Nanzhuang hydrological station (see Figure 1).

Analyzing the hydroclimatic trend

In this study, the nonparametric Mann–Kendall test (Mann 1945; Kendall 1975) was used to analyze the monotonic of trend of annual and monthly hydroclimatic time series i.e., precipitation, mean temperature, and observed runoff in HRB for the period 1961–2000. Pettit's (Pettitt 1979) test method was further utilized to investigate the homogeneity of the hydroclimatic data by detecting the break points in the mean of time series. These methods have been proved to be a very useful tool to quantify the significance and magnitude of change in hydroclimatic data. The methodologies of these statistical tests are broadly documented in many literatures (e.g., Partal & Kahya 2006; Salarijazi *et al.* 2012).

SWAT calibration and validation

After preparing the required maps (land use, soil, DEM) and database files such as climate and soil characteristics, a new SWAT project was set up for Hutuo catchment. Through delineating the sub-watershed and creating HRU, the

SWAT project can simulate the runoff of HRB. However, SWAT is a high parameterized model, and the associated uncertainty must be adjusted within a realistic range (Arnold *et al.* 2012). In a practical sense, a preliminary step in the model calibration process is to determine the most sensitive parameters to the input changes. In this study, the sensitivity analysis was conducted using the SWAT-CUP software (Abbaspour 2013), which merges different calibration/uncertainty analysis procedures for SWAT.

After determining the sensitive parameters, SWAT calibration was processed at monthly and yearly time steps by matching simulated runoff with the measured runoff from Nanzhuang station. The model was calibrated during the period 1962–1979 and further validated during 1980–1997. Land use maps of 1974 and 2000 were used as the land use input data to run the model for the calibration and validation period, respectively. The performance of SWAT during the calibration and validation periods was evaluated using three common statistical indices: Nash–Sutcliffe efficiency (*Ens*), relative error (Re), and coefficient of determination (R^2) (Moriasi *et al.* 2007).

Framework for integrated assessment of the impacts of climate variability and anthropogenic activities on runoff

Evaluating the individual and combined impacts

Based on the hydroclimatic trend analysis, the whole runoff time series in HRB during 1961–2000 was divided into two periods: natural period (1962–1971) and impacted period (1991–2000). Compared with the average runoff in the baseline period (1962–1971), runoff variability in the impacted period (1991–2000) was mainly due to three factors: direct human activities, climate variability, and land use change. In this study, the direct human activities refer to the direct withdrawal of water from river channels for irrigation, industrial and domestic usage (hereafter referred to as D.HA), while climate variability refers to changes in precipitation and temperature. To evaluate the impacts of these factors on river runoff, five scenarios were considered as follows:

- SR.A: Climate conditions of 1962–1971 and land use map for 1974

- SR.B: Climate conditions of 1962–1971 and land use map for 2000
- SR.C: Climate conditions of 1991–2000 and land use map for 1974
- SR.D: Climate conditions of 1991–2000 and land use map for 2000
- SR.E: Observed runoff during period 1991–2000.

In the first scenario (SR.A), simulation was carried out for the baseline period 1962–1971 with land use for 1974. For the following two scenarios (SR.B and SR.C), the calibrated SWAT model was run based on a one-factor approach (Li *et al.* 2009), i.e., changing one factor at an instant while holding the other invariant. SR.B and SR.C were constructed to quantify the individual impacts of the land use change and climate variability on runoff, comparing with SR.A. In SR.D, the simulation was carried out for 1991–2000, changing both climate and land use inputs corresponding to 1962–1971, and thus serving to estimate combined (land use + climate variability) effects comparing with SR.A. With the reconstructed runoff under SR.D and the coincident observed runoff series, it is possible to quantify the impact of D.HA, which is considered by the fifth scenario (SR.E).

Estimating climate–land use interactive effect

Herein, the runoff variability during the impacted period is considered as a function of land use and climate variability:

$$Q = f(L, C) \tag{1}$$

where (Q) is runoff, (f) is a highly nonlinear function, (L) stands for land use and (C) for climate variability. For a given catchment, the runoff change due to land use (ΔQ_L) and climate variability (ΔQ_C) can be approximated as:

$$\Delta Q \approx \Delta Q_L + \Delta Q_C \tag{2}$$

where land use change (ΔL) and climate variability (ΔC) can be approximated as:

$$f\Delta Q_L = (\partial f / \partial L)\Delta L, \quad \text{and} \quad f\Delta Q_C = (\partial f / \partial c)\Delta C \tag{3}$$

The contrast between SR.A and SR.D indicates the combined effect of land use and climate variability on runoff (ΔQ_{Int}), which can be approximated as:

$$\Delta Q_{Int} \approx \Delta Q_L \Delta Q_C + \frac{1}{2!} \frac{\partial^2 f}{\partial l \partial c} \Delta L \Delta C$$
$$\approx \Delta Q_L \Delta Q_C + (\text{nonlinear} - \text{Interaction}) \tag{4}$$

Climate variability and land use are not readily independent factors; therefore, the nonlinear interaction cannot be negligible. Accordingly, the residue of climate variability (SR.C) and combined effect scenario (SR.D) not only comprised the single effect of land use change but also the exacerbated or ameliorated impact of land use caused by climate variability (Zang *et al.* 2013), which can be approximated as:

$$\Delta Q_L^C = \Delta Q_{LC} - \Delta Q_C \tag{5}$$

Thereby, the land–climate interactive effect (ΔQ_I) can be estimated by subtracting the single impact of land use (ΔQ_L) and its modified impact (ΔQ_L^C):

$$\Delta Q_I = \Delta Q_C - \Delta Q_L^C \tag{6}$$

RESULTS

Land use change

Classification of multi-temporal Landsat imagery resulted in land use maps for the HRB that are presented in Figure 3. Land use change analysis was performed for two sub-periods (1974–1984 and 1984–2000) over the period 1974–2000, taking land use conditions in 1974 as a reference. It can be seen from Table 1 that during 1974–1984 the HRB exhibited a substantial land use alteration. An obvious increase in grassland, farmland, and urban areas can be observed with the respective proportions of 23.8%, 26.94%, and 31.93%, while an opposite decreasing tendency was found in the forest (water body) category, by 13.13% (45.01%). During 1984–2000, farmland and urban classes
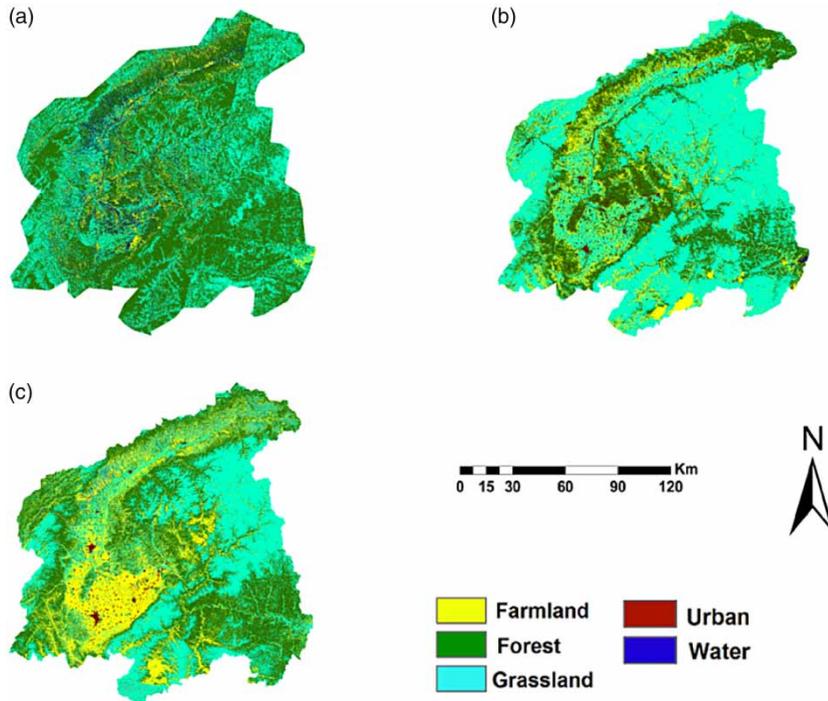
Figure 3 │ Land use maps for 1974 (a), 1984 (b), and 2000 (c) in HRB.

Table 1 │ Land use/land cover change (LUCC) during three periods in HRB

	LUCC					
	1974–1984		1984–2000		1974–2000	
LU type	Km²	%	Km²	%	Km²	%
Grassland	1,283	23.80	−13	−0.24	1,270	23.56
Farmland	690	26.94	891	34.79	1,581	61.73
Forest	−771	−13.13	−759	−12.93	−1,530	−26.06
Urban	137	31.93	95	22.14	232	54.08
Water	−212	−45.01	−188	−39.92	−400	−84.93

increased by 34.79% and 22.14%, whereas grassland underwent a slight decrease of about 0.24%. In contrast, remarkable downward trends were detected in the forest (water body) category of 12.93% (39.92%). Comparing the two sub-periods (1974–1984 and 1984–2000), it can be seen that the land use change has the same qualitative aspects in all categories except for the grassland class. Forest and water body have shown convergent regular downward trends in the two sub-periods, while non-uniform characteristics can be seen in farmland and urban trends.

There is a considerable increase in farmland area during the second sub-period from the first stage. In contrast, the ratio of the urban area increase during the first and second stages is 1.5:1.

Land use change in any region occurs gradually over a period of time, and thus starting and ending years could satisfactorily represent the potential alteration that has occurred in each land use category. Therefore, only the land use maps of 1974 and 2000 were considered by hydrological modeling in this study.

Hydroclimatic trend in the HRB

The annual trends of mean temperature, precipitation, and runoff and their magnitude obtained by the Mann–Kendall test are given in Table 2. In can be observed that trends for all hydroclimatic time series were statistically significant at $\alpha = 0.01$ level of significance. All hydroclimatic series show upward (i.e., mean temperature) and downward trends (i.e., precipitation and runoff) throughout the study period (Figure 4). However, Pettit's procedure (Figure 5) shows that the significant upward shift for mean temperature has occurred since 1986, while the significant downward shift was detected for precipitation and streamflow series in 1988 and 1979, respectively.

The monotonic trends of monthly mean temperature, precipitation, and runoff throughout the study period were varied, within different levels of significance (Figure 6). It can be seen that all the 12 months showed an increasing trend for monthly mean temperature, with a total of 6 months having statistical significance varying within $\alpha = 0.05$, 0.01, and 0.001 levels. In contrast, monthly precipitation series revealed a decreasing trend in all 12 months;

however, the trend was significant only in December and April at the $\alpha = 0.05$ level (Figure 6). Monthly river runoff decreased considerably, with different levels of significance varying within 0.05, 0.1, and 0.001 in all months (except for May, June, and September).

The above results suggested that climate in the HRB during 1961–2000 was getting warmer and drier. Compared to 1962–1971, the annual mean temperature in 1991–2000 increased by 2.5 °C, while the precipitation and runoff obviously decreased by 29% and 72%, respectively. Furthermore, winter and spring months exhibited the highest increase (temperature) and decrease trends (precipitation, runoff) among the other months.

Hydrological model calibration and validation

The ranks of the most sensitive parameters and their final calibrated values are given in Table 3. SWAT was first calibrated at a monthly time step (Table 4 and Figure 7). The Ens, R^2, and Re for the period were 0.83, 0.83, and 4.28%, respectively. The Ens, R^2, and Re for the validation period (1980–1997) were 0.69, 0.77, and 36.36%, respectively.

SWAT model performance was further tested at a yearly time step (Table 5 and Figure 8). The Ens, R^2, and Re of the calibration period (1962–1979) were 0.77, 0.79, and 5.56%, respectively, whereas during the validation period they were 0.59, 0.78, and 28.7%, respectively.

The results suggest that SWAT performance was very good during the calibration period and satisfactory during the validation period, according to Moriasi *et al.* (2007). However, the simulated runoff during the validation
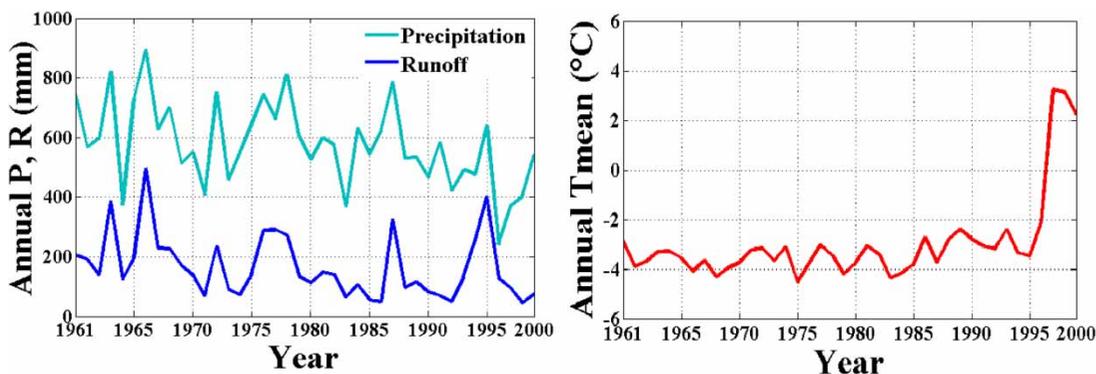
Table 2 | Mann–Kendall statistics for annual precipitation (P), mean temperature (Tmean), and runoff (R) in HRB during 1961–2000

Variables	Test Z	Significant	β
P	−2.9	**	−5.89
Tmean	3.25	**	3.43
R	−2.76	**	−3.59

**Significant at $\alpha = 0.01$.

Figure 4 | Time series of annual precipitation (P), runoff (R) and mean temperature (Tmean), from 1961 to 2000 in HRB.
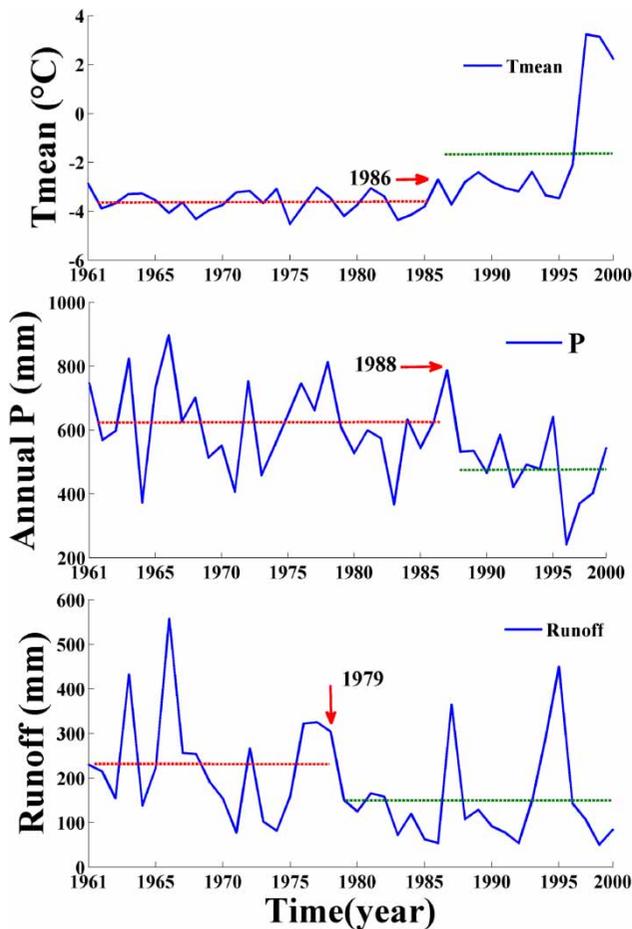
Figure 5 | Change points of annual mean temperature (Tmean), precipitation (P) and runoff time series in HRB during 1961–2000.

period at a yearly time step (Figure 8(b)) was evidently greater than the measured values in most years. This could be, therefore, reliable for supporting the hypothesis (SR.E) that isolates the extent of direct human influence on runoff from the other factors based on the differences between simulated runoff (without the human modifications effect) and observed (with human modifications).

Individual and combined impacts of climate variability and anthropogenic activities on runoff

Table 6 shows the individual and combined impacts of land use and climate variability as well as the isolated impact of D.HA on annual mean runoff depth, obtained under the five scenarios. Compared with SR.A, the

observed runoff during the impacted period decreased by 98.37 mm, which represented the total runoff change due to the integrated effect of D.HA, climate, and land use change. From Table 6 it can be found that the runoff reduction caused by land use change, climate, and the combined change accounted for 2.06%, 45.30%, and 47.84% of the total change (−98.37 mm), respectively. While the contrast between the observed runoff during 1991–2000 and reconstructed runoff under SR.D indicates D.HA impact, which accounted for 52.16% of the total change. It should be pointed out that the average annual runoff reconstructed for the baseline period (231.84 mm) was slightly greater than the observed runoff during the same period (230.07 mm), which indicates that there might be some human activities within HRB affecting the runoff during this period.

Figure 9 illustrates monthly contributions of land use change, climate, and D.HA to HRB runoff reduction. It can be seen that D.HA had a more pronounced contribution in most months compared to the other factors. The contributions of D.HA in March, September, and November were the biggest monthly ones (>75%). The highest climatic contribution was in June and August, by 64% and 75% respectively. On the other hand, land use change contributed not as much to the decrease in monthly runoff as the other factors. However, the highest contribution of land use change that can be noticed was in the summer and rainy months from May to September.

It should be noted that the combined impact of climate and land use change on runoff (47.84%) was greater than the sum of their individual impacts (47.36%), due to an interaction between the two factors. However, no clear inference about the implication of the climate–land use interactive effect on runoff can be achieved from the total runoff change (−98.37 mm), due to the large runoff reduction caused by D.HA.

Interactive impact of climate and land use change

To estimate quantitatively the climate–land use interactive effect, the proposed approach primarily requires the outputs of the scenarios SR.A, SR.B, SR.C, and SR.D. Table 7 shows the annual runoff response to isolated and interactive impacts of land use and climate variability. It can be seen
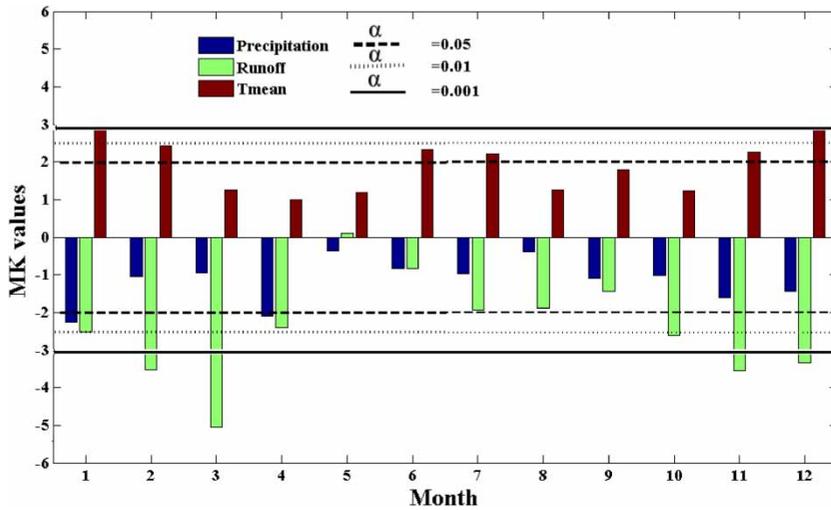
Figure 6 │ Mann–Kendall statistics for monthly precipitation, mean temperature, and runoff in HRB during 1961–2000.

Table 3 │ Ranking of the most sensitive parameters and their final fitted values

Order	Parameter	Min. value	Max. value	Fitted value
1	CN2.mgt	35	98	46–98[a]
2	ALPHA_BF.gw	0	1	0.878
3	GW_DELAY.gw	0	500	406
4	GWQMN.gw	0	5,000	1704
5	GW_REVAP.gw	0.02	0.2	0.138
6	ESCO.hru	0	1	0.593
7	CH_N2.rte	−0.01	0.3	0.245
8	CH_K2.rte	−0.5	500	80.1
9	ALPHA_BNK.rte	0	1	0.177
10	SOL_AWC(1).sol	0	1	0.05–0.23[a]
11	SOL_K(1).sol	0	2,000	0–19.02[a]
12	SOL_BD(1).sol	0.9	2.5	0.9–2.17[a]
13	SFTMP.bsn	−20	20	3.62

[a]The maximum and minimum parameters for the entire watershed values were varied within the range.

Table 4 │ Monthly runoff simulation results for HRB during the calibration and validation periods

Period	Monthly (mm)				
	Observation	Simulation	Ens	R^2	Re%
Calibration	18.6	19.39	0.83	0.83	4.28
Validation	11.42	15.58	0.69	0.77	36.36

that the total runoff decline due to land use and climate variability was 47.06 mm obtained by the difference between SR.A and SR.D. The single impacts of climate variability (ΔQ_C) and land use (ΔQ_L) were responsible for 94.3% (SR.A–SR.C) and 4.33% (SR.A–SR.C) of the total simulated change (47.06 mm), respectively. Based on Equation (5), the exacerbated impact of land use due to climate variability (ΔQ_L^C) was estimated by 5.33% (SR.C–SR.D) of total change. The contrast between the individual and amplified effect of land use change (Equation (6)) represents the land-climate interactive effect (ΔQ_I). The interactive effect of land use change and climate variability accounted for 1.02% of the total simulated change.

Based on the proposed approach, annual evapotranspiration variability during the impacted period was further analyzed in order to provide an insight about how land use and climate system interact to impact runoff in HRB. Figure 10 illustrates the individual, combined, and interactive effects of climate and land use change on evapotranspiration. It can be seen that land use change decreased the evapotranspiration by 28%, while climate variability increased the evapotranspiration by 53.86%. The combined change resulted in evapotranspiration decrease of 22.98%. Climate variability has obviously exacerbated the negative impact of land use to 30.88% through the interactive effect calculated to be 2.10%.
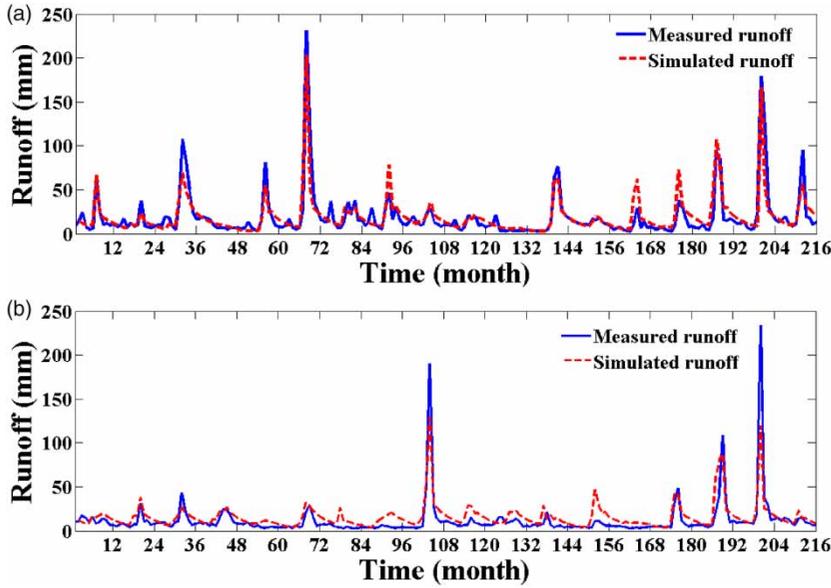
Figure 7 | Hydrographs of observed and simulated monthly runoff during the calibration (a) and validation period (b).

Table 5 | Annual runoff simulation results for HRB during the calibration and validation periods

Period	Average annual value (mm)		Ens	R²	Re %
	Observation	Simulation			
Calibration	18.6	19.63	0.77	0.79	5.56
Validation	11.42	14.7	0.59	0.78	28.7

DISCUSSION

Driving factors for runoff decline in HRB

Results from Table 6 suggest that runoff decline was mainly caused by D.HA. As a result of urbanization and farmland expansion during the two sub-periods 1974–1984 and
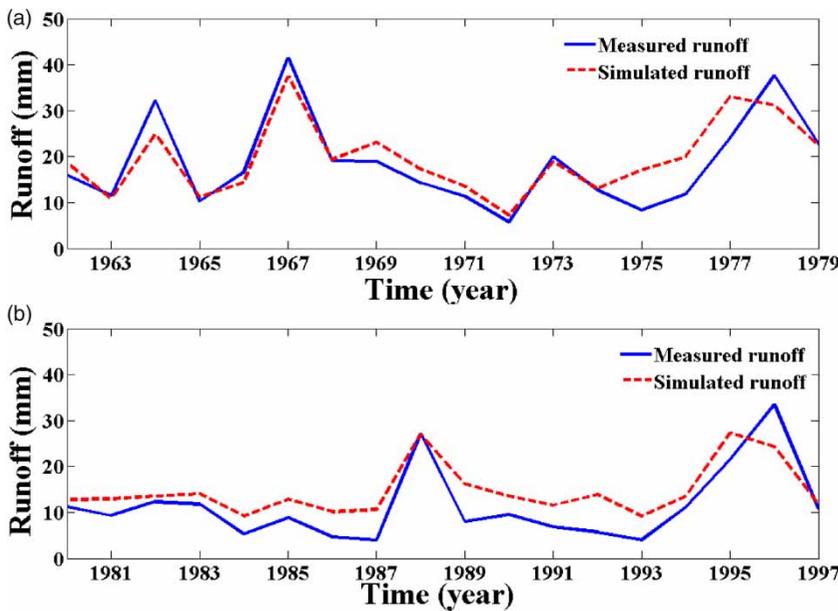

Figure 8 | Hydrographs of observed and simulated annual runoff during calibration (a) and validation period (b).

Table 6 │ Annual average runoff depth obtained under the five isolation scenarios

Scenarios	Land use	Climate	Simulated (mm)	Observed (mm)	Change (mm)	Change %
SR.A	1974	1962–1971	231.84	230.07	–	–
SR.B	2000	1962–1971	229.81	–	−2.03	−2.06
SR.C	1974	1991–2000	187.28	–	−44.56	−45.30
SR.D	2000	1991–2000	184.78	133.47	−47.06	−47.84
SR.E	–	1991–2000	–	133.47	−51.31	−52.16
Total	–	–	–	–	−98.37	−100
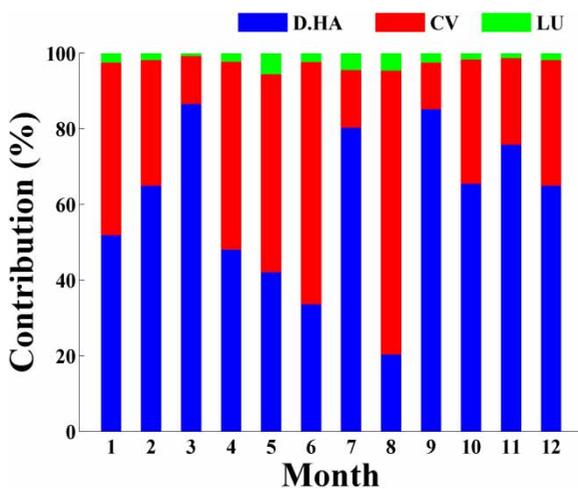
Figure 9 │ Contributions of direct human activities (D.HA), climate variability (CV), and land use (LU) change to average monthly runoff reduction in HRB.

Table 7 │ Isolated and interactive effects of land use and climate variability on annual runoff

Runoff condition	Q (mm)	Simulated change (mm)	Proportional change in annual runoff depth due to (%)			
			ΔQ_L	ΔQ_C	ΔQ_L^C	ΔQ_I
Natural flow	231.84					
Impacted flow	184.78	47.06	4.33	94.3	5.33	1.02

runoff regimes suddenly and directionally, whereas climate variability affects runoff regimes periodically and lastingly (Miao et al. 2011). The most influential human activities in HRB occurred during 1980–2000. However, runoff has had a remarkable decreasing trend since the late 1960s in conjunction with precipitation decrease (Figure 4). This may infer that climate variability has a lasting negative impact on runoff. The results obtained based on the second approach (Table 7) suggest that climate variability is the predominant contributor to runoff reduction in HRB (>90%) when the impact of D.HA is isolated. The large variability in observed runoff (−96.60 mm) corresponding to the variability in rainfall (−10.33 mm) leads to an underestimation of the potential impact of climate variability.

The results show that the annual runoff in HRB is influenced more by D.HA and climate variability compared to land use change. This finding is in line with Ma et al. (2010), who found that the indirect impact of land use change was less than direct abstraction of water and climate variability in the Miyun Reservoir catchment (a nearby catchment). Although the deforestation in HRB (−26.06%) is expected to increase surface runoff (Stednick 1996), the reconstructed runoff under impact of land use showed a significant decreasing trend. The heavily direct water abstraction most likely ameliorates the effect of deforestation on surface runoff. However, in general, the impacts of land use change on hydrological regimes is not easy to quantify because they are the result of interplay between various processes, such as climatic factors, vegetation characteristics, site-specific conditions, and management factors (Conway 2001).

The impacts' separation approach was successfully managed to isolate the effect of D.HA, land use, and climate variability. In spite of this, a clear inference about the implications of land use change, climate variability, and the
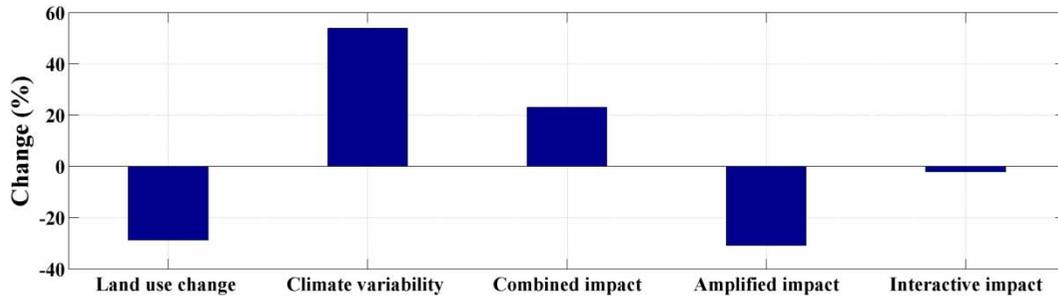
1984–2000, the water demand by industry, domestic usage, and irrigation has intensified, subsequently resulting in a sharp runoff decline in HRB. This finding is relatively consistent with Tian et al. (2009), who suggested that the abrupt decline in HRB was driven mainly by human activities, and especially agricultural water use.

Climate variability is also a dominant driving factor for runoff decline in HRB. Human activities usually affect

Figure 10 │ Evapotranspiration responses to individual and combined impacts of land use and climate variability as well as the amplified impact of land use and the interactive effect of the two factors.

involved interactions were not provided owing to the large variability imposed by D.HA. It is hence useful to isolate the impacts of land use change and climate variability from that of D.HA.

Interaction between the driving factors within HRB

The results from Table 6 show that the combined effect of land use and climate leads to runoff reduction greater than the sum of their individual impacts. One factor is most likely the exacerbated impact of the other factor, hence resulting in a synergistic effect. This hypothesis is further confirmed by the results from Table 7, which indicate that climate variability has clearly amplified the impact of land use by 23.67%.

Saha et al. (2012) found that evapotranspiration over land control is responsible for about 10–20% of the inter-annual variability in rainfall over central India. In this study, the calculation shows that land use change decreased the annual evapotranspiration over the basin by 2.98 mm. This constitutes about 71% of the annual rainfall decrease that has occurred during the impacted period. Moreover, as shown by Figure 10, land use change has dampened the evapotranspiration flux back to atmosphere through an antagonistic interaction estimated to be 2.10%. This possibly had an influence on cloud formation and precipitation over the basin. The temporal trend of precipitation and temperature could be influenced by the large-scale human activities in land surface, such as farmland expansion, deforestation, and urbanization (Wang et al. 2010; Tao et al. 2011; Miller & Cotter 2013). If this is also valid in HRB, the significant alterations in the precipitation and temperature time series (Figure 5) are presumably influenced by the extensive human activities and the imposed land use changes that

occurred during past decades. On the other hand, the analysis presented here indicates that the grassland and farmland areas in HRB were increasing significantly (Table 1) over the study period, while the precipitation was decreasing (Figure 4). From this it may also be deduced that the rainfall decrease over the basin is most likely caused by long-term changes in land use, in particular the conversion of forest to grassland and farmland (Lambin 1997). As the canopy interception in the basin decreased with the decrease in forest, a higher decrease of evapotranspiratable water is suggested, as can be seen from Figure 10.

Further insight indicates that the driving factors to runoff decrease in HRB are also determined by modification interactions. The climate variability over HRB during 1961–2000 caused a significant increase (>50%) in the annual evapotranspiration (Figure 10). The land surface state includes variables such as soil moisture and temperature, snowpack and other surface water stores, and the state of vegetation. Of these, soil moisture is perhaps the most important (Dirmeyer & Studies 1995). As the transpiration from land surface increases with temperature, the soil wetness decreases and suggests a higher infiltration rate. Land use variations play a vital role in local water cycle changes, especially for the water movement within the soil layer (Tan et al. 2015). The changes in land use and land cover that occurred in HRB most likely caused an increase in infiltration and a decrease in surface flow and under the changed climatic conditions contributed to more runoff decline. Accordingly, the increasing (decreasing) trend of temperature (rainfall) in the basin most likely exacerbated the impact of land use change on runoff. Moreover, the high temperature increment after 1986 likely increased the irrigation water demand (Awan et al. 2016), and hence

intensified the direct withdrawal of water. It can be seen from Figure 9 that the contributions of D.HA to runoff decrease in January, February, November, and December are particularly high, corresponding to the high temperature increment observed in these months (Figure 6).

Uncertainty analysis

Major sources of uncertainty in the simulation from the SWAT model may arise from the meteorological input data, model parameters and Landsat imagery classification and model land use inputs involved. The meteorological data were from a very limited number of stations, which might not be of sufficient coverage for a mountainous catchment area of 15,900 km^2. Also, there are some unavoidable errors in the calibration of model parameters. Moreover, there are still some limitations associated with assessing the interactive effect of climate variability and anthropogenic activities in the present work. In fact, the reciprocal influences between human and climate systems occur within a wide range of complex mechanisms (Brovkin 2002). However, in this study, these mechanisms were only briefly addressed. Further study should consider these uncertainties and quantify their impacts on the final analysis results.

CONCLUSIONS

The primary objective of this study was to explore the complexities that are associated with multi-driver analyses, by examining both the separated and interactive natural–human influences on river runoff. A generic framework-based hydrological model (SWAT) and two approaches were developed and utilized to quantitatively estimate the individual, combined, and interactive impacts of three main processes, i.e., direct human activities, climate variability, and land use change on runoff. The analysis was conducted for the HRB, for the period 1961–2000, which has been heavily influenced by environmental change.

Climate variability alone has a negative lasting effect on runoff in HRB, while direct human activities mainly cause the abrupt runoff reduction. Land use change has less effect on runoff, but it imposes significant water-related

direct human activities. The combined effect of land use and climate on runoff is observed to be more pronounced compared to their individual impacts in the basin.

The analysis of the interactive effect indicated that the driving factors on river runoff are multiplicative rather than additive. Climate variability clearly exacerbates the impacts of land use change on runoff through a noticeable synergistic effect. Moreover, it could be found that the driving factors interact to impact runoff through chain effects, whereby one factor tends to increases the magnitude of another factor. Thus, the interactive effect of environmental change drivers should be given more attention when assessing the potential impacts and predicting future changes.

Despite the uncertainties involved, the results of this study provide an insight about the linear and nonlinear responses of the runoff to environmental change in the study region. Based on understanding of the interaction effects between human-induced changes in the land surface and climate system, risks and opportunities can be summarized. Risks include ineffective conservation management; but opportunities also arise by which the negative impacts of climate variability can be reduced through appropriate land management as an adaptation measure. The proposed framework could be useful for the assessment of the potential effect of adaptation measures to cope with global change particularly in regions with high climate sensitivity and rapid socio-economic development.

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REFERENCES

Abbaspour, K. C. 2013 *SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs-A User Manual*. Eawag, Dübendorf, Switzerland, p. 103.

Allan, J. D. 2004 Influence of land use and landscape setting on the ecological status of rivers. *Limnetica* **23** (3–4), 187–198.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams, J. R. 1998 Large-area hydrologic modeling and assessment: Part I. model development. *J. Am. Water Resour. Assoc.* **34** (1), 73–89.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R. & Jha, M. K. 2012 SWAT: model use, calibration, and validation. *Trans. ASABE* **55** (4), 1491–1508.

Awan, U. K., Liaqat, U. W., Choi, M. & Ismaeel, A. 2016 A SWAT modeling approach to assess the impact of climate change on consumptive water use in Lower Chenab Canal area of Indus basin. *Hydrol. Res*. **47** (5), 1025–1037. Doi: 10.2166/nh.2016.102.

Bao, Z., Zhang, J., Wang, G., Fu, G., He, R., Yan, X., Jin, J., Liu, Y. & Zhang, A. 2012 Attribution for decreasing streamflow of the Haihe River basin, northern China: climate variability or human activities? *J. Hydrol.* **460**, 117–129.

Bogena, H., Kunkel, R., Schöbel, T., Schrey, H. & Wendland, F. 2005 Distributed modeling of groundwater recharge at the macroscale. *Ecol. Modell.* **187** (1), 15–26.

Brovkin, V. 2002 Climate-vegetation interaction. *J. Phys.* **12** (10), 57–72.

Conway, D. 2001 Understanding the hydrological impacts of land-cover and land-use change. *IHDP Update* **1**, 5–6.

Dirmeyer, P. A. & Studies, C. f. O. -L.-A. 1995 Meeting on Problems in Initializing Soil Wetness: Review. Center for Ocean-Land-Atmosphere Studies, Fairfax, VA, USA.

Du, J., Rui, H., Zuo, T., Li, Q., Zheng, D., Chen, A., Xu, Y. & Xu, C. Y. 2013 Hydrological simulation by SWAT model with fixed and varied parameterization approaches under land-use change. *Water Resour. Manage.* **27** (8), 2823–2838.

El-Khoury, A., Seidou, O., Lapen, D. R. L., Que, Z., Mohammadian, M., Sunohara, M. & Bahram, D. 2015 Combined impacts of future climate and land-use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. *J. Environ. Manage.* **151**, 76–86.

Fan, J., Tian, F., Yang, Y., Han, S. & Qiu, G. 2010 Quantifying the magnitude of the impact of climate change and human activity on runoff decline in Mian River Basin, China. *Water Sci. Technol.* **62** (4), 783–791.

Jiang, S., Ren, L., Yong, B., Fu, C. & Yang, X. 2012 Analyzing the effects of climate variability and human activities on runoff from the Laohahe basin in northern China. *Hydrol. Res.* **43** (1–2), 3–13.

Kendall, M. G. 1975 *Rank Correlation Methods*, 4th edn. Charles Griffin, London, UK. p. 212.

Lambin, E. F. 1997 Modelling and monitoring land-cover change processes in tropical regions. *Prog. Phys. Geogr.* **21** (3), 375–393.

Li, Z., Liu, W.-Z., Zhang, X.-C. & Zheng, F.-L. 2009 Impacts of land-use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *J. Hydrol.* **377** (1), 35–42.

Liu, C. & Xia, J. 2004 Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China. *Hydrol. Process.* **18** (12), 2197–2210.

Ma, H., Yang, D., Tan, S. K., Gao, B. & Hu, Q. 2010 Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment. *J. Hydrol.* **389** (3), 317–324.

Mango, L., Melesse, A., McClain, M., Gann, D. & Setegn, S. 2011 Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: Results of a modeling study to support better resource management. *Hydrol. Earth Syst. Sci.* **15** (7), 2245–2258.

Mann, H. B. 1945 Nonparametric tests against trend. *Econometrica* **13** (3), 245–259.

McIntyre, N., Ballard, C., Bruen, M., Bulygina, N., Buytaert, W., Cluckie, I., Dunn, S., Ehret, U., Ewen, J., Gelfan, A., Hess, T., Hughes, D., Jackson, B., Kjeldsen, T. R., Merz, R., Park, J.-S., O'Connell, E., O'Donnell, G., Oudin, L., Todini, E., Wagener, T. & Wheater, H. 2014 Modelling the hydrological impacts of rural land use change. *Hydrol. Res.* **45** (6), 737–754.

Miao, C., Yang, L., Liu, B., Gao, Y. & Li, S. 2011 Streamflow changes and its influencing factors in the mainstream of the Songhua River basin, Northeast China over the past 50 years. *Environ. Earth Sci.* **63** (3), 489–499.

Miller, C. & Cotter, J. 2013 An Impending Storm: Impacts of Deforestation on Weather and Agriculture. Greenpeace Research Laboratories Technical Report (Review) 04-2013.

Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R. & Veith, T. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* **50** (3), 885–900.

Nijssen, B., O'Donnell, G. M., Hamlet, A. F. & Lettenmaier, D. P. 2001 Hydrologic sensitivity of global rivers to climate change. *Clim. Change* **50** (1–2), 143–175.

Partal, T. & Kahya, E. 2006 Trend analysis in Turkish precipitation data. *Hydrol. Process.* **20** (9), 2011–2026.

Peng, S., Liu, W., Wang, W., Shao, Q., Jiao, X., Yu, Z., Xing, W., Xu, J., Zhang, Z. & Luo, Y. 2012 Estimating the effects of climatic variability and human activities on streamflow in the Hutuo River Basin, China. *J. Hydrol. Eng.* **18** (4), 422–430.

Pettitt, A. 1979 A non-parametric approach to the change-point problem. *Appl. Stat.* **28** (1), 126–135.

Qian, Y., Huang, M., Yang, B. & Berg, L. K. 2013 A modeling study of irrigation effects on surface fluxes and land–air–cloud interactions in the Southern Great Plains. *J. Hydrometeor.* **14** (3), 700–721.

Refsgaard, J. C. & Knudsen, J. 1996 Operational validation and intercomparison of different types of hydrological models. *Water Resour. Res.* **32** (7), 2189–2202.

Saha, S. K., Halder, S., Suryachandra Rao, A. & Goswami, B. N. 2012 Modulation of ISOs by land–atmosphere feedback and contribution to the interannual variability of Indian summer monsoon. *J. Geophys. Res. Atmos.* **117** (D13).

Salarijazi, M., Akhond-Ali, A. M., Adib, A. & Daneshkhah, A. 2012 Trend and change-point detection for the annual stream-flow series of the Karun River at the Ahvaz hydrometric station. *Afr. J. Agric. Res.* **7** (32), 4540–4552.

Scott, D., Prinsloo, F., Moses, G., Mehlomakulu, M. & Simmers, A. 2000 A re-analysis of the South African catchment

afforestation experimental data. WRC Report No. 810/1/00. Water Research Commission, Pretoria, South Africa.

Singh, H. V., Kalin, L., Morrison, A., Srivastava, P., Lockaby, G. & Pan, S. 2015 Post-validation of SWAT model in a coastal watershed for predicting land use/cover change impacts. *Hydrol. Res.* **46** (6), 837–853.

Stednick, J. D. 1996 Monitoring the effects of timber harvest on annual water yield. *J. Hydrol.* **176** (1), 79–95.

Tan, M. L., Ibrahim, A. L., Yusop, Z., Duan, Z. & Ling, L. 2015 Impacts of land-use and climate variability on hydrological components in the Johor River basin, Malaysia. *Hydrol. Sci. J.* **60** (5), 873–889.

Tao, H., Gemmer, M., Bai, Y., Su, B. & Mao, W. 2011 Trends of streamflow in the Tarim River Basin during the past 50 years: human impact or climate change? *J. Hydrol.* **400** (1), 1–9.

Tao, X., Chen, H., Xu, C., Hou, Y. & Jie, M. 2015 Analysis and prediction of reference evapotranspiration with climate change in Xiangjiang River Basin, China. *Water Sci. Eng.* **8** (4), 273–281.

Tian, F., Yang, Y. H. & Han, S. M. 2009 Using runoff slope-break to determine dominate factors of runoff decline in Hutuo River Basin, North China. *Water Sci. Technol.* **60** (8), 2135–2144.

Wang, J., Hong, Y., Gourley, J., Adhikari, P., Li, L. & Su, F. 2010 Quantitative assessment of climate change and human impacts on long-term hydrologic response: a case study in a sub-basin of the Yellow River, China. *Int. J. Climatol.* **30** (14), 2130–2137.

Wang, W., Peng, S., Yang, T., Shao, Q., Xu, J. & Xing, W. 2011 Spatial and temporal characteristics of reference

evapotranspiration trends in the Haihe River basin, China. *J. Hydrol. Eng.* **16** (3), 239–252.

Wang, W., Shao, Q., Yang, T., Peng, S., Xing, W., Sun, F. & Luo, Y. 2013 Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. *Hydrol. Process.* **27** (8), 1158–1174.

Wang, R., Kalin, L., Kuang, W. & Tian, H. 2014 Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama. *Hydrol. Process.* **28** (22), 5530–5546.

Xu, X., Yang, H., Yang, D. & Ma, H. 2013 Assessing the impacts of climate variability and human activities on annual runoff in the Luan River basin, China. *Hydrol. Res.* **44** (5), 940–952.

Yan, R., Huang, J., Wang, Y., Gao, J. & Qi, L. 2015 Modeling the combined impact of future climate and land-use changes on streamflow of Xinjiang Basin, China. *Hydrol. Res.* **47** (1), 272–356.

Zang, C., Liu, J., Jiang, L. & Gerten, D. 2013 Impacts of human activities and climate variability on Green and blue water flows in the Heihe River Basin in Northwest China. *Hydrol. Earth Syst. Sci. Discuss.* **10** (7), 9477–9504.

Zhang, Y. K. & Schilling, K. E. 2006 Increasing streamflow and baseflow in Mississippi River since the 1940s: effect of land use change. *J. Hydrol.* **324** (1), 412–422.

Zheng, H., Zhang, L., Zhu, R., Liu, C., Sato, Y. & Fukushima, Y. 2009 Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. *Water Resour. Res.* **45** (7), W00A19.