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Assessing the response of runoff to climate change and human activities for a typical basin in the Northern Taihang Mountain, China

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Climate change and human activities are the two main factors on runoff change. Quantifying the contribution of climate change and human activities on runoff change is important for water resources planning and management. In this study, the variation trend and abrupt change point of hydro-meteorological factors during 1960–2012 were detected by using the Mann–Kendall test and Pettitt change-point statistics. Then the runoff was simulated by SWAT model. The contribution of climate change and human activities on runoff change was calculated based on the SWAT model and the elasticity coefficient method. The results showed that in contrast to the increasing trend for annual temperature, the significant decreasing trends were detected for annual runoff and precipitation, with an abrupt change point in 1982. The simulated results of SWAT had good consistency with observed ones, and the values of R^2 and E_{NS} all exceeded 0.75. The two methods used for assessing the contribution of climate change and human activities on runoff reduction yielded consistent results. The contribution of climate change (precipitation reduction and temperature rise) was ∼37.5%, while the contribution of human activities (the increase of economic forest and built-up land, hydrologic projects) was ∼62.5%.

Keywords. Runoff variation; climate change; human activities; SWAT model; elasticity coefficient method; Taihang Mountain.

1. Introduction

Hydrological cycle and water resources are commonly influenced by climate change and human activities (Vorosmarty *et al.* 2000; Beven 2001; Kezer and Matsuyama 2006; IPCC 2007; Zhang *et al.* 2007). Human activities such as Land Use/ Cover Change (LUCC), alter vegetation retention, soil water infiltration, and surface evapotranspiration and result to significant hydrological alteration (Li *et al.* 2007; Wei and Zhang 2010). Compared to the short-term impact of land cover changes, climate change influences the spatial and temporal distribution of runoff based on the change of precipitation, temperature and evapotranspiration, which is mainly on long-term scales. Assessing the response of runoff to human activities and climate change (precipitation and temperature variation) is valuable on water resource planning and management (Vorosmarty *et al.* 2000), and is the basic science issue on economic, social and environmental sustainable development in a basin (Bao *et al.* 2012).

The impacts of climate change and human activities on runoff change are quantified mainly through physically based hydrological models. The commonly used models include SWAT (Soil and Water Assessment Tool) model (Arnold *et al.* 1998; Lee and Chung 2007; Li *et al.* 2009; Zhang *et al.* 2012) and the VIC (Variable Infiltration Capacity) model (Wang *et al.* 2010; Bao *et al.* 2012). In this study, the SWAT model was used.

In the previous studies, SWAT model was usually used to evaluate the impacts of climate change and human activities on runoff at the basin-scale: Guo *et al.* (2016) presented that stream flow was dominated by climate change which led to a 102.8% increase, whereas LUCC produced a decrease of 2.8% in the Xiying River basin from 1990 to 2008. Ghaffari *et al.* (2010) presented that land use played a dominant role in changing hydrology and runoff in the Zanjanrood basin, northwest Iran. Guo *et al.* (2008) concluded that climate change played a dominant role in runoff change in the Xinjiang River basin of the Poyang Lake by using SWAT model. In addition, the SWAT model was further extended to scenario assessment (land use change scenarios and climate change scenarios) of runoff simulation. In order to investigate the stream flow variation under the Grain for Green Project in the rivers of the Yellow River basin, Wang *et al.* (2017) designed five land use scenarios that converted agricultural land into mixed forest. They found that the stream flow consistently increased with agricultural land converted into forest by about 7.4 mm per 10%. Guo *et al.* (2016) further presented that the mean annual stream flow will decrease by 5.4% and 4.5% during 2010–2039, and it will decrease by 21.2% and 16.9% during 2040–2069 in the Xiying River basin. Uniyal *et al.* (2015) considered 12 independent as well as 28 combined area-specific climatic scenarios to evaluate the impact of climate change on runoff in the Upper Baitarani River basin. Mango *et al.* (2011) applied the SWAT model to investigate the response of the headwater hydrology of the Mara River to land use change scenarios and climate change scenarios.

In order to make the results more reliable and persuasive, the elasticity coefficient method was employed for comparison and validation. Through analyzing the sensitivity of annual runoff to precipitation and potential evaporation, the elasticity coefficient method separated the contribution of climate change and human activities (Dooge *et al.* 1999; Dai 2002; Milly and Dunne 2002).

In this study, a typical basin (the control basin of Fuping hydrological station) in the upper reaches of Baiyangdian basin, which is located in the northern Taihang Mountain, was chosen as the study area. Since the 1960s, under the strong interference of climate change and human activities, the surface runoff constantly decreased, which reduced the amount of inflow water to the lake area, and the 'dry lake' phenomena occurred frequently. Due to the increasing water consumption, a large number of domestic sewage and industrial waste water were discharged, which seriously threatened the water environment. The decrease of water quantity and the deterioration of water quality reduced the basin's ecological function, and further affected the social and economic development, and ecological environment security. Although existing studies pointed that runoff appeared a decreasing trend and the primary driving factors are climate change and human activities (Liu *et al.* 2011; Zhou *et al.* 2011), their contribution on runoff change is still not clear. Therefore, further study is needed for analyzing the contribution of climate change and human activities on runoff change.

The objectives of this study were (1) to determine variation trend and abrupt change points of hydro-meteorological factors, (2) to quantitatively analyze the contribution of climate change and human activities on the runoff change through SWAT model and the elasticity coefficient method, and (3) to discuss the evolution rules and driving mechanisms of runoff.

2. Study area

The control basin of Fuping hydrological station covers an area of about 2200 km^2 and locates within latitude of 38°46′–39°22′N and longitude of 113°40′–114°20′E. Elevations in the watershed, which are high in northwest and low in southeast, range from 249 to 2784 m. Geographically, the basin belongs to mountainous regions. Land use

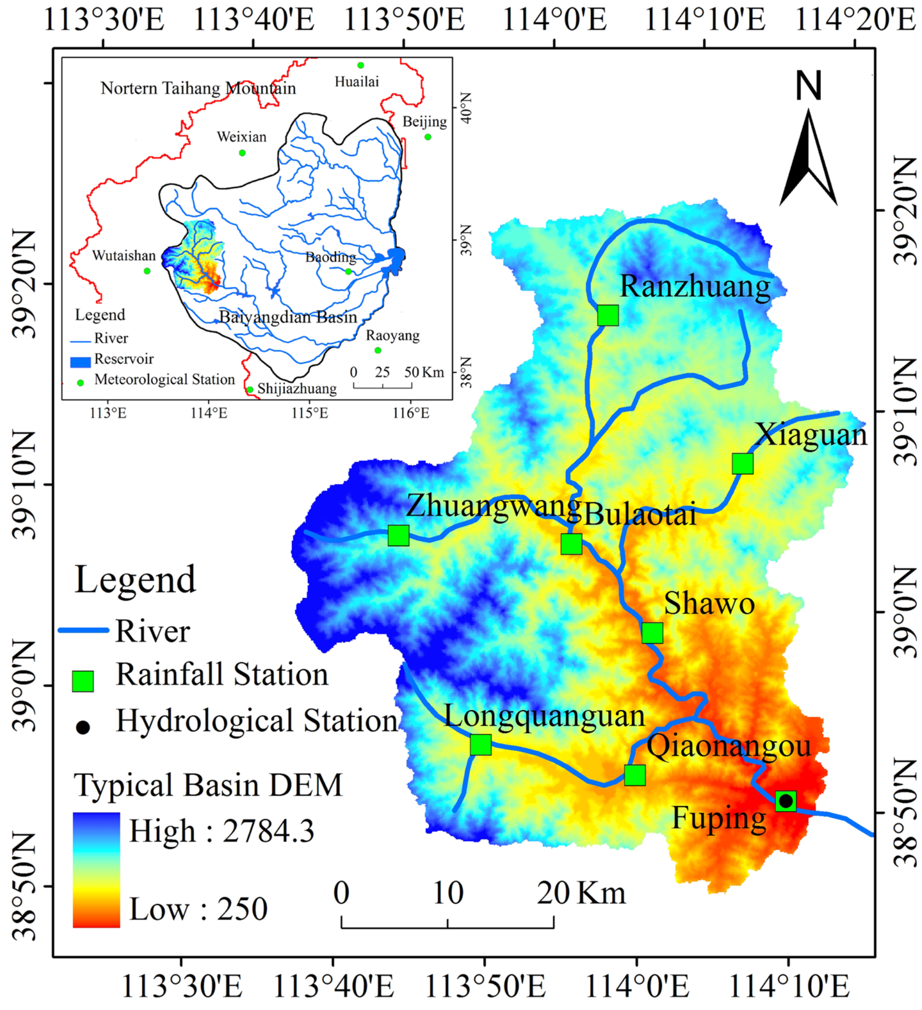

Figure 1. Location of the study area and the observation stations.

types are mainly forest and grassland. The basin belongs to temperate continental monsoon semi-humid and semi-arid climate, and has four distinct seasons. The mean maximum and minimum temperatures of the study area were about 15.44° and 4.35°C during 1960–2012, and the average annual precipitation is about 564 mm. The seasonal distribution of precipitation is extremely uneven, and 70–80% concentrates in June to August, with the form of heavy rain. The watershed has diverse soil types. The major ones, which are brown soil, cinnamon soil, skeleton soil and moisture soil, cover >92% of the total area. The location of the study area, hydrological station, meteorological stations and rainfall stations are shown in figure 1.

3. Data and methods

3.1 *Data*

The datasets used in this study included a digital elevation model (DEM), land use/cover change maps, soil data, meteorological data and runoff data.

(1) *DEM* – A 90 × 90 m resolution DEM of Shuttle Radar Topography Mission was downloaded from Geospatial Data Cloud. The DEM was used to extract basin boundaries, slope and aspect information, divide sub-basins and generate a digital river network.

(2) *Land use/cover change maps* – Land use/cover maps for 1990 and 2010 were obtained from the State Key Laboratory of Resources and Environmental Information System (http://www.resdc.cn/), Chinese Academy of Sciences. The land use data of 1990 was used to divide sub-basin and hydrological response units in the SWAT model with the spatial resolution of 100 m.

(3) *Soil data* – Soil data included soil type map, soil type index table and soil property file. The datasets were provided by Resources and Environment Science Data Center, Chinese Academy of Sciences. Soil data were mainly used to divide sub-basin and hydrological response units.

(4) *Meteorological data* – Meteorological data were obtained from seven national meteorological stations (precipitation, maximum and minimum temperature, relative humidity, wind speed, solar radiation and dew point temperature) and eight rainfall stations during 1960–2012. The national meteorological stations' data were downloaded from China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do), and the rainfall stations' data were from Hydrological Year book of Haihe River Basin.

(5) *Runoff data* – Monthly runoff data of Fuping station during 1960–2012 were obtained from Hydrological Year book of Haihe River Basin. The data was used for sensitivity analysis of model parameter, model calibration and validation.

3.2 *Methods*

3.2.1 *Mann–Kendall test*

The Mann–Kendall test does not require the sample to comply with certain distribution characteristic, and can directly test the change trend of variables (Mann 1945; Kendall 1975; Burn and Hag Elnur 2002; Wei 1999). Therefore, this method is widely used for analyzing the variation trend of hydro-meteorological factors (Xu *et al.* 2003, 2004). S denotes MK test results, and can be obtained by

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\operatorname{sgn}(x_j-x_k) \tag{1}$$

where n is the sample size, x_j and x_k are the time series of sample size.

$$\operatorname{sgn}(x_j-x_k)=\begin{cases}1 & x_j-x_k>0\\ 0 & x_j-x_k=0\\ -1 & x_j-x_k<0\end{cases}. \tag{2}$$

The variance of S is

$$\mathrm{VAR}(S)=\frac{n(n-1)(2n+5)}{18}. \tag{3}$$

Then, the Mann–Kendall Z is described as

$$Z=\begin{cases}\frac{S+1}{\sqrt{\mathrm{VAR}(S)}} & S>0\\ 0 & S=0\\ \frac{S-1}{\sqrt{\mathrm{VAR}(S)}} & S<0\end{cases}. \tag{4}$$

When Z is positive, the variable shows upward trend, while the variable is in a downward trend, $|Z|>Z_{1-\alpha/2}$ indicates that the variable has a significant upward or downward trend on the significant level of α, wherein $\pm Z_{1-\alpha/2}$ can be obtained through checking table.

The non-parametric robust estimate of the magnitude of the slope, β, determined by Hirsch *et al.* (1982), is given by

$$\beta=\mathrm{Median}\left(\frac{\chi_k-\chi_j}{k-j}\right),\quad \forall j<k. \tag{5}$$

A positive value of β indicates an upward trend, whereas a negative value represents a downward trend.

3.2.2 *Pettitt change point statistics*

Pettitt change point statistics (Pettitt 1979, 1980a, b) is widely used for detecting the change point of hydro-meteorological variables' time series. For the time series x with n samples, a rank sequence is constructed

$$U_{t,n}=U_{t-1,n}+V_{t,n} \tag{6}$$

$$\overline{x}=\frac{1}{n}\sum_{i=1}^{n}x_i \tag{7}$$

wherein,

$$V_{t,n}=\sum_{j=1}^{n}r_i \tag{8}$$

$$r_i=\begin{cases}+1 & x_i>x_j\\ 0 & x_i=x_j\\ -1x_i & <x_j\end{cases}\qquad j=1,2,\ldots,i. \tag{9}$$

The rank sequence r_i is the cumulative number of the value at the time i greater than that at the time j.

Pettitt directly uses the rank sequence to detect change point, if t meets

$$K_t=\max|U_t| \tag{10}$$

then t is the abrupt change point.

The statistic P

$$P=2\exp\left[-6K_t^2(n^3+n^2)\right]. \tag{11}$$

When P is smaller than the significant level α, the change point is significant in the statistical sense.

3.2.3 *The elasticity coefficient method*

Climate elasticity coefficient method. The climate elasticity coefficient method is used to quantitatively distinguish the effects of climate change and human activities on runoff using the water balance equation, and determines the sensitivity of runoff to precipitation and evaporation. The concept of water balance provides a framework for study hydrological behaviour in the basin. The water balance equation is

$$P = E + Q + \Delta S \tag{12}$$

where P (mm) is precipitation; E (mm) is actual evaporation; Q (mm) is runoff depth; and ΔS (mm) is variation of water storage in a basin.

According to the hypothesis, a basin's annual average evaporation is determined by the balance between precipitation and potential evaporation capacity because the actual evaporation is difficult to obtain. Many scholars have proposed various formulas after studying this balance.

In this paper, long-term average evapotranspiration can be estimated as (Zhang *et al.* 2001):

$$\frac{E}{P} = \frac{1 + \omega\,(E_0/P)}{1+\omega\,(E_0/P) + (E_0/P)^{-1}} \tag{13}$$

where ω ($\omega = 0.2$) is a plant-available water coefficient that reflects the water availability of different types of plants. E_0 (mm) is potential evaporation. Precipitation and evaporation are the main meteorological factors controlling annual water balance (Budyko 1974; Dooge *et al.* 1999; Zhang *et al.* 2001). Change in these factors is a direct reason for runoff change. Three relationships can be represented by the following formula (Koster and Suarez 1999; Milly and Dunne 2002)

$$\Delta\bar{Q}_{\text{climate}} = \beta\Delta P + \gamma\Delta E_0 \tag{14}$$

where $\triangle P$ (mm) is precipitation change; $\triangle E_0$ (mm) is potential evaporation change. β is the sensitivity coefficient of runoff to precipitation, and γ is the sensitivity coefficient of runoff to potential evaporation. Hydrological sensitivity can be defined as a percentage of annual runoff variation to annual precipitation and potential evaporation change. The sensitivity coefficient can be calculated as follows (Li *et al.* 2007)

$$\beta = \frac{1 + 2E_0/P + 3\omega E_0/P}{\left[1 + E_0/P + \omega\,(E_0/P)^2\right]^2} \tag{15}$$

$$\gamma = -\frac{1 + 2\omega E_0/P}{\left[1 + E_0/P + \omega\,(E_0/P)^2\right]^2} \tag{16}$$

3.2.4 *SWAT model*

The Soil and Water Assessment tool (SWAT), which is used to simulate and analyze the impact of climate change and human activities on hydrological processes, could consider the spatial distribution effects of precipitation, evaporation and land cover on runoff (Arnold *et al.* 1993; Neitsch *et al.* 2002).

Based on land use type, soil type and slope distribution, the study basin is divided into sub-basins, which are further subdivided into a series of Hydrological Response Units (HRUs) by using SWAT model (Hjelmfelt 1991). The runoff of each HRU will be simulated through the model and then gathered to the respective sub-basin, and eventually collected to a basin export.

In order to acquire the optimized simulated results, the parameters used in constructing the SWAT model are calibrated by using the runoff data from 1960 to 1982. The rest runoff data (1983–2012) is used for model validation. Further goodness-of-fit is quantified by the square of the coefficient of determination (R^2) and Nash–Sutcliff (E_{NS}) coefficient between the observations and simulation.

R^2 is calculated as:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_{\text{obsi}} - Q_{\text{avg}}\right)\left(Q_{\text{simi}} - Q_{\text{avg}}\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{\text{obsi}} - Q_{\text{avg}}\right)^2 \sum_{i=1}^{n}\left(Q_{\text{simi}} - Q_{\text{avg}}\right)^2} \tag{17}$$

The E_{NS} is obtained by (Nash and Sutcliffe 1970)

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\text{simi}} - Q_{\text{obsi}}\right)^2}{\sum_{i=1}^{n}\left(Q_{\text{obsi}} - Q_{\text{avg}}\right)^2} \tag{18}$$

where n is the number of time steps (months and years), Q_{simi} and Q_{obsi} are the simulated and observed runoff at the time step i, respectively. Q_{avg} is the average observed runoff in the simulated period. When the value of

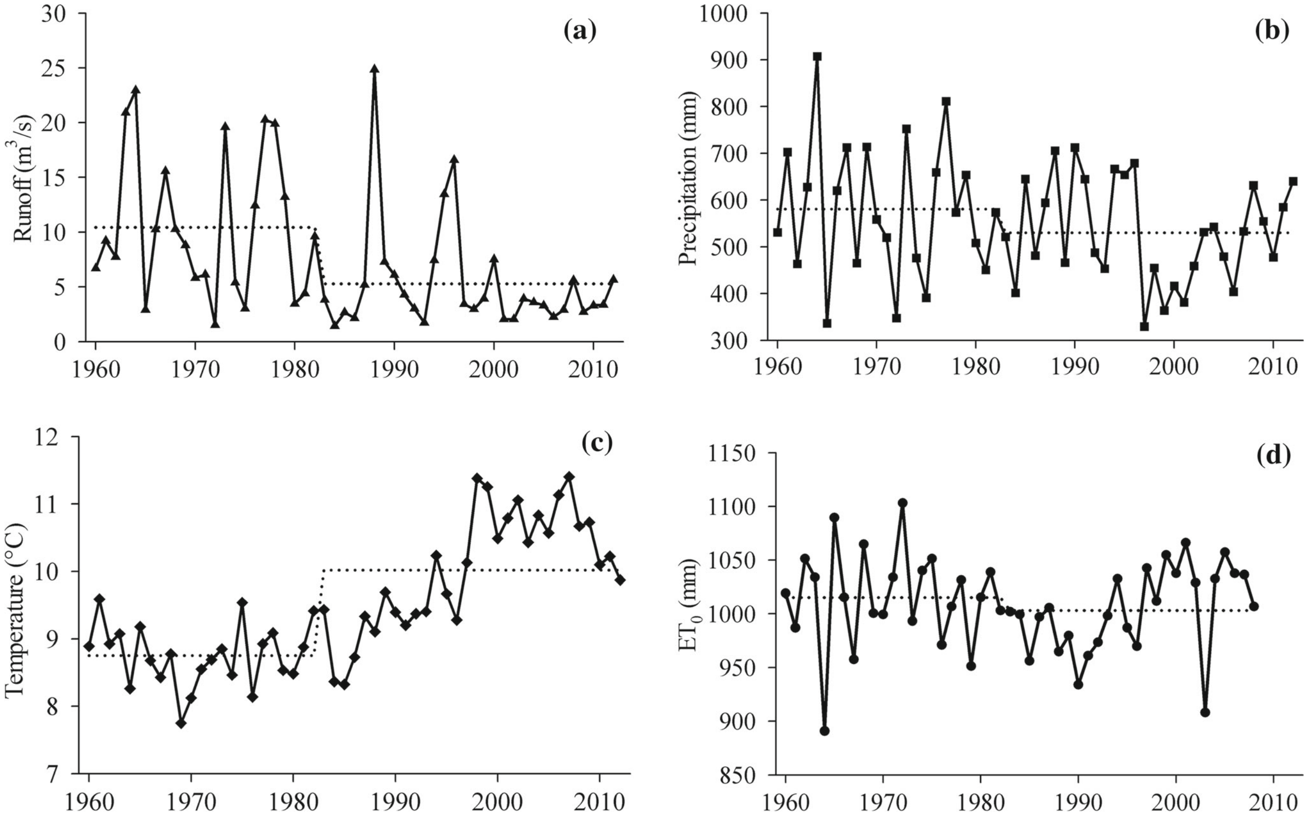

Figure 2. Long-term variation of annual **(a)** runoff, **(b)** precipitation, **(c)** temperature and **(d)** potential evapotranspiration.

E_{NS} is close to 1, the simulation results are more accurate.

4. Results and discussions

4.1 *Variation trend and abrupt change point of hydro-meteorological factors*

The Mann–Kendall method was applied to test the variation trend of temperature, precipitation, evapotranspiration and runoff. Figure 2 was used to determine whether the time series of the observed hydro-meteorological factors had a statistically significant trend. During 1960–2012, a significant increasing trend was detected for annual temperature at the 0.001 confidence level, which increased by 0.05°C per year. Annual runoff and precipitation showed a significant decreasing trend at the 0.001 confidence level, which decreased by 2.43 and 1.83 mm, respectively. The annual potential evapotranspiration also decreased, but not significant.

The abrupt change analysis of above hydro-meteorological factors was tested by using the Pettitt change point statistics. The results were showed in table 1. One of the most likely abrupt change points of annual temperature, precipitation, evapotranspiration and runoff all occurred around 1982, and the results passed the significant test at 0.001 level except evapotranspiration. Based on the test results, 1982 was determined as the abrupt change point. Therefore, the whole period was divided into 'the natural period' (1960–1982) and 'the impacted period' (1983–2012). It was clear that variables' values during the two periods were significantly different (table 1).

4.2 *The runoff regime in the two periods*

Significant changes of intra-annual runoff appeared in the basin, which showed a unimodal distribution with flood seasons (July to October) and non-flood seasons (November to June). Most runoff occurred in flood seasons, which accounted for 61% of the annual total runoff. This was because the high-intensity rainfall events mainly occurred in June to September. The distribution of runoff and precipitation was consistent, and the peak value of runoff was about one month lag behind that of precipitation. The average monthly runoff during 1983–2012 presented dramatic reductions compared to the values in 1960–1982. The greatest absolute and relative reductions of runoff were both in August,

Table 1. *Results of Pettitt change point statistics and the mean values before and after change-point (1982).*

	The most likely abrupt change point	Signicant level	1960−1982	1983−2012
Temperature (°C)	1981, 1990	****	8.75	10.02
Runoff (mm)	1979, 1982	****	149.62	75.79
Precipitation (mm)	1982, 1990	****	580.63	529.71
Evaporation (mm)	1982	R	1013	1003

**** Significant at $P = 0.001$, R: Reject the null hypothesis.

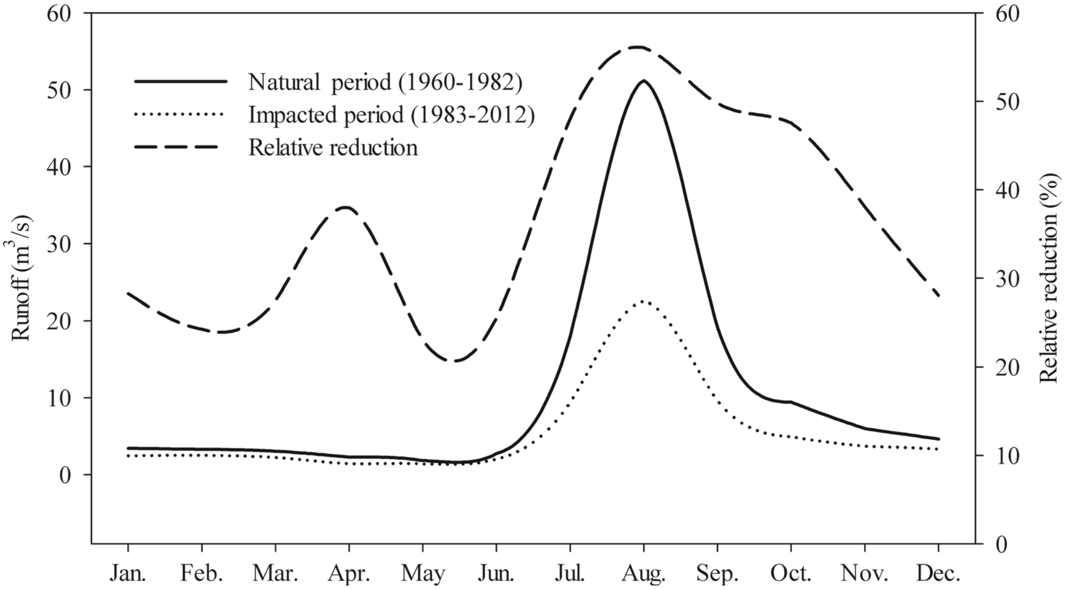

Figure 3. Average monthly runoff between the natural and impacted periods.

with the values of 30.65 and 64.74 m^3/s, respectively (figure 3).

The Flow Duration Curves (FDC) could provide a graphical summary of runoff variation (Smakhtin 1999). In this study, the FDC was constructed by using monthly runoff. Based on the abrupt change point, the monthly runoff series was divided into two periods to analyze the characteristics of runoff change. Figure 4 showed the monthly FDCs for the two periods and the relative reduction in monthly runoff with the same percentile. The runoff reduction levels decreased from high to low runoff. The relative reduction of most runoff exceeded 25%, especially for high runoff (>50%). A runoff characteristic index was defined as the ratio between the runoff under the characteristic frequency and the runoff at 50% frequency (Q50). Generally, low runoff is defined as the runoff exceeding 70–99% of the time, and high runoff is taken as the runoff exceeding 1–10% of the time (Smakhtin 2001). According to the hydrological characteristics of the study area, the runoff exceeding 1 and 5% of the time were chosen as high runoff, and the runoff exceeding 90 and 95% of the time represented the low runoff, and the values were denoted by Q1, Q10, Q90 and Q95, respectively. The high and low runoff indices in the two periods are shown in table 2. Compared to the natural period, the high runoff indices in the impacted period decreased significantly, while the low runoff index had almost no decrease or even slight increase. Therefore, the total amount of runoff decreased significantly, and the runoff in the basin presented a more uniform regime.

4.3 *Model construction and runoff simulation*

Based on the DEM, the basin was divided into 33 sub-basins through SWAT model. The critical threshold of land use and soil were both 2%, and the sub-basins were further divided into 301 HRUs. Runoff was estimated by using a modified Soil Conservation Service-Curve Number (SCS-CN) method with the time steps of 1 day. The potential evapotranspiration was estimated by using the Penman–Monteith method (Monteith

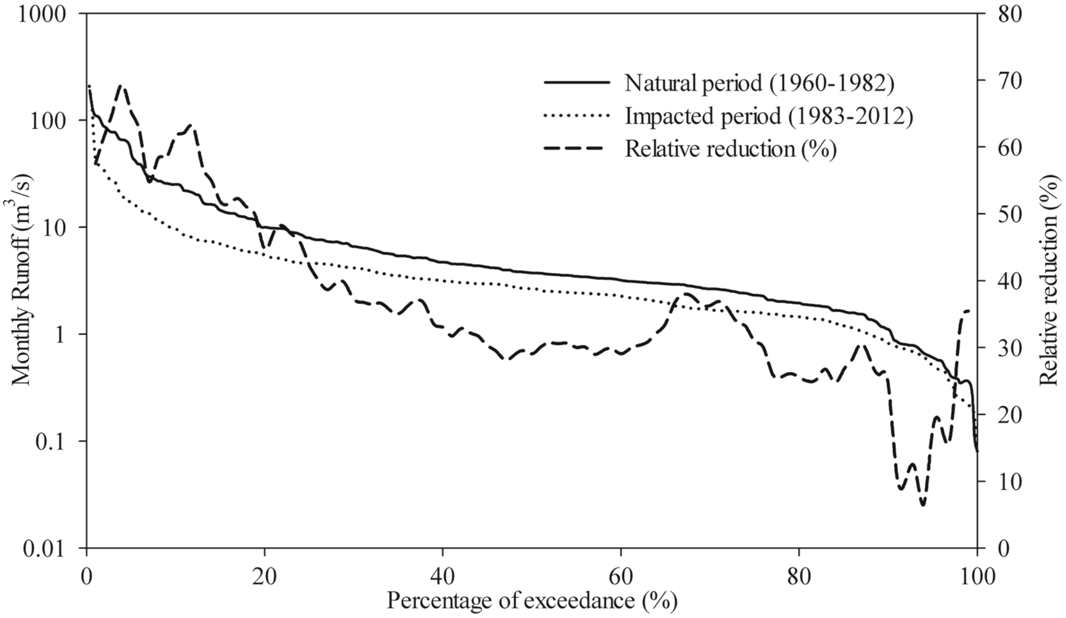

Figure 4. Changes in flow duration curves between the natural and impacted periods.

Table 2. *Character index of FDC in the two periods.*

Periods		1960–1982	1983–2012
High runoff index	Q1/Q50	35.91	18.07
	Q10/Q50	6.67	3.61
Low runoff index	Q90/Q50	0.29	0.31
	Q95/Q50	0.192	0.187

1965). In the natural period (1960–1982), according to the measured hydro-meteorological data, the model parameters were calibrated to test the applicability of the SWAT model in the study area. Then the runoff in the impacted period (1983–2012) was simulated using the calibrated model, and the results were validated by using the monthly runoff data of Fuping hydrological station during the same period.

4.3.1 *Parameter sensitivity analysis*

A set of hydrological parameters were manually and automatically calibrated through SUFI-2 (the Sequential Uncertainty Fitting Version 2) of SWAT-CUP. According to the above analysis, 10 highest sensitive parameters, which could represent the surface runoff, groundwater and soil properties, were chosen for calibrating and validating the model. The optimal values in terms of the 10 highest sensitive parameters are listed in table 3.

4.3.2 *Model calibration and validation*

SWAT model was calibrated and validated based on the observed monthly and annual runoff. R^2 and E_{NS} were chosen as the most suitable indices for judging goodness-of-fit of calibrated and validated results. The calibrated and validated results were summarized in table 4. All the values of R^2 and E_{NS} exceeded 0.75, which suggest that there was a good agreement between observed and simulated results, and SWAT model performed well.

Figure 5 shows the observed and simulated monthly runoff in the natural and the impacted periods. The simulated and observed monthly runoff had the same trend. During the natural period, the values of R^2 and E_{NS} were 0.78 and 0.76, respectively and during the impacted period, R^2 and E_{NS} were 0.75 and 0.76, respectively. These results denoted good model performance. The monthly simulations were generally good in the whole period, except the months with extreme storm events and hydrological condition. The peak values were overpredicted in June to September in some years, and were underestimated for August

Table 3. *Sensitive parameters and the optimal values after calibration by using SUFI-2.*

Parameter	Description	Optimal value
CN2	SCS runoff curve number	0.15
SOL_AWC	Available water capacity of the soil layer (mm/mm)	−0.14
SOL_K	Saturated hydraulic conductivity (mm/hr)	−0.09
GWQMN	Threshold water depth in the shallow aquifer for follow (mm)	18.14
GW_REVAP	Groundwater ‘revap’ coefficient	−0.04
REVAPMN	Threshold depth of water in the shallow aquifer for ‘revap’ to occur (mm)	5.72
ESCO	Soil evaporation compensation factor	0.02
CH_N	Manning’s roughness coefficient in main channel routing	0.21
CH_K2	Channel effective hydraulic conductivity	116.27
SFTMP	Snow melt base temperature (°C)	0.59

Table 4. *Performance of the SWAT model for monthly and annual runoff.*

	Calibration		Validation	
Index	Monthly	Yearly	Monthly	Yearly
R^2	0.78	0.82	0.75	0.80
E_{NS}	0.76	0.78	0.76	0.77

in 1963, 1966, 1973, 1977 and 1988. This might be due to the limited meteorological stations (data) at high altitude areas.

The simulated and observed average monthly runoff are shown in figure 6. Although there were slight differences between the simulated and observed values in some months due to the underestimation of peak runoff or the model error, the simulated results could still well reflect the actual runoff process of the basin. The seasonal distribution of simulated and observed values was basically identical, and the values of R^2 and E_{NS} were both up to 0.96.

The annual hydrographs of observed and simulated runoff during the two periods are shown in figure 7. In the natural period, the values of R^2 and E_{NS} (table 4) were 0.82 and 0.78, respectively. In the impacted period, R^2 and E_{NS} were 0.80 and 0.77, respectively. The beginning year of the obvious differences between the observed and simulated annual runoff was consistent with the abrupt change point. The gap represented the impact of human activities on runoff reduction. The results indicated that the SWAT model could be used for analyzing responses of the basin’s runoff to climate change and human activities.

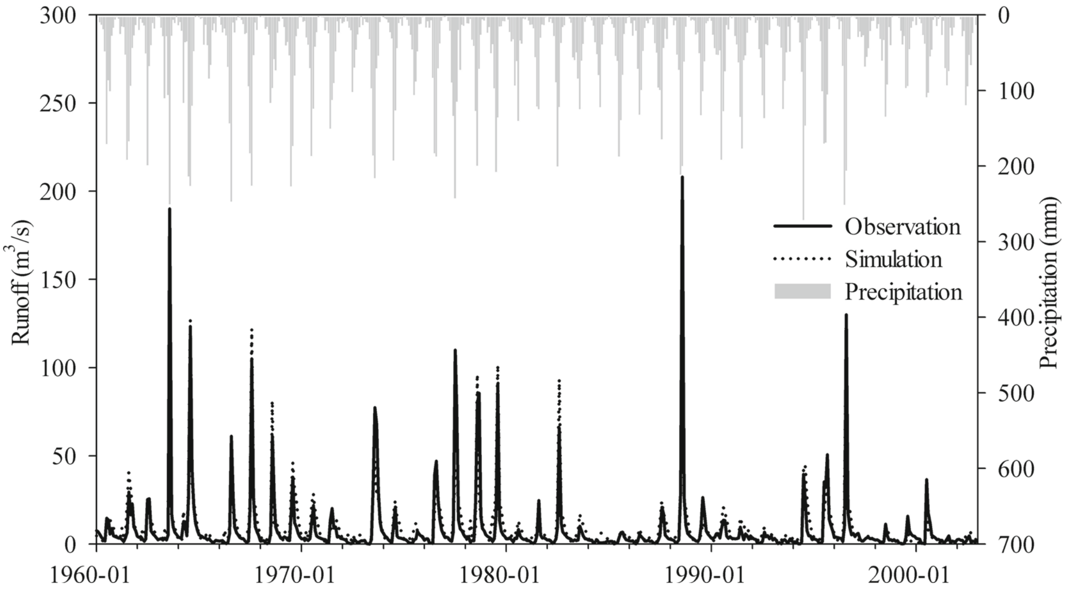

Figure 5. Observed and simulated monthly runoff in the natural and the impacted periods.

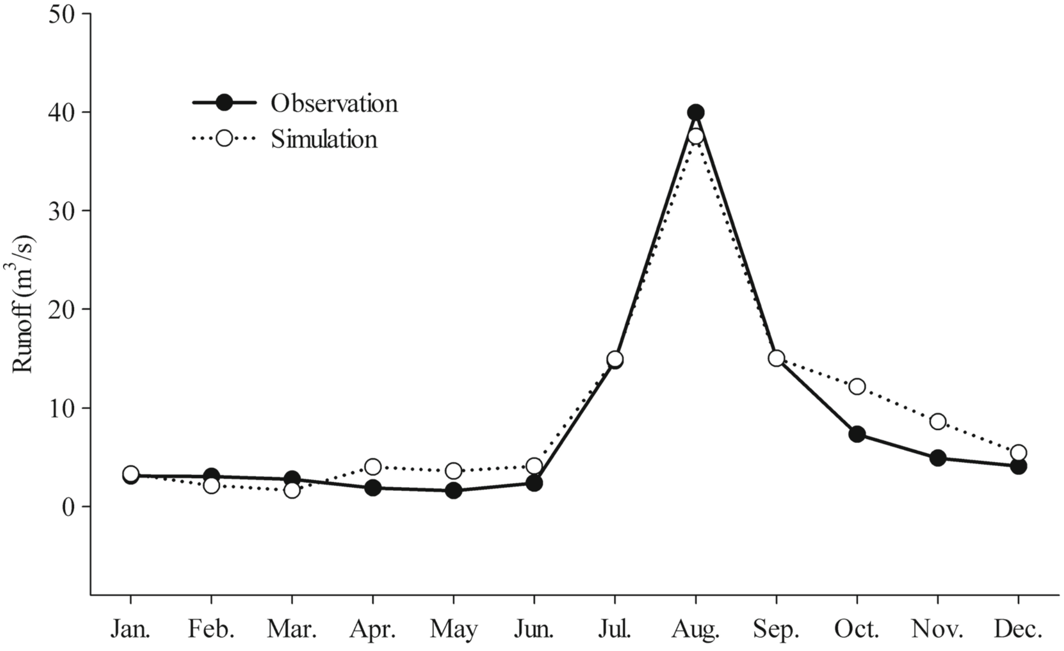

Figure 6. Observed and simulated multi-year monthly average runoff.

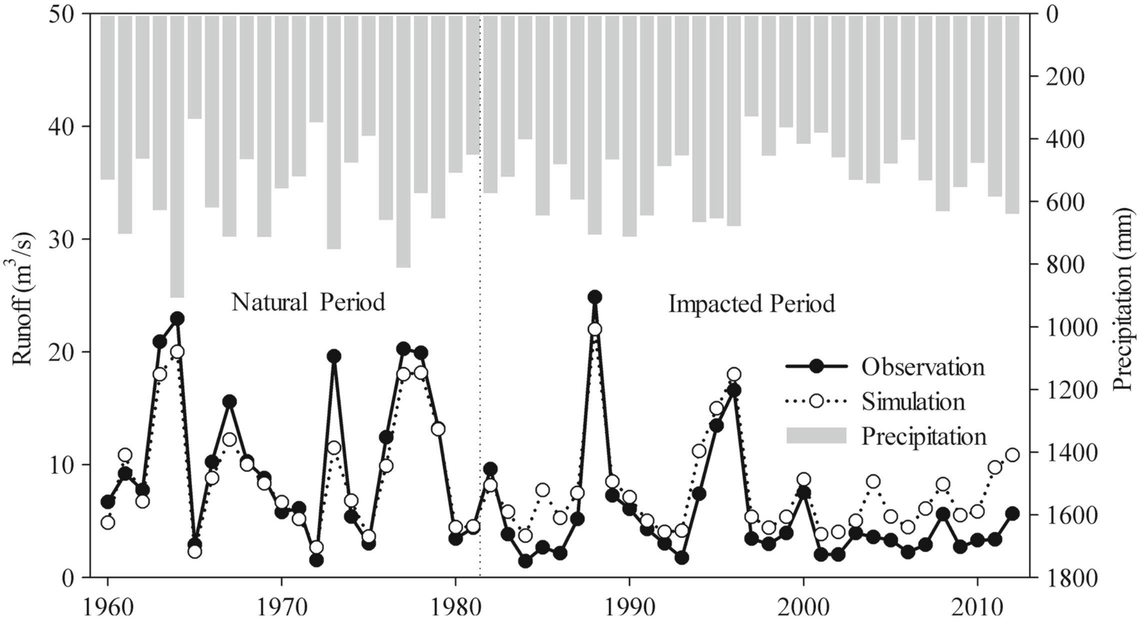

Figure 7. Observed and simulated annual runoff in the natural and impacted period.

4.4 *Contribution of climate change and human activities on runoff reduction*

The runoff change could be driven by climate change and human activities. In this study, the contribution of climate change and human activities on runoff reduction was discussed by using SWAT model and the elastic coefficient method. Among the factors, temperature, precipitation and evapotranspiration were discussed as the main climate factors, while human activities mainly included land use/cover change and water resource exploitation.

The detailed separation process of SWAT model is explained as follows: based on the simulated results, the difference of simulated runoff before and after the abrupt change point presented the impact of climate change on runoff reduction. The simulated average annual runoff was 133.89 mm in 1960–1982, which reduced to 105.36 mm in

Table 5. *Impact of climate change and human activities on runoff reduction.*

				SWAT model		Budyko hypothesis	
Periods	Q_{observe} (m^3/s)	Q_{simulate} (m^3/s)	ΔQ (m^3/s)	$\Delta Q_{\text{climate}}$ (%)	ΔQ_{human} (%)	$\Delta Q_{\text{climate}}$ (%)	ΔQ_{human} (%)
1960–1982	10.44	9.34	–	–	–	–	–
1983–2012	5.29	7.35	5.15	38.64	61.36	36.31	63.69

Table 6. *Mann–Kendall test on monthly runoff, temperature and precipitation.*

	Runoff			Temperature			Precipitation		
Month	β	Z		β	Z		β	Z	
Jan.	−0.011	−3.11	***	0.05	4.00	****	−0.05	−2.71	***
Feb.	−0.009	−3.25	***	0.08	3.92	****	−0.06	−1.65	R
Mar.	−0.013	−3.84	****	0.06	3.67	****	−0.10	−1.51	R
Apr.	−0.006	−1.71	R	0.05	4.39	****	−0.02	−0.22	R
May.	−0.002	−0.74	R	0.03	3.72	****	0.30	2.18	**
Jun.	−0.006	−1.41	R	0.03	3.40	****	0.34	1.34	R
Jul.	−0.035	−2.07	**	0.03	3.35	****	−0.85	−1.94	R
Aug.	−0.169	−2.61	***	0.03	3.55	****	−1.30	−2.52	**
Sep.	−0.052	−2.00	**	0.04	4.25	****	0.15	0.56	R
Oct.	−0.031	−2.40	**	0.04	4.22	****	0.02	0.12	R
Nov.	−0.019	−2.73	***	0.04	2.54	**	−0.15	−1.53	R
Dec.	−0.013	−2.82	***	0.04	3.16	***	−0.04	−1.60	R

β is 10^8m^3/a in R, mm/a in P and °C/a in Ta.
****Significant at $P = 0.001$, ***Significant at $P = 0.01$ and ** Significant at $P = 0.05$, R = Reject the null hypothesis.

1983–2012. Compared to the 73.82 mm total runoff reduction, the simulated annual runoff decreased by 28.53 mm, which presented that 38.64% of annual runoff reduction was caused by climate change, and 61.36% of annual runoff reduction was caused by human activities (table 5).

The impact of climate change and human activity on runoff reduction also could be estimated using the elasticity coefficient method (table 5). In this study, the runoff sensitivity to precipitation and potential evapotranspiration was calculated during 1960–2012, and the values of β and γ were 0.507 and −0.157, respectively. Then the effect of climate change on runoff reduction was isolated through equation (14): 50 mm precipitation reduction led to 28.2 mm runoff reduction, while 10 mm potential evapotranspiration reduction led to 1.4 mm runoff reduction. The decreasing precipitation and potential evapotranspiration resulted to 26.8 mm runoff reduction. Therefore, considering the 73.82 mm total runoff reduction, the effect of climate change and human activities on runoff reduction accounted for 36.31 and 63.69%, respectively.

In general, the isolated results through SWAT model and the elasticity coefficient method were consistent, and the results had good reliability and persuasion. In the North China Plain, some existing research (Liu and Xia 2004; Wang *et al.* 2008; Bao *et al.* 2012) indicated that human activities (∼60%) were the dominant factors for runoff reduction, which were consistent with our study.

4.4.1 *The impact of climate change on runoff*

Temperature and precipitation are two main climate factors associated with runoff change. In order to further understand their relationship, the variation of monthly and seasonal temperature, precipitation and runoff was analyzed through Mann–Kendall test, and the results are presented in tables 6 and 7. The mean monthly temperature all shows a significant increasing trend in 12 months, with 11 months having statistical significance at $\alpha = 0.001$ level except November ($\alpha = 0.05$). According to the β values, the highest increasing rate appeared in February and the

Table 7. *Mann–Kendall test on seasonal runoff, temperature and precipitation.*

Season	Runoff			Temperature			Precipitation		
	β	Z		β	Z		β	Z	
Spring	−0.02	−1.82	R	0.05	4.98	****	0.17	0.67	R
Summer	−0.27	−2.76	***	0.03	3.91	****	−1.72	−2.23	**
Autumn	−0.11	−2.37	**	0.04	4.94	****	0.17	0.42	R
Winter	−0.04	−3.83	****	0.06	4.93	****	−0.16	−2.45	**

β is $10^8 \mathrm{m}^3$/a in R, mm/a in P and °C/a in Ta.
****Significant at $P = 0.001$, ***Significant at $P = 0.01$ and ** Significant at $P = 0.05$, R = Reject the null hypothesis.

lower ones appeared in May to August. Thus, winter months had larger increasing rate than summer months, which was consistent to the seasonal trend in table 7. The β values of precipitation varied monthly and seasonally. There was an increasing trend in May, June, September and October. The increasing trend was not significant, only the value in May passed the confidence test ($\alpha = 0.05$). A decreasing trend was tested for the rest 8 months, with statistically significant trend only in two months (August and January). Seasonally, the highest decreasing rate of precipitation happened in summer, which was the most important reason for precipitation decrease. The runoff in each month and season had a statistically significant decreasing trend according to the negative β values. Seasonally, the highest decreasing rate of runoff appeared in summer (August), which was consistent with the change trend of precipitation.

Temperature rise aggravated evaporation, coupled with precipitation reduction, led to the decrease of runoff. The decrease of summer runoff was mainly due to the precipitation reduction and temperature rise over the same period, but the decrease of runoff in other seasons was mainly affected by precipitation reduction. The temperature and runoff presented significant negative correlation, while precipitation and runoff showed positive correlation.

4.4.2 *The impact of human activities on runoff reduction*

In addition to climate change, human activities, such as land use/cover change and water resource consumption, are more important factor on runoff reduction. In this study, land use was divided into six types: cultivated land, woodland, grassland, water, construction land and unused land. Woodland and grassland accounted for 90% of the total area. During 1990–2010, grassland decreased by $23.29\,\mathrm{km}^2$. Cultivated land, water and unused land remained stable (table 8). On the contrary, the construction land expanded from 3.71 to $15.35\,\mathrm{km}^2$. The increase of construction land could reflect the industry development and population expansion, which resulted to the increase of domestic water and industrial water usage. Meanwhile, woodland increased by $15.93\,\mathrm{km}^2$. The woodland were mainly transferred from grassland, with the area of $14.74\,\mathrm{km}^2$. The newly woodland were mainly economic crops, such as walnuts, which consumed large amount of water and further led to runoff reduction. This was consistent with some related studies (Li *et al.* 2012; Zhang *et al.* 2012).

Besides the impact of land use/cover change, water conservancy projects and agricultural measures also affected water resources. In this region, numerous water conservancy projects had been built since 1958, which included five large reservoirs (Wangkuai, Xidayang, Longmen, Hengshanling and Koutou) and 105 medium or small reservoirs. The control area of these reservoirs was up to $10,000\,\mathrm{km}^2$, which accounted for 88% of the southern mountain area. The water conservancy projects destroyed the natural path of water cycle, which caused water loss due to the increase of evaporation and seepage (Yang 2010). Meanwhile, reservoirs strongly retained and regulated river runoff, which resulted to runoff reduction (table 8).

The abrupt change year (1982) of runoff was consistent with the beginning period of rural land reform. New land policy enhanced the farmers' enthusiasm, and food production increased significantly. However, the cultivated land remained stable and the water production efficiency is almost unchanged, which caused rapid increase of agricultural water usage (Hu *et al.* 2012). This could partly explain the rapid decreasing runoff after 1982. Therefore, agriculture development was also an important factor for runoff

Table 8. *The transition area among land use types from 1990 to 2010 (km^2).*

1990	2010 Cultivated land	Woodland	Grassland	Water	Construction land	Unused land	Total
Cultivated land	75.75	5.45	15.74	2.75	1.91	0	101.6
Woodland	3.31	746.66	74.18	1.42	1.49	0	827.06
Grassland	16.25	88.92	1089.17	4.28	9.26	0.02	1207.9
Water	2.57	1.87	5.16	9.69	0.02	0	19.31
Construction land	0.5	0.09	0.31	0.14	2.67	0	3.71
Unused land	0	0	0.05	0	0	0.08	0.13
Total	98.38	842.99	1184.61	18.28	15.35	0.1	2156

reduction in the upper reaches of the northern Taihang Mountain.

4.4.3 *Uncertainty analysis*

The uncertainty for the model mainly lies in the determination of runoff discontinuity and reconstruction of the natural runoff. It is mainly influenced by the hydro-meteorological data, model parameters and model structure. The limited meteorological data are difficult to truly represent the actual climate condition. There are some unavoidable errors for calibrating the model parameters. The SWAT model cannot simulate the entire physical process of hydrological cycle in a basin scale. Though the SWAT model obtained a satisfactory result, the reconstructed annual runoff in the natural phase has some difference compared with the measured annual runoff.

5. Conclusions

Climate change and human activities are the two main factors on runoff change. Quantifying the contribution of climate change and human activities on runoff change is important for water resources planning and management. In this study, the non-parametric Mann–Kendall rank test and the Pettitt change-point statistics were employed to detect variation trend and abrupt change points of hydro-meteorological factors in 1960–2012. And then the flow duration curve (FDC) was used to analyze the runoff regime. Then, the contribution of climate change and human activities on runoff change was calculated based on the SWAT model and the elasticity coefficient method. The evolution rules and driving mechanisms of runoff change were discussed. According to this study, several facts were worth highlighting:

Compared to the increasing trend for annual temperature, the significant decreasing trend was detected for annual precipitation and runoff, with an abrupt change point in 1982. The whole period was divided into the natural period (1960–1982) and the impacted period (1983–2012). The runoff regime showed a 25% relative reduction for most percentile runoff, especially for high runoff, which showed a 50% reduction.

The simulated results of SWAT presented good consistency with observed ones, and the values of R^2 and E_{NS} all exceeded 0.75. The contribution of climate change and human activities on runoff reduction was 38.64 and 61.36%, respectively. The elasticity coefficient method also obtained the same results, with the contribution of 36.31 and 63.69%, respectively. The results presented good reliability and persuasion.

Besides the precipitation reduction and temperature rise, excessive human activities were the main factors for runoff reduction: the increase of economic forest and construction land to some extent reflected the economic development and population expansion, which led to more domestic and industrial water consumption. Meanwhile, water conservancy projects changed the runoff generation condition.

The results could be useful for understanding the variation process and driving factors for runoff reduction in the basin. Yet, human activities and climate change are usually assumed independent factors without considering their relationship and interaction. How to separate their impact more scientifically and reasonably is still a difficulty in the future research. In addition, human activities contain many aspects, and the exact quantification of each individual factor is difficult. Those above issues all should be improved in future research.

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